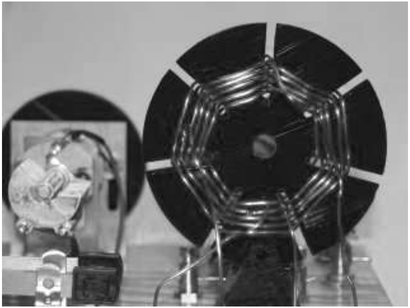
KEVIN'S WEBSURFER HANDBOOK VI
FOR CRYSTAL RADIO

RADIO WAVE PROPAGATION



Kevin Smith
2013

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http://www.lessmiths.com/~kjsmith/crystal/catalog.shtml

KJ Smith

NOTES:

Introduction

This handbook is primarily devoted to radio wave propagation. This is not a topic specific to crystal radio but to radio generally and here with a mind to LW/MW propagation. For many in the crystal radio hobby, long-distance reception, or DX, is an interesting and sought after goal. Understanding propagation adds to the joy of the hunt. Additionally, as crystal sets have no amplification or signal modification other than rectification, they are more subject to the vagaries of atmospherics and propagation irregularities.

We open with Tom Giella's excellent layman's overview of MF propagation. This discussion reviews medium frequency propagation from a thoroughly modern standpoint, benefitting from land and space-based tools and 100 years of progress in understanding the phenomenon. This is the answer and if propagation is your only interest then you can stop reading after this article. Following this we step back in time to the days of spark transmission and unamplified reception. First Chen-Pang Yang reviews the intellectual background of the scientists and engineers who were involved and the new observations they were working to explain. From here I provide source documents written by the players themselves. These give a feel for the excitement of discovery and advancement that characterize the early days of radio. Finally, I provide a personal study on propagation made in the late 1980's. This gives some personal perspective as well as highlights the interesting kind of projects available to the hobbyist.

Of general note, the web is a marvelous source of data and information. Many long-time crystal set builders, and many others have created dedicated sites to disseminate information and resources, to share their creations and knowledge. I am eternally in your debt. All of the material in this handbook is copyright for which I have not sought permission. Therefore this is not presented for publication or copy. It is only my personal resource. I encourage anyone finding this copy to pursue ON THE WEB the web pages identified within. I include the name of the author and web address of each section. I wish to sincerely thank every author presented for their excellent pages and ask forgiveness for my editing into this handbook.

Kevin Smith
2013

www.lessmiths.com/~kjsmith/crystal/cr0intro.shtml

NOTES:

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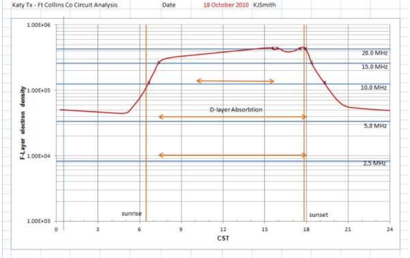
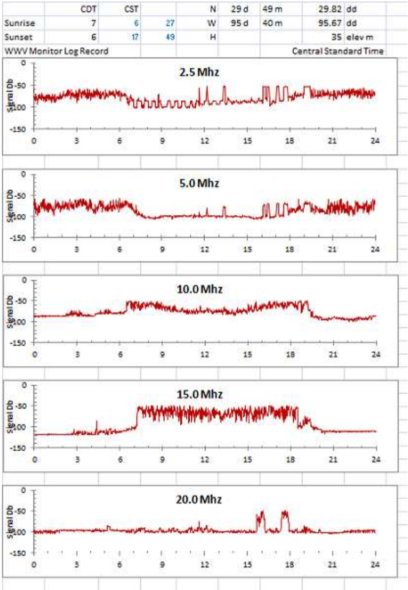
Below is my “ionosond” display for that day.



Would that I had such equipment back in 1987. Times have changed and so has the hardware with which we use, but the work goes on!

Kevin Smith
2010


CDT CST N 29 d 49 m 29.82 dd
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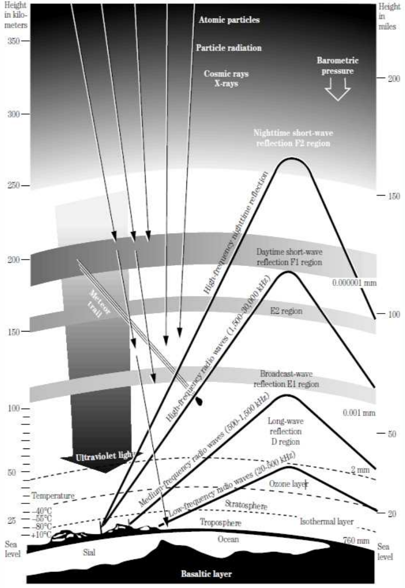
Signal Db



2-7 Radio propagation in the ionosphere is affected by a number of different physical factors: cosmic rays, atomic particles, solar radiation.

Joseph J. Carr

Postscript 2010

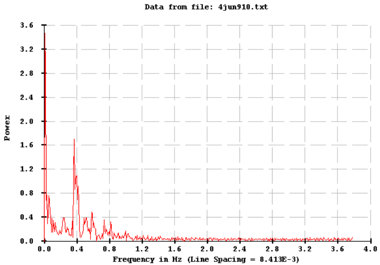
The above report describes a study I made back in 1987 – 1991. At the time my tools included a good communications receiver (Yaesu 7700) coupled to a Commodore 64 computer. The connection was cobbled together via the game port interface. Looking back, it seems amazing that it worked at all. Today with modern receivers like my Icom R75 we can connect directly to a modern personal computer with the radio's built-in interface. Monitoring several bands becomes an easy pursuit with the correct software.

Below I provide two figures made with my current setup. The date 18 October. The record shows simultaneous monitors on 2.5, 5.0, 10.0, 15.0, and 20.0 MHz WWV. The easiest bands to interpret are for 10 and 15 MHz. For 2.5 and 5 Mhz the record is best interpreted in terms of D-layer absorption. 20 MHz is barely reached except for two small blips at 16 and 17h CST.

small compared to the 15MHz carrier. On top of that is a second interesting beat in the amplitude with 40 to 50 second period or about 0.02Hz (also seen on the power spectrum).

Voila! No noise at all, just signal everywhere.

Supplemental Records



Power spectrum of the data collected on 04 June, 1998. The data was converted to the frequency domain via a Fourier transform.

Fin.

MEDIUM FREQUENCY RADIO WAVE PROPAGATION THEORY NOTES

Layman Level Explanations Of "Seemingly" Mysterious MF Radio Wave Propagation Occurrences

By: Thomas F. Giella, W4HM

http://www.wcflunatall.com/propagation5.htm

0.) Introduction.

Welcome to the "W4HM Medium Frequency Radio Propagation Theory Notes" weblog styled website. Contained within you will find the most comprehensive explanation of medium frequency radio propagation occurrences on the Internet.

In my personal opinion understanding and taking advantage of low/medium/high frequency radio propagation conditions is an integral part of successful DX operation. Therefore this site exists as an educational tool.

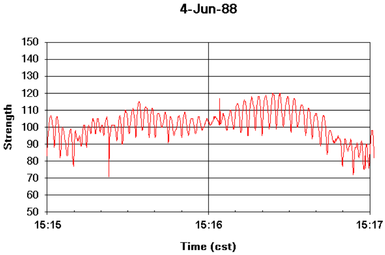
This website is permanently under construction as I add new data and research information continuously. If you see any spelling or sentence structure errors I've overlooked "please" feel free to advise me, thanks! Also feel free to ask for inclusion on this website of "legitimate" propagation theory. Remember that the definition of "theory" means that the concept has not or can not be definitively proven in a laboratory setting but can be inferred via systematic study.

These theory notes are primarily applicable to the 300-529 kc long wave aviation and marine navigation beacon band, 600 meter band, 530-1700 kc AM broadcast band, 160 meter amateur band and 120 meter shortwave tropical broadcast band. However much of the content is also applicable to the 3000-30000 kc HF shortwave spectrum.

A while back I became involved in a propagation research project of sorts on 10, 6 and 2 meters. I have set up a propagation beacon currently on 10 meters, the frequency is 28131 kc USB +1500 Hz using 25 watts. Actually there is a group of hams running the propagation beacons in the U.S. and around the world. Basically it's a marriage between digital PSK31 and APRS technology, actually software's run on a computer that is interfaced to a transceiver. Beacon transmission will commence on other HF bands in the future, with the ultimate aim of all HF bands and even 160 meters. It's been very interesting so far watching Es and F2 propagation openings on 10 meters, when conventional propagation wisdom says that the opening should not be occurring. A knowledgeable observer can also pick out Sporadic-E (Es) openings. You can learn more about the concept by clicking here for HF PropNET.

I have attempted to keep the propagation theory explanations in simple to understand layman terms, because long complicated technical explanations can be boring and make one's eyes glaze over. Unfortunately though sometimes while trying to keep things simple, certain definitions, meanings and technical aspects can get watered down or even lost, which tends to open me up to criticism from certain fellow space weather scientists that just don't understand the educational and public relations concept of the keep it simple stupid (KISS) principle. I choose to use W6SAI's (SK) "KISS" method of writing and communicating. I have found that this method works best whether it be in teaching about space or atmospheric weather or any other subject.

seen the characteristic signature of signal fading. There are in fact two periods of fading superimposed, one of about 50 seconds, the second about 5 seconds. The fading has the typical rounded crests and sharp drop to the separating nodes. This pattern results from the beat amplitude of two or more interfering signal frequencies.

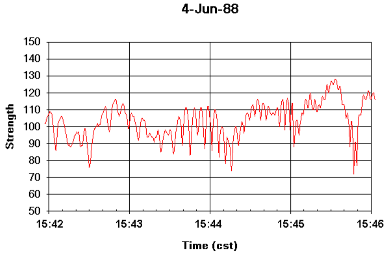


characteristic signature of signal fading

The second chart is from a run of only seven minutes giving about a tenth second interval between readings. There the fading signature shows with about 50 beats over the two-minute interval shown. Fading generally results from the interference of the same signal arriving from two paths at the receiver. A power spectrum of the data shows a strong peak around 0.4 hertz corresponding to the dominant beat (25b/m or 0.4b/s). For a beat to be set up the signals traveling along separate paths, (presumably a single hop and a double hop) they must not merely be arriving slightly out of phase but also with a difference in frequency of 0.4Hz. That shift is extremely

The "Grass", Noise Revealed

Some final words and observations concerning the "grass", the noise on the records with the very high frequency. Hidden within that noise lies some interesting signals and an interesting message. This "noise" seen on the records is in fact just more signal, but at a higher frequency than I have been presenting. The following charts were made on 04 June, 1988. They were taken specifically to look at the high frequency content of the signal. It should be noted that in both charts the signal strength scale remains exactly the same as in all the previous charts so the amplitude of the "noise", the range from crest to node is quite significant when compared to the daily variations being measured.



characteristic signature of signal fading

In the above case I gathered a standard 3200 points over 29 minutes with no filter giving a half-second period between points. The chart shows four minutes of data and on it can be

We hams are a curious lot with inquiring minds. A good number of us have a keen interest in low, medium, high and very high frequency radio wave propagation mechanisms and this website conglomeration is directed at this forward looking group.

We also have a segment in our radio service that is basically disinterested in radio propagation and don't feel it necessary to understand it in order to successfully work DX, which is certainly okay. However within this group exists a total lack of understanding concerning the most basic aspects of the subject. Often times I will hear them say, "The band is shifting". This lack of basic knowledge can be traced back to the licensing process where very few questions exist in the exam pools.

Then we have a third and smaller group with gigantic runaway egos that insist that they are omniscient by virtue of their Extra Class license, ARRL DXCC entity totals and "possible" electrical engineering backgrounds. Anal Retentive types?! They spend their time arguing with ignorance (Alchemists) against explanations put forth via this and other scientists, with solid backgrounds in atmospheric and/or space weather physics. You know who you are and should be ashamed of yourselves.

1.) Medium Frequency Radio Wave Propagation Overview-

Popular Myth- We don't understand medium frequency radio wave propagation mechanisms and therefore it can't be forecasted.

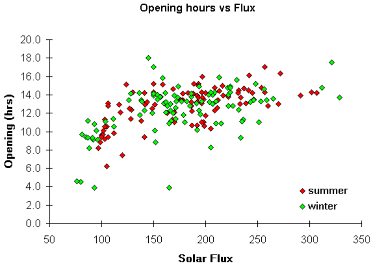
Fact- Yes it can and is on a regular basis at W4HM MF/HF/6M Frequency Radio wave Propagation Forecast http://www.solarcycle24.org and MF at http://www.wcflunatall.com/propagation.htm .

a.) Medium frequencies encompass 300 to 3000 kc. The simplest way to look at medium frequencies with respect to propagation issues from a layman's point of view, is to accept the fact that propagation is poor the majority of the time (See definition #6. Electron Gyro Frequency Absorption), especially past approximately 1250 miles (one refraction off of the E layer), with occasional short-lived good periods as far as 3200 miles.

Medium frequency radio waves possess elliptical polarization, with the signal splitting into ordinary and extra-ordinary rays. These rays can propagate in or out of phase, more often out of phase. The out of phase extra-ordinary ray represents a 50% power loss on the receive end of a path.

b.) Why is medium frequency propagation poor the majority of the time? D layer absorption! At daytime the D layer which is at an approximate height of 30-60 miles in the mesosphere, totally absorbs medium frequency RF signals the majority of the time. I say the majority of the time because at higher latitudes, during the winter season and especially at the low part of a sunspot cycle, daytime penetration of RF signals through the weakened D layer and then refraction via the E layer and/or Sporadic E (Es) clouds does occur. Another issue is the fact that the D layer does not totally disappear at night. Many books that deal with wave propagation erroneously state that the D and E layer's disappear after sunset, totally incorrect thanks to Galactic X-Rays, Galactic Cosmic Rays and Lightning.

otherwise. Increased ionization levels increase the signal absorption as well. Also, times of high solar activity bring instabilities in the earth's geomagnetic field. Both of these effects have an important impact on signal strength.

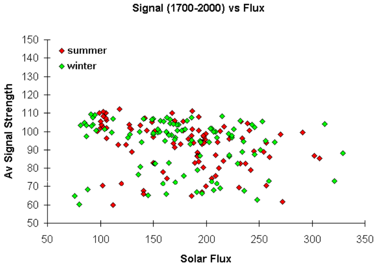


Solar activity (flux) vs length of openings

Solar activity (flux) on the other hand does indeed improve the conditions in terms of the length of the openings, especially for levels of flux above about 120. This is logical when considering the overall increased ionization levels. While the increased ionization may actually hurt signals by increasing absorption and causing greater geomagnetic instability, it does make for longer openings. Next: The "grass", noise revealed..

Signal Strength by Solar Activity

The following charts show the relationship of solar flux to signal strength and to the length of time for an opening for propagation along a circuit. Color coding provides an indication of the variation due to season as seen in the previous section. In this case I have distinguished "summer" from "winter" data on these charts in the following way: Winter = October to March, Summer = April to September.



Plot of signal strength averaged over the midday period 1700 - 2000UT

Plot of signal strength averaged over the midday period 1700 - 2000UT (11-13 CST).

For both summer and winter seasons I see a weak but real inverse relationship of decreasing average signal strength with increasing solar flux. It has often been stated that propagation improves during times of high solar activity, this data suggests

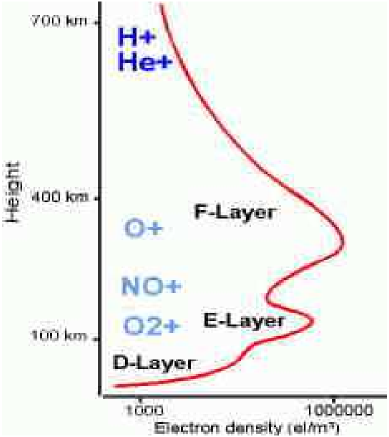
c.) Background electromagnetic radiation in the 1 to 10 Angstrom range (Hard X-Rays) is a major source of ionization of the day time D layer, with our Sun as the source of Cosmic Rays, also playing a role.

The following information was contributed by Carl Luetzelschwab K9LA, a scientist and all around great guy with a very good understanding of radio wave propagation.

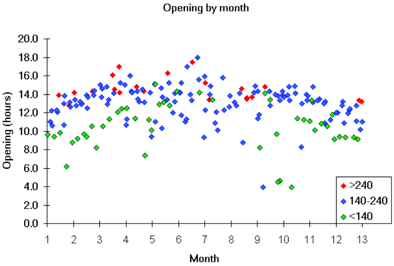
.....A couple years ago I was playing with Proplab Pro on a one-hop 936km path on 160m during daylight. I plotted absorption versus sunspot number. I expected a nice monotonic increase as the sunspot number increased. But the plot showed that absorption started at about 60dB at zero sunspots and was constant out to a sunspot number of about 50. Then it started climbing, reaching 100dB at a sunspot number of 150. This suggested that there was something other than hard X-rays and Galactic Cosmic Rays as the source of daytime D region absorption. So I dug into Davies 1990 (page 61), Hunsucker and Hargreaves (page 31), and Brekke (page 233). They all seem to point to the Lyman-alpha line of the solar spectrum at 1215 Angstroms ionizing NO as the main source of the quiet daytime D region. So in terms of my absorption versus sunspot number plot, the flat portion up to a sunspot number of 50 is probably due to the Lyman-alpha line ionizing NO. Then above a sunspot number of 50 the hard X-rays start contributing as the Sun becomes more active.....

Carl has produced two really good .pdf files on 160 meter propagation in 2003 and 2004. Read them here: 160 Meter Propagation & Disturbances To Propagation . He also has a propagation website with allot of good information on it at K9LA's Amateur Radio Propagation. In 2009 Carl produced yet another excellent article on 160 meter operation at Is This

Solar Minimum Better or Worse Than the Last Solar Minimum on 160m?

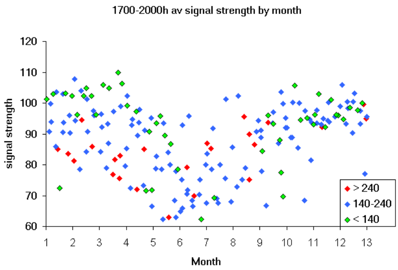


Ionosphere Ion Types



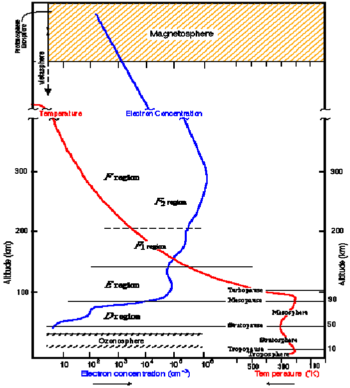
opening hours versus season

When plotting the length of time of the openings by season the situation is reversed with longer openings showing a weak but real preference to the summer season. This results principally from the longer time of ionizing radiation on the ionosphere, but in this case moderate to high levels of solar flux can add one to two hours of additional opening per day. I agree with the oft-stated general conclusion that winter is the best time for long distance communication by HF radio, but given the scatter I would temper that by addressing more closely the question of solar activity. Next: Signal strength by solar activity..



signal strength versus season

This chart, already presented in section 3.2, clearly shows that the summer season does not provide the same signal strength that can be found in winter. In general summer openings have low signal strength and greater variation from day to day. Overall they are less dependable. The chart distinguishes data collected under conditions of different levels of solar flux, (low flux in green to high flux in red). Curiously, there is a clear association between the strongest signals and the lowest levels of solar flux.



Ionosphere Profile

Also speaking of the ionosphere at and near solar minimum the mid and high latitude D layer of the ionosphere at mesosphere altitude cools approximately 2 degrees C, contracts in thickness and signal absorption in the layer increases.

While I'm visiting the subject of electromagnetic radiation, our Sun emits electromagnetic radiation and matter, as a result of the nuclear fusion process. Electromagnetic radiation at wavelengths of 100 to 1000 Angstroms (Ultraviolet) ionizes the F layer, radiation at 10 to 100 Angstroms (Soft X-rays), as well as Galactic Cosmic Rays ionize the E layer. Galactic X-rays, Galactic Cosmic Rays and Lightning are the reason that the E layer is "always" present at night time, the D layer also. Background electromagnetic radiation in the 1 to 10 Angstrom range (Hard X-Rays) is a major source of ionization of the day time D layer,

Via K7RA's weekly ARRL Propagation Forecast Bulletin #46 published on November 9, 2007:

In last week's bulletin, Carl Luetzelschwab K9LA said the closest measurement we have to radiation that ionizes the F2 region is the GOES X-ray data at 0.1 to 0.8 nm. K9LA says that is not correct- he received an e-mail from Michael Keane, K1MK, with the following information:

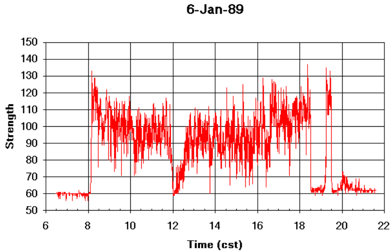
"There does exist an instrument that measures solar EUV flux directly. That is the SOHO Solar EUV Monitor (SEM) at http://umtof.umd.edu/semflux. One SEM channel covers solar EUV in the 17-70 nm range. The other channel monitors just the 30.4 nm resonance line of singly ionized helium. In most models, this 30.4 nm line by itself represents 25-50% of the energy input to the thermosphere/ionosphere."

Galactic Cosmic Rays are not rays at all, but particles. They are ionized atoms, atoms with missing electrons ranging from a single proton up to an iron nucleus and beyond but typically protons and alpha particles, which have 2 protons and 2 neutrons. They originate from deep space, being produced by a number of different sources, such as other stars, and more exotic objects, such as supernova, which are exploding stars and their remnants, neutron stars, black holes, and distant galaxies. Cosmic Ray particles travel very close to the speed of light, and are highly energetic.

Signal Strength by Season

After spending some four years collecting and analyzing propagation data, it is reasonable to have a few observations concerning the subject. I have often read general statements concerning propagation versus time of year and solar cycle, so how did this study compare? Keep in mind that the entire data set is from a single circuit, Ft. Collins, Colorado to Houston, Texas, and that it is for a single frequency, 15.000 MHz. While it cannot be generalized to all HF radio, it provides a good test under semi-controlled conditions. Another assumption that is implicit in all this data is that the transmitted power remained constant over the whole period. I will make that assumption while noting that I did not ever confirm it to be true.

The following charts addresses the question of signal strength and opening hours versus season. Color coding provides an indication of the variation due to solar flux, but this will be explored more in the next section.



06jan89
Major flare at 1805UT, (1205 CST). Also note the evening signal dropout and return.

While on the subject of distant galactic objects, on 12/27/2004 more than a dozen spacecraft recorded the brightest event from outside the solar system ever observed in the history of astronomy. This gamma and x-ray producing super flare was emitted by a Magnetar star named SGR 1806–20. This star is an estimated 50,000 light years distant in the constellation Sagittarius on the far side of the Milky Way galaxy and obscured behind dense interstellar clouds. A similar event also occurred in 1998.

Upon arrival at Earth the X-rays were powerful enough to increase absorption in the D layer of our ionosphere and create a dayside Sudden Ionosphere Disturbance (SID) and a blackout of radio signals, amazing!!! To read more about this rare event check out this link at: http://skyandtelescope.com/news/article_1464_1.asp and http://www.sciencedaily.com/releases/2006/02/060221084628.htm .

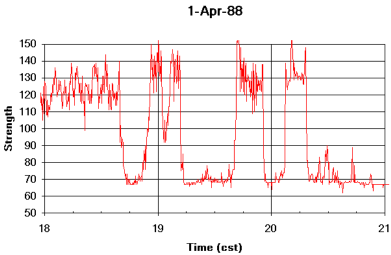
d.) Recently I saw a post on the Topband Reflector lamenting the seemingly unexplainable differences in 160 propagation on certain paths from night-to-night. is there a reasonable explanation? Yes, unfortunately small increases in the density of the night time D layer over short periods of time, caused by smaller solar flares and also the general variability of the solar background X-Ray flux level of greater than A0, can have a profound negative impact on propagation in the form of increased absorption of high and even mid latitude medium frequency signal paths, both on the medium frequency AM broadcast band, 160 and 120 meters. Why? It only takes 10 electron volts (ev) of energy to ionize the atmosphere and 1-10 Angstrom x-ray photons energize the atmosphere at a factor of 100. This translates into D layer absorption of medium frequency signals. The lower half of the medium frequency broadcast is always affected first followed by the upper half of the medium frequency AM broadcast band, then 160 and 120 meters. If you learn nothing else on this website, remember this simple explanation and pass the word.

e.) After much personal observational research over a 35 year period, I've come to the conclusion that high and mid latitude TA and TP propagation paths tend to open up only after an approximate three day period of time passes with an energetic proton event of no greater then (10+0) on the medium frequency AM broadcast band, 160 and 120 meters.

f.) Also there are daily extremes of the background x-ray flux level. So even though the daily average might have been pretty good at say A1.1, the daily "extreme" maximum could have been C1.5, which would have been bad and would have caused a short period of increased D layer absorption.

g.) Though high latitude paths on the day light side of the Earth are primarily effected, night time high latitude paths can also be impacted by higher intensity energetic proton events. This fact is still stubbornly opposed by some otherwise very knowledgeable space weather physicists hung up on high latitude threshold Riometer data tied to Polar Cap Absorption (PCA).

h.) Another wrench in the gears preventing consistent good propagation on medium frequencies is related to Sporadic-D (Ds) absorption. Sporadic-D (Ds) occurrences have an inter-relationship with brief but intense Sun based and Galactic Cosmic Rays, extremely large positive cloud to ground lightning strokes and interrelated Elves. Very large bursts of Gamma Rays have also been observed to occur in conjunction with Sprites.



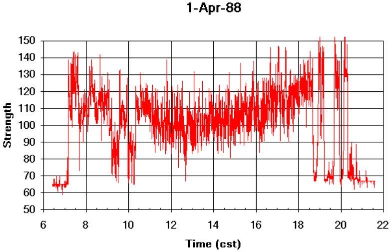
record for 01 April, 1988, detail

The above view focuses in on 18 to 21 CST showing more detail in the features. They clearly represent moments where the ionosphere electron density is passing repeatedly through the critical density for propagation. These features show a sinusoidal variation in electron density with a period between 25 and 30 minutes, (from drop to drop). I interpret the variations as density waves propagating in the ionosphere. A test of this would require one or preferable two other beacons being monitored at a close frequency to see whether the same features appear offset in time. Note also on the first chart that there are two signal loss periods between 9 and 11 CST as well, more evidence of unsettled conditions in the F layer that day.

Similar features appear on other records already presented in this article such as 06 January, 1989.

Density Waves

On a number of records I found interesting features which were not easily explainable. The record below for 01 April, 1988 shows a series of falls and jumps in signal strength between 18 and 21 CST. Similar features can occur on the morning side as well as the evening side, but seldom near midday.

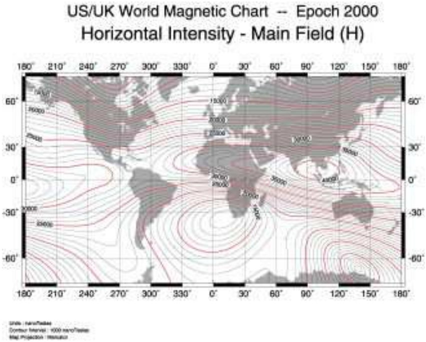


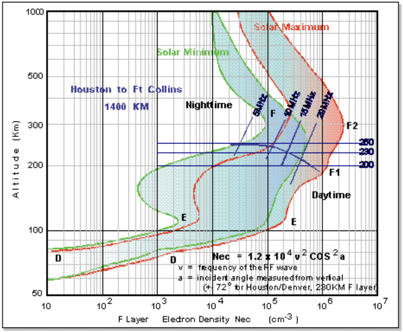
record for 01 April, 1988

i.) Also there is another unavoidable problem, Magneto Ionic Power Coupling. Antenna polarization plays a large role in the success of a long haul DX contact. As a medium frequency RF signal traverses Earth's magnetic lines of force in a perpendicular manner on high and mid latitude paths say between W3 land and SM, higher angle horizontally polarized signals are more readily absorbed than lower angle vertically polarized signals. On other propagation paths on the globe opposite results can be found, i.e., horizontally polarized signals suffer less absorption on a propagation path between VK6 and W6 or S9 and W4.

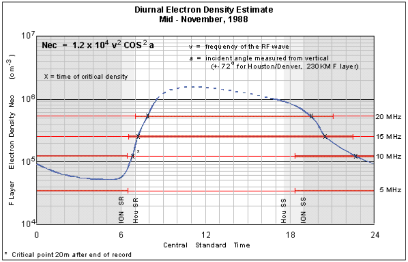
Magneto Ionic Power Coupling expert NM7M Robert Brown, PhD. has a good educational thread on this bugaboo on the May 2002 Topband Reflector. The thread can read in its entirety by going to this link Topband Reflector May 2002 Archives Layer .

Also an excellent but more technically oriented website covering 160 meter propagation and more is the "HF Propagation Tutorial" by NM7M Bob Brown, Ph.D. and hosted by ON4SKY Thierry Lombry and can be found at: http://www.astrosurf.com/luxorion/qsl-hf-tutorial-nm7m.htm .





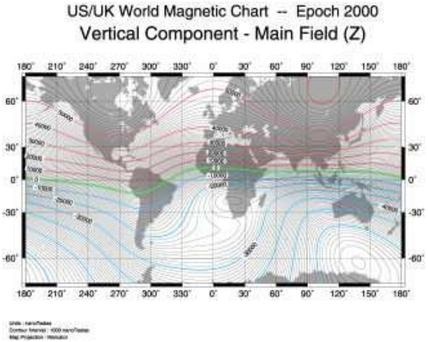
Electron density versus altitude as per section 2.2. This chart shows lines of criticality for different transmission frequencies on the Houston - Ft. Collins circuit. As the ionosphere ionizes in the morning or recombines in the evening, the density passes critical in the altitude range of 220 to 250 Km. Note that the F-Layer density never falls below critical for 5MHz, but does affect 10 through 20MHz. The November 1988 test was somewhere between solar minimum and maximum. (from Tascione, 1988)



curve of the diurnal change in ionosphere density

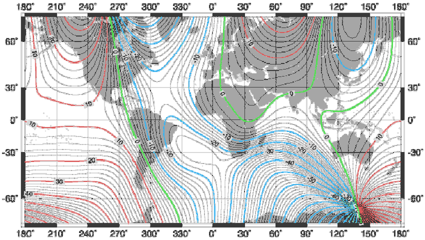
The plot shows that the ionosphere goes through a morning period of fairly rapid ionization peaking perhaps around 10am CST (1600UT). Then the process stops and reverses, going through a slower recombination period in the evening and into the night until near ionosphere sunrise the process again reverses and repeats the rapid ionization. This plot in fact compares quite well to published mid-latitude ionosonde data such as Olivier and others, 1988. It is even possible, where circumstances permit, to see more rapid ionospheric variations as described in the following section. Next: Density waves..

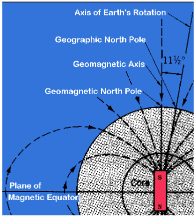
Supplemental Records



Horizontal & Vertical Components Of Earths Geomagnetic Field

US/UK World Magnetic Chart -- Epoch 2000
Declination - Main Field (D)





Earth's Geomagnetic Field

Poor Man's Ionosonde

My reading suggested a solution to the ionization problem described in the previous section. This solution dispensed with the notion that the jump in signal strength was caused by some jump in F layer ionization. It can be found in the relationship between the main parameters affecting propagation: Nec - electron density (cm^-3), v - frequency, and a - incident angle measured from vertical. The expression is as follows:

Nec = 1.2 x 10^4 v^2 cos^2 a

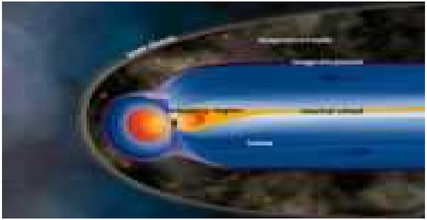
If this expression were true, then it was simple to devise a test to confirm it. If the ionization truly proceeded at a much slower rate, it should affect different radio frequencies at different times, in a regular manner. The beacon, WWV, transmits as previously stated at several frequencies, 2.5, 5.0, 10.0, 15.0, and 20.0 MHz. With this beacon, I could maintain the same basic circuit geometry. In mid November, 1988 I conducted a series of recordings at 5.0, 10.0, 15.0, and 20.0 MHz which, when plugged into the above expression gave me discreet electron densities.

F Elev	Angle a	Frequency			
		5 MHz	10 MHz	15 MHz	20 MHz
250	71	3.34+E4			
240	71		1.24+E5		
230	72			2.59+E5	
220	73				4.26+E5

The signal jump would give me the exact time that the F layer passed the calculated critical density. The following chart is my curve of the diurnal change in density, a sort of "Poor-man's" ionosonde.

electron density, radio frequency, and incident angle which I explained in section 2.3. The answer to the problem presented itself quite simply: My circuit, Ft. Collins to Houston had a fairly fixed geometry (if you assume a constant 230 Km height for the refracting region, close but clearly not constant), and a single radio frequency of 15 MHz. The only variable then is the F layer density which goes critical at about 2.6 x 10^5 cm^-3. Below that density there can be no propagation. As the F layer ionizes, quite slowly perhaps, it passes that critical density and causes the sudden jump in strength seen on my records.

Pretty neat.. If you gather data and think about a thing, you are bound to learn something fascinating. The above relationship quickly suggested to me the experiment described in the following section.



Earth's Magnetosphere

j.) Geological effects such as earthquakes and volcanic eruptions, as well as meteorological effects such as troposphere originating Internal Buoyancy/Gravity Waves (IBGW), stratospheric level Quasi-Biennial Oscillations (QBO) and stratospheric warming (See definition #20 on Stratospheric Warming) have a negative effect on medium frequency RF signals in the form of small to medium increased absorption variations of medium frequency RF signals via the D layer caused by traveling ionosphere disturbances (TID's). Also temperature and moisture discontinuities (frontal inversions) can refract/scatter medium frequency radio signals in unpredictable ways, most notably on high transmitted RF power levels.

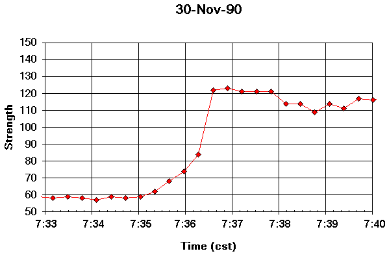
k.) The Quasi-Biennial Oscillation (QBO) is a wind shift in the equatorial stratosphere, an oscillation from easterly to westerly and back on the time scale of approximately two years (26 months) and is a source of Internal Buoyancy/Gravity Waves (IBGW's) which create absorptive perturbations in the D and E layers.

l.) A note, the E-valley/F layer ducting propagation mechanism does not exist only during gray line periods. Internal Buoyancy/Gravity Waves (IBGW's) are a source of the ducting mechanism and allow for occurrences of ducting along any propagation path in total darkness. Measurement of the timing of arrival of propagated medium frequency RF signals demonstrates the existence of the ducting mechanism, versus conventional numerous E layer land/ocean surface hops which, would allow for approximately 40 db of attenuation on a North America to Europe propagation path.

Another note! When it comes to 160 meter vertical antenna's you can get a lower take off angle (TOA) from a full 1/4 wave vertical or electrical 1/4 wave tee vertical of 10-20 deg., versus ~30 deg. with the inverted L. However it's a moot point as the night time E layer MUF blocks 160 meter low angle transmitted radio signals from ever reaching the F layer to be propagated. So unlike with high frequency propagation, medium frequency propagation success does not require the lowest of take off angles.

Also higher take off angles of 30-40 deg. via the inverted L are better able to take advantage of the low signal loss E valley-F layer propagation duct mechanism, a form of Chordal Hop propagation.

A solar flux of at least 150 is necessary for routine stable formation of the E Valley/F Layer ducting mechanism. Therefore formation of the duct is less prevalent at the bottom of solar cycle and long haul propagation poorer at solar minimum.



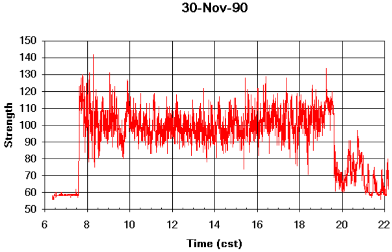
Record for 30 November 1990, detail

At the time I had the idea that the rise in signal strength in the morning, (and drop in the evening) was associated directly with the ionization of the reflecting F layer. As the layer ionized under the rising sun the signal would pick up. The records though could not be interpreted in that manner. As I thought about it, I realized that there were two problems with my theory: First, I noted the curious fact that sunrise on the F layer, and therefore ionization, took place up to one or two hours prior to the morning jump in signal strength (and vise versa in the evening). If the rise in strength was caused by a rise in ionization, why didn’t it occur earlier? Secondly, the duration of the jump, sometimes in just seconds was far too rapid. The volume of refracting space in the ionosphere was simply too large to be illuminated by sunrise and ionize so rapidly.

Thinking about this problem sent me to the textbooks and literature. There I learned about the relationship between the

Ionization Problem

Early on in my project I encountered a problem in the interpretation of the data. Most records like the one below for 30 November 1990, showed a very rapid increase in signal strength from near 60 (S0, no reception) to a maximum of 120 or more (S9+, extremely strong).



Record for 30 November 1990

The time from nothing to maximum was often under a minute or two, as shown in the detail chart below where in the minute around 7:36 am CST the signal makes its jump. (This also shows some of the tight detail available on the records which looks spiky on the normal 15-hour presentation charts).

m.) Yet another mechanism to deal with that impacts medium frequency radio wave propagation in a negative fashion is the D Layer Mid Winter Anomaly. It is a period of increased medium frequency radio wave absorption at high and mid latitudes occurring in mid winter and is associated with sudden stratospheric warming and the Quasi Biennial Oscillation (QBO).

n.) The HAARP ionosphere research program, earthquakes, volcanic eruptions, thunderstorms, lightning (especially positive cloud to ground strokes), elves, tornadoes, hurricanes and even man made activities such as rocket launches including the space shuttle, are all sources of (IBGW's). Many times I've heard ham's lament that propagation was going to go to crap due to another space shuttle launch, in a sense they are correct.

o.) Another issue facing medium frequency AM broadcast Band DXers and 160 meter operators is lower latitude propagation path absorption due to the Equatorial Ring Current. This phenomenon acts as a repository for precipitated electrons and the end result is unpredictable medium frequency RF signal blockage absorption and refraction. Absorption is similar to higher latitude Aurora absorption.

p.) LF propagation theory is out of my realm from a standpoint of formal education. Alan Melia G3YNK is studying LF propagation and has made some very interesting observations and put forth some fascinating theories.

Here are some interesting website links concerning LF and ELF radio propagation theory.

LF PROPAGATION THEORY INFO BY ALAN MELIA G3YNK (link broken)

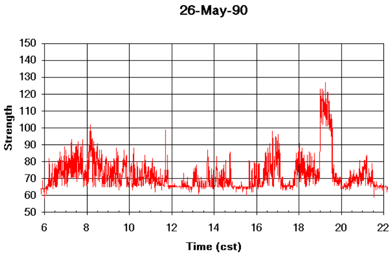
PROPAGATION OF LONG RADIO WAVES BY J.A. ADCOCK VK3ACA (link broken)

RADIO WAVES BELOW 22 KC
http://www.vlf.it/

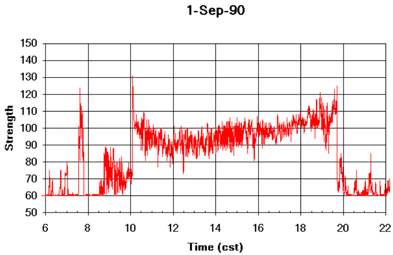
2.) Aurora Oval Blockage, Absorption And Refraction-

The aurora ovals "generally" have a negative impact on medium frequency propagation. If the path over which you are communicating lies along or inside one of the Aurora Ovals, you will experience degraded propagation in one of several forms; strong signal absorption, brief periods of strong signal enhancement, which is mainly caused by tilts in the ionosphere that allow signals to become focused at your location or very erratic signal behavior in the form of strong and rapid fading, etc., caused by a variety of effects such as multi-pathing, anomalous and rapid variations in absorption, non-great-circle propagation, horizontal or side refraction and/or scatter (skewing) due to changes in electron density and polarization changes. (See definition #7. Propagation Path Skewing).

When the Aurora Oval zones are contracted and latitudinally-thin coinciding with low geomagnetic activity, it is possible for a medium-frequency transmitted signal to propagate through the Aurora Oval zone without being heavily absorbed by skirting underneath it.



26may90
Major flare and geomagnetic storm, propagation never had much of a chance! Return..

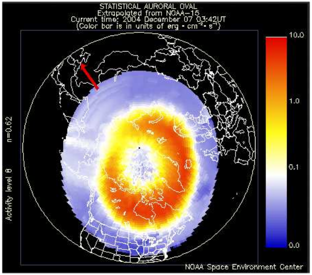


record of 01 September, 1990

This record for 01 September, 1990 indicates that not all geomagnetic activity necessarily destroys propagation. This day with Ap=26 had conditions ranging from quiet to major storm yet the openings remain generally good. Geomagnetic storms in fact can be quite local and do not a priori indicate poor communications. Recall that my recordings only probe a small portion of the ionosphere located about halfway between Ft. Collins, Colorado and Houston, Texas.

Supplemental Records

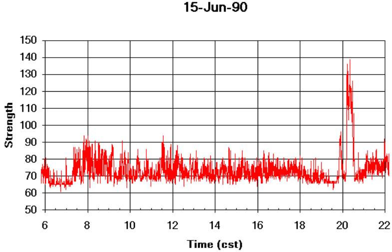
During periods of very low geomagnetic activity, areas of the Aurora Oval zones may only have a latitudinal thickness of approximately 300 miles. But radio signals reflected from the E layer can travel over distances of as much as 300 to 1250 miles at heights below the ionosphere for low take-off angles of between 10 and 25 degrees. When the geometry is just right, the medium-frequency transmitted signal can literally propagate underneath and through the Aurora Oval zones into the polar ionosphere which is less disturbed and from the polar ionosphere back into the middle latitude ionosphere, without ever coming in contact with the highly absorptive Aurora Ionosphere. This type of propagation is not as rare as you might think and it can provide unusually stable polar region path openings to (TA) Transatlantic and (TP) Transpacific regions. But because the Aurora Oval zone expands and contracts constantly, such conditions often do not last very long. (See definition #3. Equatorial Ring Current).



3.) Equatorial Ring Current-

A phenomenon that acts as a repository for precipitated electrons in the vicinity of the magnetic equator. The electrons travel by spiraling around north south magnetic field lines at a frequency called the 'gyro frequency. The end result is lower latitude propagation path medium frequency transmitted RF signal blockage and absorption via the D layer. Absorption is similar to higher latitude Aurora Oval absorption and is inter-related with same.

A reliable gauge for measuring the up to three day lingering post geomagnetic storming medium frequency transmitted RF absorption is the Dst index, measured in nT's. It is an estimated value from Kyoto Japan and is based on a formula. Large negative values after a major geomagnetic storm indicates a high Equatorial Ring Current level. (See definition #2. Aurora Oval Blockage, Absorption And Refraction). Here is a website link to the Kyoto, Japan Dst Index http://swdcwww.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html and the U.C. Berkeley website link http://sprg.ssl.berkeley.edu/dst_index and a NASA GSFC website link http://sprg.ssl.berkeley.edu/dst_index . (See definition #2. Aurora Oval Blockage, Absorption And Refraction). Another excellent source of a daily Dst figure is at http://www.alan.melia.btinternet.co.uk/latest.htm .

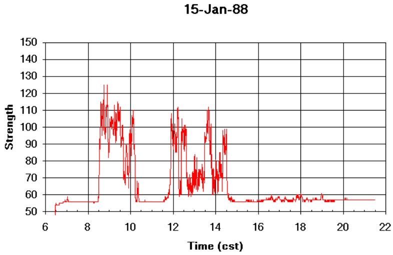


record of 15 June, 1990

Another storm ending on 15 June, 1990 in the summer season has in this record nearly wiped out the opening totally. Ap for the record also a high 47. Similarly, the flare and storm on 26 May, 1990 with an Ap=38 had terrible results for communications.

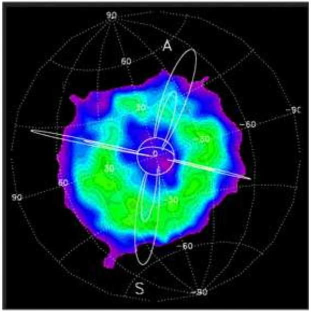
Unsettled to Active Field Response

Solar activity can cause disruptions of the earth's magnetic field leading to choppy or poor openings. The usual cause of these disruptions is the interaction of charged particles expelled from the sun by flares with the earth's ionosphere. Being charged, they carry magnetic field lines from the sun and distort the local earth field lines. The effects are most pronounced when the sun's magnetic poles are reversed with respect to the earth's. Even when sunspot activity seems low particles can still be ejected through coronal holes and disrupt local conditions.



record of 15 January, 1988

This record of 15 January, 1988 was taken on the last day of a major geomagnetic storm. The planetary "Ap" value, (a measure of geomagnetic activity) was a high 45. The openings here are choppy, short lived but still with good signal strengths typical of a winter record.



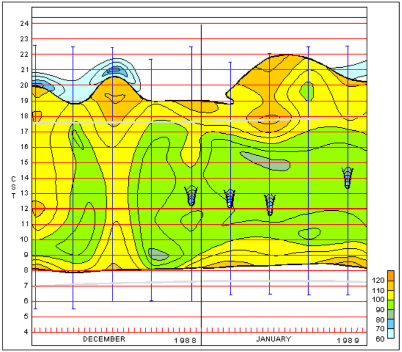
4.) Coronal Mass Ejection (CME)-

A Coronal Mass Ejection is the name given to an ejection of a large amount of matter from the Sun's outer atmosphere or corona. These ejections typically comprise millions of tons of material in the form of charged particles and can be seen because the material reflects sunlight. When one of these ejections is directed towards the Earth (or conversely, directly away from the Earth), it looks like a roughly circular "halo" surrounding the blanked out Sun.

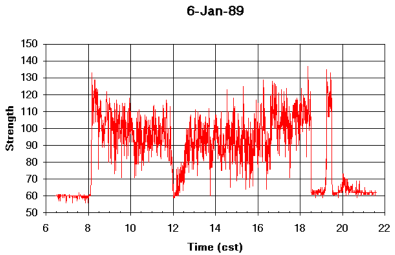
The "Halo CME's" are those CME's which are more likely to impact the Earth than those which are shot out at right angles to the Earth-Sun line. Energetic protons emitted during CME's play a major role in increased day time and night-time D layer absorption of medium frequencies.

Coronal Mass Ejections were once thought to be completely initiated by solar flares. However it is now known that many (CME's) are not associated with Solar Flares but instead with collapsing Solar Filaments. If a (CME) collides with the Earth, it can excite a Geomagnetic Storm if the polarity of the Interplanetary Magnetic Field (IMF) has a negative sign. We must be vigilant in watching for geo-effective (CME's), in order to not be caught by surprise with a seemingly sudden and unexpected Geomagnetic Storm. (See definition #6. Solar Filament). (See definition #11. Geomagnetic/Ionosphere Storm). (See definition #16. Solar Flare).

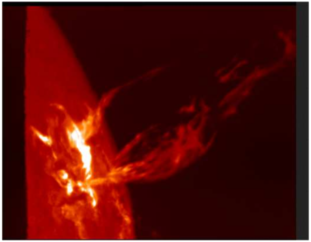
Coronal Mass Ejections are not random meaningless eruptions but instead a process by which the Sun expels complex magnetic signatures enroute to changing its magnetic polarity or said a different way the swapping of the Sun's magnetic poles. Basically the Sun swapped its magnetic polarity at the peak of present solar cycle 23 somewhere between July 2000 and December 2001. The next polarity swap will occur during solar cycle 24 somewhere around 2012.



Map for the winter 88/89 which shows the typical short openings and strong signals. Major flares on 30 Dec, 88, 1802 UT (1202 CST); 06 Jan, 90, 1805 UT (1205 CST); 13 Jan, 89, 1734UT (1134 CST); and 27 Jan, 89, 1917UT (1317 CST). Solar flux during the period was understandably high hovering between 154 and 170 in early December, jumping to 180 to 290 through January 89.



Major flare at 1805UT, (1205 CST). Also note the evening signal dropout and return.

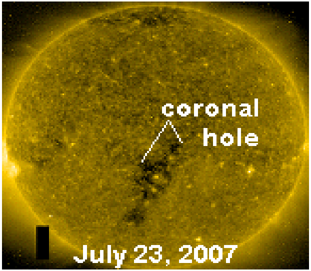


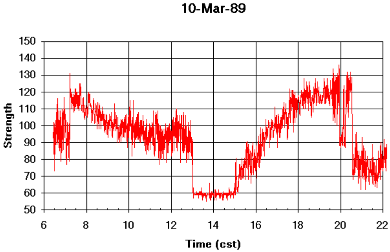
5.) Coronal Hole-

The Corona is not part of the Sun's surface. It is instead part of the Sun's atmosphere, much like Earth's troposphere. Coronal Holes are low density areas associated with open magnetic field lines and are found near the Sun's poles at the bottom of a sunspot cycle and everywhere during a cycle maximum. A Coronal Hole is a dark region where a breakdown in the magnetic field structure in the solar corona has occurred. From these regions stream the high velocity solar wind that is a source of geomagnetic storming on Earth.

Coronal Holes occur most often on the downside of a solar cycle and their absence at the bottom of a solar cycle and at the beginning of the next, allow for the best medium frequency radio propagation conditions. Many think it's the lower solar flux values seen at the bottom of a solar cycle that accounts for improved propagation conditions but it's actually pretty much a lack of Coronal Holes and geomagnetic storming. (See definition #11. Geomagnetic/Ionosphere Storm).

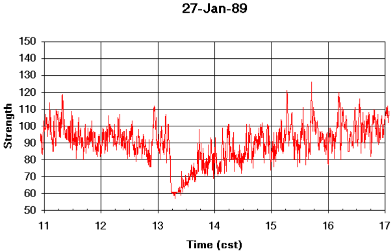
One thing to keep in mind is that the high velocity solar wind stream emanating from a Coronal Hole is a neutral phenomenon with respect to the Bz (magnetic component) of the Interplanetary Magnetic Field (IMF). If the Bz component is negative (southward) prior to arrival of the solar stream, there will exist a tendency to see a larger swing negative after the disturbance arrives. If the Bz component is positive (northward) prior to arrival of the solar stream, there will exist a tendency to see a larger swing positive after the disturbance arrives.





See «http://www.ips.oz.au/background/richard/power_1989.shtmll » for a description of the event and its effects in Quebec. Next: Unsettled to active field response..

Supplemental Records

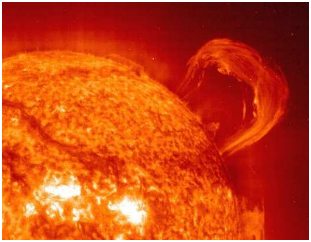


record of 27 January, 1989, detail

The above detail shows more clearly the sudden drop followed be a rise back to the former signal level. This was a pretty typical flare, strong but not truly large. Another example of a typical flare comes from the record of 06 January, 1989. The winter and spring of 1989 was a very active period for flares and I caught them repeatedly on many records as the map for December 89 / January 90 shows. On the 10th of March, 1989 there occurred a truly powerful outburst which blocked radio communications for several hours and the geomagnetic storm that followed three days later was so severe that it knocked out the power grid in Quebec, Canada, and caused wonderful auroral displays as far south as Florida.
record of 10 March, 1989

6.) Solar Filament-

A relatively cool and dense ribbon of gas held together by solar magnetic fields. From Earth they usually appear as relatively dark lines across the face of the Sun. At times the magnetic lines holding the filament open up creating a tremendous eruption similar in size and impact of a Coronal Mass Ejection (CME). (See definition #4. Coronal Mass Ejection). (See definition #11. Geomagnetic/Ionosphere Storm).



7.) Correlation Of Energetic Protons, Solar Flux and Ap & Kp Indices With Medium Frequencies-

I've been observing energetic proton levels, as well as the Ap & Kp indices for 35 years and see a direct correlation between high energetic proton levels above 10 MeV (10+0) and poor propagation on high and at times mid latitude medium frequency paths at day AND night, where as the A & K indices don't as readily correlate. (See paragraph three of definition #2. Aurora Oval Blockage, Absorption And Refraction) and (definition #7. High Latitude Path Skewing) for a further explanation on the lack of correlation of Ap & Kp indices with medium frequency propagation conditions.

High solar flux values are "incorrectly" considered to be detrimental to medium frequency signals both domestic and TA/TP, as more absorption can be present as the transmitted signal makes two trips through the D layer, near sunrise and sunset. However most medium wave frequency RF signals in excess of 3100 miles are propagated via the E valley/F layer ducting and/or Chordal Hop/Pederson Ray propagation mechanism and a high solar flux value ensures a strong E valley/F layer duct mechanism. Actually a solar flux of at least 150 is needed for a consistent E valley/F layer ducting mode.

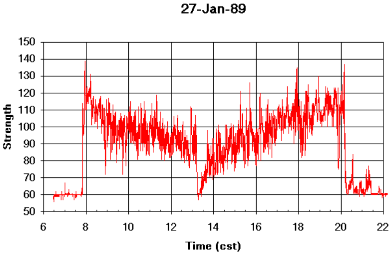
The main reason that medium frequency radio propagation "seems to be better" at the bottom of a sunspot cycle is not so much due to lower solar flux levels BUT due to much less geomagnetic activity.

Keep in mind though that the 10.7 cm (2800 MHz) solar flux index is not a "reliable" gauge of ionization in our atmosphere, as the energy of photons at this frequency is to low on the order of one million times. However most are used to solar flux and sunspot number and it's a hard habit to break. A better indicator is the inter-related background X-ray flux. (See definition #1 paragraphs e & f).

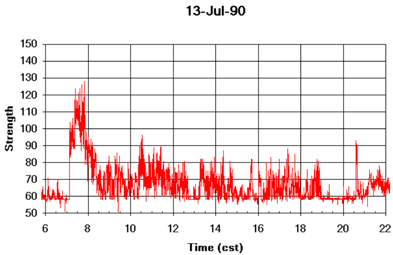
An elevated energetic proton flux level greater then (10+0) creates noticeably increased winter time day and year round night time D layer absorption of medium wave frequencies, especially on high latitude propagation paths but it can also

Flare Response

Flares result from the sudden release of tremendous amounts of energy from the sun's surface. Some eight minutes after a flare bursts on the sun, high energy ultraviolet radiation impacts the earth ionizing all the ionosphere layers in the process. While this might be expected to enhance F layer propagation, the D layer density quickly becomes opaque to the signal causing a sudden fadeout. Depending on the duration of the flare, the fadeout will last from minutes to hours and then as the ions recombine there follows a logarithmic rise back to normal. The following record of 27 January shows a classic flare signature against a clean winter record.



record of 27 January, 1989



Summertime blues, solar flux good at 153, Ap=10, pretty quiet day but with lousy reception.

negatively impact mid latitudes, depending on the intensity of the event.

Elevated energetic proton events too small to be categorized as a Polar Cap Absorption event (PCA) can still impact high and at times mid latitude medium frequency propagation paths in the form of excessive D layer absorption.

((((Note, high latitude medium frequency radio propagation paths can still be disturbed for days and up to weeks, following the end of an official >10 MeV (10+0) proton event.))))

GENERAL GUIDELINES CONCERNING CORRELATION OF PROPAGATION INDICES TO ACTUAL MF PROPAGATION CONDITIONS-

NOTE!!! The propagation indices "interpretations" are my personal intellectual property. Therefore the propagation indices interpretations contained herein is copyrighted © 1988-2013 by Thomas F. Giella, W4HM, all rights reserved. Reproduction of information herein is allowed without permission in advance as long as proper credit is given.

All 13 of the following indices have to occur as described below in order to see the best global medium frequency (MF) radio wave propagation possible.

1.) Dropping geomagnetic field indices numbers are better, Kp of 0 best.

2.) A daily sunspot number under 100, under 70 best.

3.) A daily sunspot number no higher then the 100 for routine stable formation of the E Valley/F Layer ducting mechanism.

4.) Previous 24 hour Ap index under 10, fewer than 7 for several days consecutively are best.

5.) Previous 3 hours Kp index fewer than 3 for mid latitude paths, fewer than 2 for high latitude paths, 0 for several days consecutively is best.

6.) Energetic proton flux levels no greater than 10 MeV (10+0).

7.) Background x-ray flux levels of A0 for several days consecutively.

8.) No current STRATWARM alert.

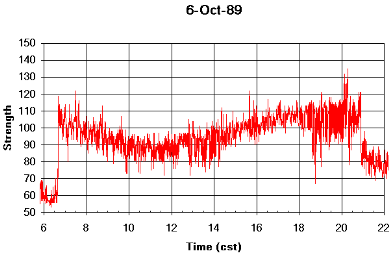
9.) Interplanetary magnetic field (IMF) Bz with a (positive number) sign, indicates a lesser chance of high latitude path aurora absorption/unpredictable refraction or scattering of medium frequency RF signals, when the Kp is above 3.

10.) A -10 or better towards a positive number Dst index during the recovery time after a geomagnetic storm, as related to the equatorial ring current. A positive number is best.

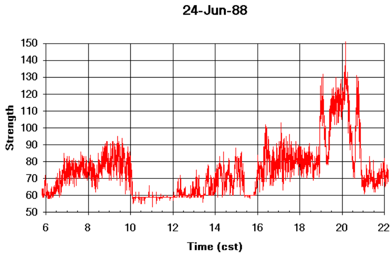
11.) Galactic cosmic rays decrease to -3 units below zero and trending towards zero.

12.) Energetic electrons no greater than 2 MeV (2+0).

13. A solar wind speed of less than 300 km/s for several days consecutively.

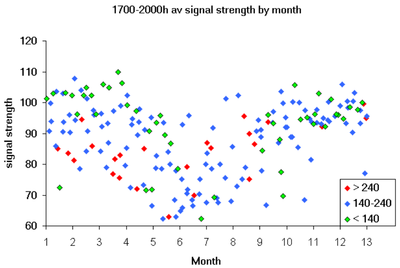


"Ideal" recording with winter response, good opening, midday sag, and long evening period with strong signal reception.



Major flare at 1609UT (1009 CST).

average strength for the midday period 1700 - 2000 UT



The following section shows the signature of a solar flare since finally, that's what all this is about!

Supplemental:

GENERAL GUIDELINES CONCERNING CORRELATION OF PROPAGATION INDICES TO ACTUAL HF PROPAGATION CONDITIONS-

All 14 of the following indices have to occur as described below in order to see the best global high frequency (HF) radio wave propagation possible.

1.) Dropping geomagnetic field indices numbers are better, Kp of 0 best.

2.) A daily sunspot number of 150 or higher, 200 or higher best.

3.) A daily sunspot number of greater than 100 for routine stable formation of the E Valley/F Layer ducting mechanism.

4.) Previous 24 hour Ap index under 10, fewer than 7 for several days consecutively are best.

5.) Previous 3 hours Kp index fewer than 3 for mid latitude paths, fewer than 2 for high latitude paths, 0 for several days consecutively is best.

6.) Energetic proton flux levels no greater than 10 MeV (10+0).

7.) Background x-ray flux levels greater than B1 for several days consecutively, greater than C1 best.

8.) No current STRATWARM alert.

9.) Interplanetary magnetic field (IMF) Bz with a (positive number) sign, indicates a lesser chance of high latitude path aurora absorption/unpredictable refraction or scattering of medium frequency RF signals, when the Kp is above 3.

10.) A -10 or better towards a positive number Dst index during the recovery time after a geomagnetic storm, as related to the equatorial ring current. A positive number is best.

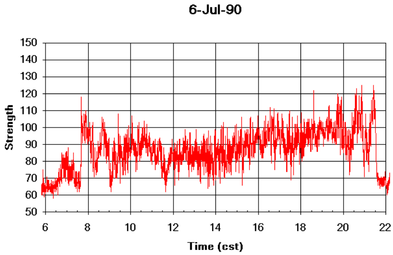
11.) Rising positive T index number. The T Index tracks with the F2 layer critical frequency (foF2) and sunspot number (SSN) and indicates the capability of the F2 layer to refract RF signals.

12.) Galactic cosmic rays decrease to -3 units below zero and trending towards zero.

13.) Energetic electron flux levels no greater than 2 Mev (2+0).

14. A solar wind speed of less than 300 km/s for several days consecutively.

8.) E Valley/F Layer Propagation Ducting Mechanism/Chordal Hop Propagation-

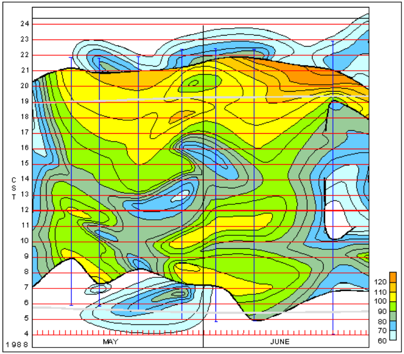


record taken on 06 July, 1990

This chart shows a fairly typical (if there is such a thing) "summer" record taken on 06 July, 1990. The day had strong solar flux at 209, and the geomagnetic field was moderately quiet. Still, the signal was weak most of the day with lots of noise and levels only in the S3 - S5 (80 - 90) range. A week later on 13 July the opening made a brief appearance in the morning and then headed south all day. Good day to go fishing.

I have taken averaged hourly signal strengths for all 200 records and put them on a spreadsheet to make further analyses. The following graph shows the average strength for the midday period 1700 - 2000 UT (10am to 1pm CST) averaged together and plotted by month. That is, all February data regardless of year together, all June and so forth. Although some years may be better overall, you can clearly see the seasonal signature with good autumn to spring signal and poor summer reception.

generally the records are choppy and noisy, fading is a far bigger problem.



period of June and July, 1988

On 24 June of this period there occurred a major flare at 1609UT (1009CST) which closed the window for several hours.

Antenna polarization plays a large role in the success of a long haul DX contact. As a medium frequency RF signal traverses our planets magnetic lines of force in a perpendicular manner on high and mid latitude paths say between W3 land and SM, higher angle horizontally polarized signals are more readily absorbed then lower angle vertically polarized signals. On other paths on the globe opposite results can be found, i.e. horizontally polarized signals suffer less absorption on a propagation path between VK6 and W4.

You would expect a true long path QSO on 160 to be theoretically possible but improbable on most paths during any season. However a G to VK long path might be possible if the E Valley/F layer ducting propagation mechanism or the Chordal Hop propagation mechanism is involved. A 160 meter signal can traverse a daylight path via these propagation modes if the transmitted signal enters/exits at each end of the path at or near sunrise/sunset when the D layer ionization is weak (ionosphere tilting).

There is an upward tilt of ionosphere layers towards the east at sunrise. As a result, signals coming from the west are refracted upward at steeper angles and are therefore heard better on higher angle antennas. The opposite is true at local sunset.

A note though, the E-valley/F layer ducting propagation mechanism does not exist only during gray line periods. Internal Buoyancy/Gravity Waves (IBGW's) are a source of the ducting mechanism and allow for occurrences of ducting along any propagation path in total darkness. Measurement of the timing of arrival of propagated medium frequency RF signals demonstrates the existence of the ducting mechanism, versus conventional numerous E layer land/ocean surface hops.

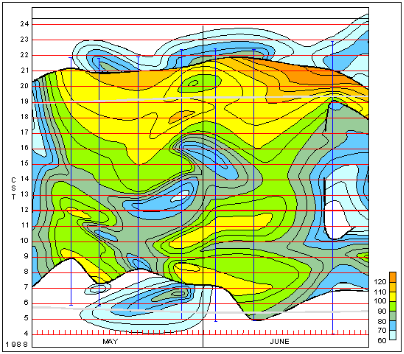
The majority of the time medium frequency RF signals in excess of approximately 3200 miles propagate via the E Valley/F Layer propagation mechanism or via the Chordal Hop (mostly on HF near local sunrise and sunset) propagation mechanism. Typically the majority of transmit antenna's radiation must be focused between 40-60 deg. to enter the E Valley/F Layer duct. (See definition #23.) The Gray line/Gray line Propagation).

A solar flux of at least 150 is necessary for routine stable formation of the E Valley/F Layer ducting mechanism. Therefore formation of the duct is less prevalent at the bottom of solar cycle and long haul propagation poorer at solar minimum.

You won't see this in any mainstream books on radio wave propagation but the vast majority of the time MF and HF signals travel around the world not by successive hops off of the F/F2 layer and the surface of the earth, whether it be landmasses and/or the ocean, but either between the E and F/F2 layer. This is especially true on long paths.
Well Known Chordal Hop LP Routes Courtesy Of Larry Duncan K4WLS-

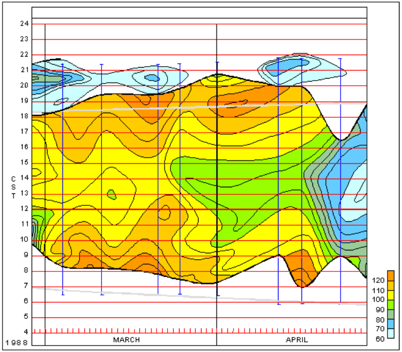
Here are some well known Chordal Hop LP routes from the East Coast and Mid-West:

Late Afternoon, Mid-February to Mid-March - Western Australia and beyond, and Southern Malaysia: Predominately 20M.



This map shows the period of March and April, 1988. In it you see the strong morning and evening signal (in browns) and the midday sag in yellow to green. On the right the signal for the record of 22 April becomes poor, (blues). This was an active day with geomagnetic disturbances disrupting the propagation. Also in this map you can see typical evening sporadic low-level propagation after the main opening has ended, especially in early March.

In contrast to the above "winter" view, the following map shows the doldrums of summer. It is for the period of May and June, 1988. I characterize the propagation in summer as generally longer duration, but with lower signal strength and much greater day to day variability. It is not unusual to have a good strong opening for an hour or two in the evening, but



0700-1000 Local, Early to Late Summer - Eastern and Southern Africa, and Indian Ocean: 20, 15, 17, 12, and 10M (17 through 10M depending on Solar Flux).

0800-1000 Local, Early Fall - Western Australia and S.E. Indian Ocean: 20M

0500-0700 Local, * December - Malaysia, Indonesia, and S.E. Asia: 40M

Sunset to 1 Hour Before, Fall to Mid-December - Middle and Eastern Asia: 40M

0700-0800 Local, Mid-December - Middle East: Predominately 20M

Sunset to 1 Hour Before, Mid-December - Northern Middle and Eastern Asia: 20 and 40M (20M depending on Solar Flux).

* Sporadically as late as early March

If one is lucky enough to be on the receive end of a ducted medium frequency signal due to an IBGW or two, a change in the vertical and/or horizontal electron gradient will allow the RF to drop out of the duct at your QTH. Galactic Cosmic Rays also play a role in where an RF signal drops out of the duct.

A note, high solar activity in the form of increased ionization created by ultraviolet and X-ray radiation, can fill in the E Valley/F Layer ducting region with medium frequency absorptive ionization and interfere with the E Valley/F Layer ducting mechanism. In a sense the E/F layer duct is shut down and the medium frequency RF signal can only propagate between the E layer and land/ocean surface, at a higher angle and with more signal loss. This closing of the duct can be reciprocal on each end of the propagation path or one way only. (((((When closing of the duct occurs the advantage of a low angle vertical radiator is lost, with a higher takeoff angle horizontal dipole making the contact still possible, albeit maybe weaker.)))))

Medium frequency radio waves possess elliptical polarization, with the signal splitting into ordinary and extra-ordinary rays. These rays can propagate in or out of phase, more often out of phase. The out of phase extra-ordinary ray represents a 50% power loss on the receive end of a propagation path.

As follows is a recent experience I had in Florida with this propagation mode on 160 meters.
I began listening for DX on 160 meters at 5:00 pm EST this evening February 05-06, 2006. I was watching the OH2AQ spot and the stations in ME to VA were working stations in Europe and Africa. I could hear the stateside stations real well but not a peep out of any DX.

Then right at my local sunset which was at 6:15 pm EST it was like flipping a switch as all the DX stations just showed up. It was a classic example of the E Valley-F Layer ducting mechanism propagation mode with the duct opening up right over Florida as the ionized layers changed height with the arrival of the gray line terminator.

Once the DX showed up I heard oodles of CW DX stations including VQ9LA and 6W/G4WFQ who were 55 on the receive loop. MM0SJH, G3FPQ and I7RIZ showed up on phone between 1841 and 1849 kc and they were 57. I didn't bother to work anything this time as the only countries I heard

Seasonal Variations

The record presented in the previous section represented a nearly "ideal" winter record. I found that winter openings were generally dependable with a distinct jumps in the morning and drop in the evening, and good strong reception all day. 06 October, 1989 was another good day. It is possible to "map" the data from week to week in order to visualize how the propagation openings change with time. The following chart shows a map of signal strength contoured against time. Local Central Standard Time is on the Y-axis and calendar time on the X-axis. Each day starts at the bottom and moves up, the next day starting again at the bottom next to (to the right of) the prior one so the calendar flows to the right. Additionally, the Gray curves running along the upper and lower portions of the map indicate local Houston sunrise and sunset respectively.

is an asymmetry to the opening as well with a longer period of strong signal in the evening than in the morning. I attribute this to the geometry of the Houston-Ft. Collins circuit with Ft. Collins being to the west. By the time the F layer ionizes in the morning at a point halfway between Houston and Ft. Collins, the lower D layer is already ionized, conversely, in the evening there is still a couple of good hours remaining for the F layer after the D has dissipated.

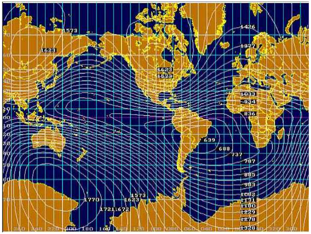
Base level, (S0) on this record is 58, the solar flux that day was quite high at 239 and the geomagnetic field was quiet. The resulting record is pretty close to ideal which is actually quite unusual. In all, the project ran for nearly four years from just after sunspot minimum to past sunspot maximum and resulted in nearly 200 weekly records. The next section provides additional views giving a flavor of the variability possible, and why.

that I've never worked were VQ9LA and 6W/G4WFQ and I couldn't break the pileups with 100 watts.

9.) Electron Gyro Frequency Absorption-

Unfortunately medium frequencies fall within or very near the electron gyro-frequency which is in the approximate range of 630 to 1630 kHz and of course the AM broadcast band and 160 meter band is very close to these electron gyro frequencies. There is a direct correlation between the strength of Earth's magnetic field lines and electron gyro frequencies.

Basically, the electron gyro frequency is a measure of the interaction between an electron in the Earth's atmosphere and the Earth's magnetic field. The closer a transmitted medium frequency carrier or sideband wave frequency is to the electron gyro frequency, the more energy that is absorbed by the gyro (spinning) electrons from that carrier wave frequency. This is especially true for medium frequency signals traveling perpendicular to the Earth's magnetic field, meaning high latitude NW and NE propagation paths. Unfortunately this form of medium frequency signal absorption is ALWAYS present.



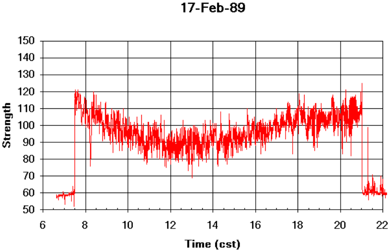
Electron Gyro-frequency Map From Prop lab Pro Software

10.) Medium & High Frequency Radio Signal Propagation Path Skewing-

Medium & High frequency radio signal propagation path skewing occurs due to changes in the "horizontal" electron gradient. Put in simple layman's terms the transmitted RF signal will "always" seek to propagate along the path with least absorption, which almost always means via a darkness path.

As an example a medium frequency signal (say 1830 kc) transmitted from Norway to New England, which is via a polar great circle path, will be directly absorbed most of the time by the Aurora Oval, with the remaining signal skirting south and then west on the darkness path via the E layer, arriving in New England from say the SE rather then the expected NE path.

Another example is a high frequency (say 28400 kc) signal transmitted from Florida that arrives from the SE at Clipperton Island (FO/TX5), which is located in the Eastern North Pacific Ocean near 11 degrees north latitude and 110 degrees west



The above record shows a fairly "classic" response for a 15 hour run. In all my runs regardless of duration I collected 3200 samples only. That was an expedient to simplify the programming, keep the record within the memory limits of a Commodore 64, and have a simple multiple of the high-resolution screen's 320 pixel width. For a nominal 15 hour run that translates to about one record each 17 seconds which is more than sufficient for the project. In addition, I actually sampled continuously between saves and read the average of many readings for each saved record. Even then, there is considerable fading and short second to minute scale noise which accounts for the "grassy" surface.

Note also two important features of the record, the very sharp discontinuities at the beginning and end of the "opening", and the general sag or lower strength of the signal at mid-day. More on the discontinuities later, the sag itself is due to increased absorption by the lower D layer at it reached full ionization near midday and dissipates by the afternoon. There

Daily Record

My study utilizes the WWV time standards beacon at Ft. Collins, Colorado. That transmitter emits at 2.500, 5.000, 10.000, 15.000, and 20.000 MHz. I monitor the 15 MHz signal which provides a strong signal at my station in Houston, Texas. 10MHz openings last longer into the night but would be useless for flare detecting at that time as the sun has set! I use a Yaesu FRG7700 receiver which is not terribly expensive and extremely stable once it has warmed up.

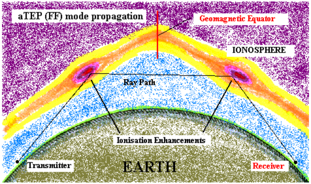
The interface between the receiver and computer uses a voltage to ohms converter which proved very acceptable but, being a resistance device, was susceptible to temperature induced drift. In Houston that was generally only a problem in the spring or fall where large changes in day to day temperature are typical in the Gulf of Mexico's battle against the continent for dominance of the climate of the region. I made occasional calibrations as necessary to the interface and kept the base level within a narrow range. The following list gives the correspondence between the digital signal strength readings presented on the charts and the radio's S-meter output:

S-meter	Computer
S0	60
S3	79
S5	90
S7	101
S9	112
+10db	132
+20db	157

record of 17 feb, 1989

longitude. This relatively short path contact gives the appearance of the double hop Sporadic E (Es) propagation mode, which frequently occurs during a low point in a solar cycle, when actually it is a skewed F2 layer propagation mode.

A general east-west band of high (25000-35000 kc) maximum usable frequencies (MUF's) exist north and south of the geomagnetic equator http://www.spacew.com/www/realtime.gif . These bands allow for the existence of the north-south propagation mode called Trans Equatorial Propagation (TEP). In any event the contact between Florida and Clipperton Island was made via the horizontal gradients that existed in the band of high MUF's north of the geomagnetic equator.



Side View Of High MUF Bands North & South Of The Geomagnetic Equator

By the way skewed propagation paths are the norm rather than the exception on medium frequencies, especially past approximately 3200 miles.

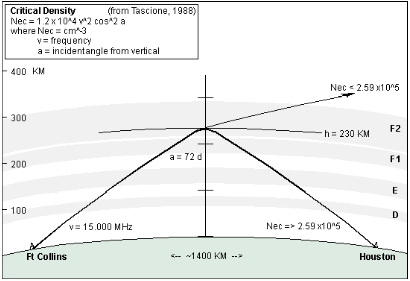
11.) Geomagnetic/Ionosphere Storm-

A worldwide disturbance of the Earth's magnetosphere and or ionosphere, induced by direct connection to the Sun's Interplanetary Magnetic Field (IMF), distinct from regular diurnal variations. Basically it's a precipitation of electrons trapped within our magnetosphere, as the electrons collide. The end result is a reduction of the MUF of the F2 layer. (See definition #3. Equatorial Ring Current). (See definition #4. Coronal Mass Ejection). (See definition #5. Coronal Hole). (See definition #6. Solar Filament).

Geomagnetic Storm Levels

Planetary K Indices	Geomagnetic Storm Level
K = 5	G1 Minor
K = 6	G2 Moderate
K = 7	G3 Strong
K = 8	G4 Severe
K= 9	G5 Extreme

Active K = 4	K- 0= A- 0
Unsettled K = 3	K- 1= A- 3
Quiet K= 0, 1, 2	K- 2= A- 7
	K- 3= A- 15
A= 100-400 Severe	K- 4= A- 27
A= 50-99 Major	K- 5= A- 48
A= 30-49 Minor	K- 6= A- 80
A= 16-29 Active	K- 7= A- 140
A= 8-15 Unsettled	K- 8= A- 240
A= 0-7 Quiet	K- 9= A- 400



Graphical presentation of the relationships between the frequency, ionosphere electron density, and propagation incident angle measured from vertical are given in the expression:

Nec = 1.2 x 10^4 v^2 cos^2 a ...(from Tascione, 1988)

For the given circuit parameters:
v = 15.000 MHz
a = 72 d ...(h = 230 KM)

Then the Critical ionosphere density from the formula is
Nec = 2.59 x 10^5 cm^-3.

For densities lower than that value the signal will pass out of the ionosphere into space. For densities above that value the signal will continue to propagate, but with increasing absorption on this circuit.

"critical" density needed to return reflections. The relationship between the three parameters (Nec = electron density (cm^-3), v = frequency, and a = incident angle measured from vertical) is given by the following expression, (Tascione, 1988):

$$Nec = 1.2 \times 10^4 v^2 \cos^2 a$$

It should be noted that this expression is for the critical situation only. Where the angle is approximately known based on the circuit geometry and the frequency is known precisely, the density calculated will be the lowest density that, below which, no return (reception) will be possible. A radio wave of a given frequency therefore will continue to travel upwards into an ionosphere layer until it reaches the elevation where the density rises to the "critical" level (Nec) and the wave will be turned back to earth.

For most HF radio communication the main reflecting layer is the F layer situated between 200 to 300 KM altitude. The D and E layers are generally too weakly ionized to be of much importance except during the day over shorter distances. Ionization, although falling, persists through much of the night in the F layer as well. Intense ionization of the F layer causes it to warm and split into a second, higher, level during the day, returning to a single layer at night. There are also seasonal variations on the theme. The E layer, about 100-150 KM up, can persist into the night to some extent and in addition there are occasional "clouds" or masses of E level ionization which can drift causing sporadic radio openings when the right geometries exist. The D layer at about 80 to 90 KM is only useful for propagation during the day recombining quickly after sunset. In the negative sense, it absorbs signals passing through it to or from the F layer.

Solar Radiation Storm Levels

Flux Level of > 10 MeV Particles	Solar Radiation Storm Level
10	S1 Minor
102	S2 Moderate
103	S3 Strong
104	S4 Severe
105	S5 Extreme

Medium Frequency Radio Blackout Levels

Peak X-Ray Level and Flux	Radio Blackout Level
M1 and (10-5)	R1 Minor
M5 and (5 x 10-5)	R2 Moderate
X1 and (10-4)	R3 Strong
X10 and (10-3)	R4 Severe
X20 and (2 x 10-3)	R5 Extreme

((((Note! Unfortunately elevated Kp indices of as little as a 3 will create absorptive conditions for medium frequency signal propagation on higher propagation paths)))).

Initial phase of a geomagnetic storm is that period when there may be an increase of the middle latitude horizontal intensity.

Main phase of a geomagnetic storm is that period when the horizontal magnetic field at middle latitudes is generally decreasing.

Recovery phase of a geomagnetic storm is that period when the depressed northward field component returns to normal levels.

By the way effects of the solar wind on the magnetosphere decreases as we approach the Summer/Winter solstice and increase at the Fall/Spring Equinox. Why? Basically it's the orientation of Earth's magnetic field with respect to the Interplanetary Magnetic Field within the Solar Wind. When solar material and shock waves reach Earth their effects may be enhanced or dampened depending on the angle at which they arrive. http://science.nasa.gov/headlines/y2001/ast26oct_1.htm?list101234.

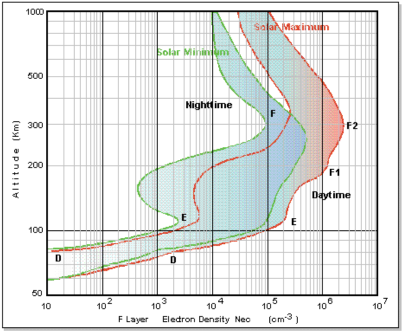
The Wang-Sheeley Interplanetary Magnetic Field (IMF) Model is used to predict Sun's IMF polarity. When the polarity of the IMF is negative a visible mid latitude Aurora display is likely as a Coronal Mass Ejection (CME) strikes the Earth's magnetic field.

Radio Wave Propagation

Because the different levels in the ionosphere are electrically conducting, they interact with electromagnetic radio waves bending them in much the same manner that glass or water bends light. The refractive index of a layer in the ionosphere depends on its electron density and has an effect on waves according to their wavelength. Levels with higher electron densities (higher altitudes where recombination is slower) have lower refractive indices. As a wave passes up from below into such layers they get refracted, or bent back down towards the lower electron density layers. The amount of bending depends on the incident angle and the frequency of the wave. Higher frequencies are less affected. Finally, in passing through conducting layers, energy in the wave vibrates the electrons thus transferring some energy into the layer and being partially absorbed in the process.

For much of the radio spectrum the frequencies are simply too high to be refracted back to the earth given the range electron densities which exist and propagation angles required. This is not true in the HF band of frequencies between a few hundred hertz and about 30 megahertz. There a delicate balance exists where, depending on the natural variations in density of the ionosphere, radio waves may be either refracted back to the earth or passed out into space. For the case of vertical incidence and a given ionospheric density there is a critical frequency above which no reflection will be received. Inversely, you can say that for a given frequency there is a

The early study of the ionosphere involved measuring its density variations and electrical properties. Most work was done in conjunction with radio studies and radio waves remain the primary way to probe its structure. Studies focus on its variability and the nature and causes of disturbances. In the process much has been learned about the solar-terrestrial connection. With a communications receiver and an inquiring mind, anyone can reach above the sky and touch the near-space environment.



Daytime to nighttime electron concentrations which constitute the midlatitude Ionosphere. Graph with variation between solar minimum and solar maximum curves. (from Tascione, 1988)

12.) Geological/Meteorological Effects On Medium Frequency Propagation-

Geological effects such as earthquakes and volcanic eruptions, as well as meteorological effects such as Troposphere originating Internal Buoyancy/Gravity Waves (IBGW's), Stratosphere level Quasi Biennial Oscillations (QBO) and warming (STRATWARM) have a negative effect on medium frequency RF signals in the form of small to medium increased absorption variations of medium frequency RF signals via the D layer, due to traveling ionosphere disturbances (TID's).

Also temperature and moisture discontinuities involved with cold frontal inversions and air mass triple points involved with extra-tropical low pressure systems can refract, diffract or scatter medium frequency radio signals in unpredictable ways, most notably on high transmitted RF power levels. This is another concept that a fellow Physicist and expert in optics took me to task over.

As far as medium frequency refraction it's more significant at say 3000 kc, then 1850 kc or 1500 kc. But it's also more noticeable with higher transmitted RF powers, i.e. WSAI 1530 50 KW and even more so with BSKA 1521 KC 1000 KW and now defunct 2000 kc region 100 KW marine stations.

We know that the medium frequency spectrum is defined as 300-3000 kc but the differences in refractive properties between 300 and 3000 is very significant At 3000 kc refraction is a good description, on 160 scattering, at 300 kc diffraction.

Using the strictest definition of RF refraction, its effect on 160 meters is small but it has been measured by government researchers as significant enough to impact 160 but near the air mass triple point. In my opinion scattering is actually the more consistent propagation medium for 160 meters along a cold front, away from the extra-tropical cyclone center.

However the temperature and moisture discontinuities in the vicinity of a triple point air mass structure such as seen with a mature extra-tropical cyclone is very complex and fluid. The NW quadrant of the extra-tropical cyclone is the location that the original government researchers identified as the region of existence for the complex temperature/moisture discontinuity structure that allows for refraction of RF signals as low as 1500 kc. I have not been successful at garnering data from the federal government that can be released to the general public. NOAA has been similarly stymied and therefore is now conducting similar research.

The QBO is a wind shift in the equatorial stratosphere, an oscillation from easterly to westerly and back on the time scale of approximately two years (26 months) and is a source of Internal Buoyancy/Gravity Waves (IBGW) which create absorptive perturbations in the D and E layers and even possibly the F 1/2 layer. A note, the E-valley/Flayer ducting propagation mechanism does not exist only during gray line periods. Internal Buoyancy/Gravity Waves (IBGW's) are a source of the ducting mechanism and allow for occurrences of ducting along any propagation path in total darkness. Measurement of the timing of arrival of propagated medium frequency RF signals demonstrates the existence of the ducting mechanism, versus conventional numerous E layer land/ocean surface hops.

The HAARP ionosphere program, earthquakes, volcanic eruptions, thunderstorms, lightning (especially positive cloud to ground strokes), elves, tornadoes and hurricanes and even

Earth's Ionosphere

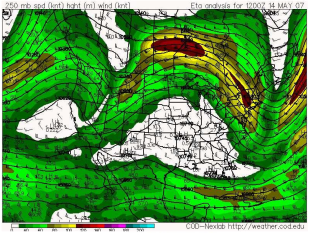
The density and composition of the earth's atmosphere changes with height above the surface. From the sun, solar ultraviolet radiation impacts the upper atmosphere, ionizing the atoms there in the process of being absorbed. As the density of the atmosphere falls to very low levels the time it takes for ionized electrons and their atomic nuclei to recombine becomes sufficiently long to form a persistent ionized zone. This zone of ionized particles is called the earth's ionosphere. Due to the chemistry of the atmosphere, density variations, and varying energy levels in the ionizing ultraviolet radiation, the ionosphere forms distinct zones or layers which have been given the rather unimaginative names of D, E, F1 and F2 with increasing height above the earth.

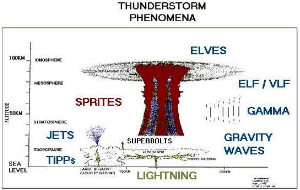
With the complex interplay of the different factors involved, the ionosphere varies considerable with time. Regular variations form from the diurnal rotation of the earth bringing different parts of the atmosphere under the radiation effects of the sun, and from seasonal changes, and from the regular change in solar energy associated with the sunspot cycle. Other more random variations result from interactions of the earth's magnetic field with the charged particles in the ionosphere, and from disturbances to the magnetic field by solar activity. Its behavior also varies by latitude, with polar, mid-latitude, and low-latitude regions all behaving in characteristic ways.

visible and radio wavelengths. Visible-light observers generally monitor the sun in Hydrogen-alpha light where the flares shine brightest. Radio observation has traditionally utilized the very low frequency band. According to Mr. Hudak, (Sky and Telescope, 1984) this method requires a radio-quiet observing site, something simply not available to most amateurs today. This report describes observations using his method of shortwave fadeout to detect flares. In addition, the data gathered reveal several other interesting phenomena which I describe as well.

man made activities such as rocket launches including the space shuttle, are all sources of (IBGW's).

Many times I've heard ham's lament that propagation was going to go to crap due to another NASA Space Shuttle launch, in a sense they are correct.





Troposphere Height Jet Streams And Lightning/Thunderstorms And Their Interaction With The Ionosphere

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13.) Polar Cap Absorption (PCA)-

An anomalous condition of the polar Ionosphere whereby medium frequency (300-3000 kc) radio waves are absorbed, and LF and VLF (3-300 kHz) radio waves are wave guided at lower altitudes than normal. In practice, the absorption is inferred from the proton flux at energies greater than 10 MeV (10+0), so that PCA's, Polar Radio Blackouts and Proton Events are interrelated and often simultaneous.

((((NOTE!!! high latitude radio propagation paths may still be disturbed for days, up to weeks, following the end of an official proton event.)))) This fact is still stubbornly opposed by some otherwise very knowledgeable space weather physicists, hung up on threshold Riometer readings.

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14. Sunspot Group-

Sunspot groups are bipolar magnetic concentration regions on the photosphere of the Sun where magnetic field strengths many thousands of times stronger than the Earth's magnetic field reside. Sunspots appear as dark spots on the surface of the Sun because temperatures in the dark centers of sunspots drop to approximately 3700 K compared to 5700 K for the surrounding photosphere. The difference in temperature makes the spots appear darker than elsewhere. Sunspots typically last for several days to several weeks. They are seen to rotate around the sun, since they are on the surface, and the sun rotates fully every 27.5 days.

Sunspot groups have a magnetic classification as follows:

Solar Flares

The study of solar flares is driven by both practical as well as scientific reasons. Flares are explosive eruptions of energy on the surface of the sun. These releases are the most powerful form of solar activity and occasionally have severe impact on terrestrial communications and power distribution. Tight magnetic fields associated with active regions on the sun form sunspots. These magnetic fields become twisted and kinked, storing tremendous amounts of energy. The process that causes the flare energy release is not well understood, and no predictive model exists which allows scientists to know in advance when or where a flare will erupt.

The energy released in a flare occurs over the full spectrum of wavelengths from the radio to visible, to ultraviolet and x-ray. By far the major release of energy is in the shorter wavelength ultraviolet and x-ray regions. Ultraviolet energy radiates away from the sun at the speed of light and, upon impacting the earth's ionosphere 8 minutes later, rapidly ionizes all levels disrupting communication. Charged particles released in the outburst take longer, arriving about 1 to 4 days after a major flare. They interact with the earth's magnetic field causing further communications disruptions and auroral displays.

Fortunately, flares last only a short time, up to several hours in their extended, or "main" phase after the initial burst. Given their terrestrial effects and short duration, flares have long been a welcome challenge to amateurs observing at both

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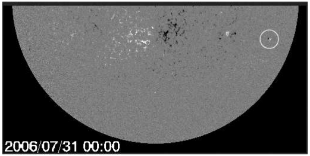
A - Alpha (a single polarity spot)
B - Beta (a bipolar spot configuration)
G - Gamma (an atypical mixture of polarities)
B-G - Beta-Gamma (a mixture of polarities in a dominantly bipolar configuration)
D - Delta (an opposite polarity umbrae within single penumbra)
B-D - Beta with a Delta configuration
B-G-D - Beta-Gamma with a Delta configuration

Sunspots usually come in groups with two opposing sets of spots. Whether two or twenty sunspots exist in a particular group they are counted as one sunspot group and numbered, such as 10500. That number would signify sunspot group number 10500, with the number counting system beginning in 1972 if my memory serves me correctly.

One set of sunspots will have a positive or north magnetic field while the other set will have a negative or south magnetic field. See image below.

The magnetic field is strongest in the darker parts of the sunspots called the umbra and weaker and more horizontal in the lighter part called the penumbra. The twisted magnetic fields associated with sunspot groups are one source of the solar flares, coronal mass ejections and geomagnetic storms that wreak havoc with the ionosphere here on Earth.



Magnetogram Image

The current system of counting sun spots hails from a previous era when direct observation of sun spots was inherently inaccurate. The sunspot number is derived by counting 10 points for each sunspot group and then adding one point for each spot. So if a sunspot group contains 1 individual sunspot the official count becomes 11. 4 individual sunspots in a sunspot group equals 44 sunspots. (See definition #24. Plage).

15.) Short Wave Fadeout (SWF)-

During a Sudden Ionosphere Disturbance (SID), which is tied to a Solar Flare and Coronal Mass Ejection, abrupt increased ionization of the D layer results in reduced to total absorption of medium frequency circuits which are refracted by the Ionosphere on the sun lit hemisphere of the earth. This is known as a Shortwave Fadeout (SWF).

Solar flares produce copious amounts of electromagnetic radiation including energetic protons which increase the ionization of the daytime D layer. Medium frequency communication depends on the refraction of signals from the

A indices (a, A, ap, and Ap)
Indices derived from the K index but converted to a linear scale as follows:

K	0	1	2	3	4	5	6	7	8	9
a	0	3	7	15	27	48	80	140	240	400

The Ap, or planetary A index is an average daily report which I have commonly used to indicate geomagnetic conditions. The equivalent values are defined thus:

Ap	Condition
0-7	Quiet
8-15	Unsettled
16-29	Active
30-49	Minor Geomagnetic Storm
50-100	Major Geomagnetic Storm
>100	Severe Geomagnetic Storm

Some Definitions

Sunspot Number
This is a measure of the number and area of both individual sunspots and sunspot groups. Naturally this is based on visual observations from a number of observatories, the data reduced and averaged. Sunspot numbers were introduced in 1848 by the Swiss astronomer J.R. Wolf and have been calculated, with caution, back to around 1610 making this the longest continuous record of solar activity available. Sunspot numbers range from lows near 0 to highs over 200 during maximums of solar activity.

Solar Flux
In many ways similar to the sunspot number, and well correlated, the solar flux index is a measure of solar radio flux at a frequency of 2800MHz, or 10.7 cm as it is commonly called. This measure was introduced in 1947 at Ottawa, Canada and has obvious advantages over the sunspot number in that it does not rely on visual, often subjective observations.

K indices (K, Kp)
Quasi-logarithmic index of geomagnetic activity relative to quiet levels for a local recording station. These measurements are taken over a 3-hour period and reported on a scale of 0 to 9. Planetary (Kp) values are determined from data from 12 to 13 stations worldwide. This indice was begun in 1949 at the Institut für Geophysic, Göttingen University, Germany.

higher E and F2 layers and these signals must travel through the D layer at least twice.

Lower frequencies are affected first and higher frequencies last. The stronger the event, the stronger the ionization of the D layer, the higher the frequency effected via absorption.

Daytime E layer propagation of the medium frequency AM broadcast band and 160 meters (See definition #1. Overview) usually only occurs during the winter season and especially at higher latitudes with a lower sun angle, also at the bottom of a sunspot cycle, therefore Swift's rarely are rarely noticed. The 80/75 meter and 40 meter bands are most noticeably affected, with the higher bands least affected.

An SWF can last from several hours on the lower frequencies to minutes on the higher frequencies. (See definition #16. Solar Flare).

16.) Solar Flare-

A day side Earth bound solar filament and/or approximate C5 class or higher solar flare can move the proton flux >10 MeV (10+0) and initiate large scale high latitude propagation path absorption but even smaller C4 class flares and weaker are the culprit behind hour-to-hour and night-to-night variations in signal strength on the MF AM broadcast band and 160 meters, both stateside and DX. This transfer of increased density and RF signal absorption from the day-side D layer to night-side of the ionosphere occurs through high level neutral winds.

X-Ray Class Solar Flare. The rank of a solar flare based on its X-ray energy output. Flares are classified by the order of magnitude of the peak burst intensity (I) measured at the earth in the 1 to 10 angstrom band as follows:
Class (in Watt/sq. Meter)
B- I less than (l.t.) 10.0E-06
C- 10.0E-06 l.e.= I l.t.= 10.0E-05
M- 10.0E-05 l.e.= I l.t.= 10.0E-04
X- I g.e.= 10.0E-04

Background radiation in the 1 to 10 Angstrom range (Hard X-Ray's), as well as Solar and Galactic Cosmic Rays and ionization of Nitric Oxide (NO) in our atmosphere is the source of ionization of the D layer.

Basically a C-class solar flare possesses energy 1/10 the level of an M- class solar flare and an M-class solar flare possesses energy 1/10 the level on an X-class solar flare. (See definition #15. Shortwave Fadeout).).

Solar flares are not random meaningless explosions but instead a process inter-related with Coronal Mass Ejections (CME's), by which the Sun expels complex magnetic signatures enroute to changing its magnetic polarity or said a different way the swapping of the Sun's magnetic poles. Basically the Sun swapped it magnetic polarity at the peak of present Solar Cycle 23 somewhere between July 2000 and December 2001. The next polarity swap will occur during Solar Cycle 24 somewhere around 2010-2011.

A true confession, while I can ponder for hours the possible physical reasons behind a discontinuity in the data, I personally get little pleasure from soldering two wires together. With modern Pentium PC computers its probably best just to purchase a manufactured A/D circuit and concentrate on the science. My own C64 retired soon after the end of this study in 1991.

described a scanner controller project for use with a Commodore 64. Two circuits were presented of which, one was an interface between the radio automatic gain control (AGC) and a C64 computer "paddle" port. I suspected that the unit would work as well with my Yaesu 7700 shortwave receiver and there followed correspondence with Dr. Maloney. He was a great help and in fact he had the same radio. The circuit had one major drawback from my perspective, it was battery operated and I was proposing to make regular observations of 15 plus hours duration. Finally the solution came in the form of a modification by my clever brother in Seattle allowing the interface to run off the 11vDC power supply or the radio itself.

With the hardware in place after my years of waiting, I was ready to go to work. September 1987 was only a year past the minimum between sunspot cycles 21 and 22 and the solar activity was still fairly low, but picking up rapidly. My goals included both detecting flares and a more general one of observing radio propagation variation from minimum to maximum in the sunspot cycle, a project therefore lasting several years. In actual fact I gathered data weekly from September 1987 until July of 1991. Each Friday early I would switch on the computer and radio and, with a homebrew Basic program, monitored WWV's signal at 15MHz.

A technical note on the interface. The device works by taking the variable voltage output of the receiver's AGC circuit, accessible easily from the rear of the unit, and converting it to a variable resistance. The Commodore 64 computer game port could read both joysticks and the even-then obsolete game "paddles" which worked on resistance. The computer read the resistance and converted it to digital values, a built-in analog to digital interface.

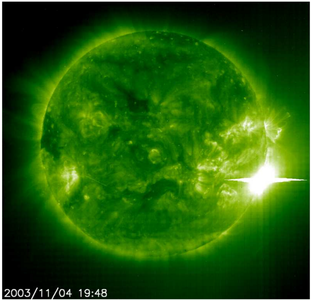


Image Of An X45 Class Solar Flare Click To Enlarge

Click for X45 Super Solar Flare Movie
http://www.wcflunatall.com/x28superflare031104.gif

17.) Sporadic-D (Ds) Absorption & Wave Guiding-

Sporadic-D (Ds) occurrences have an inter-relationship with brief but intense Sun based and Galactic X-rays and Galactic Cosmic Rays, huge positive cloud to ground lightning strokes and interrelated Elves and Sprites. Very large bursts of Gamma Rays have also been observed to occur in conjunction with Sprites.

Sporadic-D (Ds) absorption occurs both at day and night. Much of the night time occurrence of Sporadic-D (Ds) absorption is often masked by lightning QRN, as well as a lack of radio operation during thunderstorm events, due to the lightning strike hazard and also due to the operator not being able to recognize the mode due to unfamiliarity with it. It's doubtful that you will read about the Sporadic-D (Ds) phenomena anywhere else other then on this website.

While on the topic of lightning and propagation, an ionized lightning channel which normally has a maximum diameter of approximately a silver dollar, can reflect RF much like meteor trails do. I've personally noticed it on the 70 cm band, as a single propagation burst lasting 1/4 to 1/2 second. (See definition #20. D Layer Mid Winter Absorption Anomaly).

18.) Sporadic-E (Es) Absorption, Blocking & Refraction-

Just as the E layer is the main refraction medium for medium frequency (300-3000 kc) signal propagation within approximately 5000 km/3100 mi, so is a Sporadic-E (Es) cloud. Sporadic-E (Es) clouds occur at approximately 100 km/60 miles in altitude and generally move from ESE to WNW.

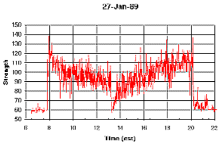
Like Stratosphere level warming and Troposphere level temperature and moisture discontinuities, Sporadic-E (Es) clouds can depending on the circumstances absorb, block or refract medium, high and very high frequency RF signals in an unpredictable manner.

The main source for "high latitude" Sporadic E (Es) clouds is geomagnetic storming induced radio aurora activity.

The main source for "mid latitude" Sporadic-E (Es) clouds is wind shear produced by internal buoyancy/gravity waves

Solar Flare detection by Shortwave Radio
Kevin Smith
http://www.lessmiths.com/~kjsmith/radio/r0ctnts.shtml

Introduction:
Fun with radio, a hobbyists' dash into the ionosphere..



This is the tale of a project long in the making, nurtured over three years of thinking and patience, of persistent attention, and finally of research and discovery. I hope it will fascinate and inspire the reader as much as it did myself.

The object of this study was to observe solar flares via shortwave radio. The technique, described in an article by Mr. John Hudak, (Sky and Telescope, Nov. 1984), involves monitoring the shortwave signal of a distant beacon and looking for a characteristic fadeout signature indicative of a solar flare. The equipment utilized in the article included a shortwave receiver and a chart recorder. I was interested in this project and had the necessary receiver, but no chart recorder so things merely stewed in my mind. It would not be easy or practical to purchase a chart recorder for a single purpose. Instead I considered ways of utilizing a Commodore 64 computer for the purpose of recording the data.

Things stood that way for three years until one day while shopping with my family I picked up a Radio Electronics magazine quite on a lark. Reading it later at home I was quite stunned to find an article by Dr. Frank Maloney which

(IBGW's), that create traveling ionosphere disturbances (TID's), most of which are produced by severe thunderstorm cell complexes with overshooting tops that penetrate into the Stratosphere. Another tie in between Sporadic-E (Es) and a severe thunderstorm is the Elve.

The main sources for "low latitude" Sporadic-E (Es) clouds is wind shear produced by internal buoyancy/gravity waves (IBGW's), that create traveling ionosphere disturbances, most of which are produced by severe thunderstorm cell complexes tied to tropical cyclones. High electron content in the Equatorial Ring Current also plays a role.

The forecasting of Sporadic-E (Es) clouds has long been considered to be impossible. However it is possible to identify certain troposphere level meteorological conditions that can lead to the formation of Sporadic E (Es) clouds. One is as mentioned above the severe thunderstorm cell complex.

Sporadic-E (Es) clouds have been observed to initially occur within approximately 150 km/90 mi to the right of a severe thunderstorm cell complex in the northern hemisphere, with the opposite being observed in the southern hemisphere. To complicate matters is the fact that Sporadic-E (Es) clouds that initially form to the right of a severe thunderstorm complex in the northern hemisphere, then move from ESE-WNW and end up to the left of the severe thunderstorm complex in the northern hemisphere. So one has to look for Sporadic-E (Es) clouds on either side of a severe thunderstorm cell complex. Things get even more complicated when two severe thunderstorm cell complexes exist approximately 1000- 2000 miles apart.

Not all thunderstorm cell complexes reach severe levels and not all severe thunderstorm cell complexes produce Sporadic-E (Es). This is where knowledge in troposphere physics and weather analyses/forecasting is necessary. Coincidentally I have a B.S. in Meteorology and an M.S. in Space Plasma Physics and am qualified to identify which severe thunderstorm cell complexes are most likely to produce Sporadic-E (Es) clouds.

Some of the key elements in identifying which severe thunderstorm cell complexes have the potential to produce Sporadic-E (Es) via wind shear, from internal buoyancy/gravity waves, that produce traveling ionosphere disturbances include:

1.) Negative tilted mid and upper level long wave troughs.

2.) Approximate 150 knot/170 mph jet stream jet maxes that produce divergence and therefore create a sucking vacuum effect above thunderstorm cells, that assist thunderstorm cells in reaching and penetrating the Tropopause into the Stratosphere.

3.) 500 mb temperatures of -20 deg. C or colder, which produce numerous positive and negative lightning bolts and inter-related Sprites and Elves.

DISCUSSION

Leonard F. Fuller (by letter): Operators using continuous waves have frequently observed that altho the received night signals may be stronger on the shorter waves, fading is so much more frequent on these that they are often commercially inferior to longer waves even for night work.

This may be explained by the following:

If the mean of the observations on curve Figure 13 of the American Institute of Electrical Engineers' paper mentioned by Professor Marchant are plotted, a curve of received watts is obtained following approximately the curve of energy radiated from the transmitting antenna.

This is as it should be and is the reason for the first of the practical observations of operators. The second may be explained by the following consideration of the theory of Fgure 3 of Professor Marchant's paper.

As he points out, interference bands, in the sense in which they are usually understood in light phenomena, do not exist if we consider the path of transmission parallel to the earth surface as a whole or even locally at A and B. Inasmuch as the possible number of Heaviside cloud arrangements are infinite, there are possibilities of an infinite number of points similar to A and B. Thus regions of weak or strong signals may be entirely irregular as to dimensions and spacing.

These regions are produced by the superposition of two waves of the same frequency, *out of phase*, rather than by the combination of two waves of different frequency. The relative amount of signal fading or amplification at a given point is therefore dependent upon the angular phase displacement of the two interfering waves. This displacement is dependent upon the actual mechanical dimensions of the convolutions on the under side of the Heaviside layer. Assuming the contours of this layer constantly changing, it is obvious that the longer the wave length the less the phase displacement of the interfering waves for a given change in the Heaviside layer. Thus fading may be less troublesome on the longer waves and their commercial value enhanced thereby.

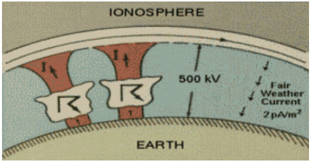
Fuller's results now confirm this explanation, tho it is necessary in addition, in the San Francisco-Honolulu tests, to assume refraction. It is to be hoped that experiments may be continued, since, besides giving a great deal of information on radio telegraphic technology, such tests may enable us to gain further knowledge of the nature of the upper atmosphere, at altitudes higher than those at which balloon observations are possible. The author wishes to express his indebtedness to Professor Wilberforce for his co-operation.

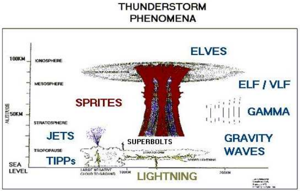
SUMMARY: Variations in received signal strength are ascribed partly to the existence of a "Heaviside cloud" layer consisting of masses of ionized gas at considerable heights. A partial bibliography of the subject is given.

The theory of interference caused by a spherical reflector is given, and results of receiving experiments due to Mr. Leonard Fuller, are studied in the light of the derived theory. It is shown that the Heaviside layer is probably quite irregular, and that refraction of the traveling waves is probably existent

Overshooting Top Is The Puffy Blister Just
To The Right Of Center Of Flat Ice Anvil Top

4.) Approximate 150-175 knot/172-200 mph updrafts within thunderstorm cells complexes that create overshooting tops (see photograph above) that penetrate the Tropopause into the Stratosphere (See definition #20 on Stratospheric Warming), launching upwardly propagating internal buoyancy/gravity waves, which create traveling ionosphere disturbances and then wind shear.





Lightning And Thunderstorms And Their Interaction With The Ionosphere

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19.) Long Delayed Echo (LDE)-

A fairly common propagation mechanism by which an RF transmitted signal returns to the sender within 1.25-5 seconds and in rare cases of up to 30 seconds. Research in the 1980's with HF OTHR discovered one propagation mechanism which involves ducting of the transmitted signal in the E-valley-F layer duct region of the ionosphere. A signal traveling along a magnetic field line much like a lightning induced whistler is another possibility.

The best time to observe an LDE is during the Fall/Spring equinox period when conditions are more balanced in the ionosphere. LDE's are very noticeable on amateur and SW broadcast signals between 17-28 mc with a peak near the maximum usable frequency (MUF). As recently as fall 2003 I did my own brief experiments using Morse code (CW) on the 15 meters band. I personally observed LDE's of my own

would be weak, whereas at *B* the difference in path would be just over 6 half wave lengths and the signals would therefore be strong. These phenomena can hardly be described as due to the production of an interference band in the sense in which it is usually understood, when speaking of interference phenomena in light. The interference between the rays traveling along the different paths is entirely tortuitous, and the regions of electromagnetic lightness and darkness are probably scattered in a most irregular way. The explanation here given, tho only one of an infinite number of possible explanations, is consistent with all the observations made by Mr. Fuller, and it is one which corresponds very closely with what may be anticipated from our knowledge of the upper atmosphere. The interesting calculation made recently by Mr. Cohen[10] that Austin's results could be represented by a formula of the form:—

$$I_R = \frac{K}{D}(1+N\,D)\,\varepsilon^{-0.0019\frac{D}{\lambda}}$$

also has a bearing on the subject, as it would seem to point to the strength of scattered waves, reflected from the lower face of the Heaviside layer. Mr. Fuller's results therefore, lend weight to the theory that the reflecting surface formed by the Heaviside layer is quite irregular, or rather they point to the existence of an irregular mass of reflecting clouds which form the lower surface of the layer. Combined with this, there must be a certain amount of refraction to enable the rays to get round the arc of nearly 30° of the earth's surface which they have to cover in going from San Francisco to Honolulu, as already explained by Eccles.[11]

Altho one can do no more than speculate on the causes of phenomena occurring in media of whose properties one can have no direct experimental knowledge, the facts seem to be adequately explained by some such conception. The Heaviside cloud theory may therefore be considered as further established. The author's own experiments which, unfortunately, have been completely interrupted by the war, pointed in the same direction, tho the distance over which he was working, London to Paris (650 km.) was comparatively short. In the account of his tests published by the Institution of Electrical Engineers[12] he emphasized the "cloud" theory first suggested by Fessenden as the most likely explanation of the phenomena observed, and Mr.

[10]Cohen. "Electrician," Volume 76, p. 743.
[11]Eccles, "Proc. Roy. Soc.", *loc. cit.*
[12]"Proc. I. E. E.", Volume 53, p. 329.

in Figure 3, interference might take place between the waves reflected from two regions $C E$ and $D F$. If one assumes a reflecting surface of such a nature[8] that the angle of incidence of a ray on it changes considerably for slightly differing altitudes as indicated in the figure, i. e., if the reflecting surface is irregular, a series of rays may be reflected at different angles by such a cloud at such points as $C E$ (closely adjacent) in directions $C A$

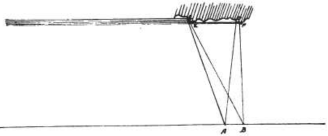

FIGURE 3

and $E B$, and it is easy to see that the difference in length of the path from C to A direct, and by the path $C D A$ may be an odd number of half wave lengths, while the difference in length of path from E to B direct, and by the path $E F B$ may be an even number of half wave lengths.[9] If this is the case, the distance between the two positions A and B at which the two waves would reinforce and neutralize each other respectively, may vary within wide limits. The diagram has been drawn to correspond, as nearly as possible, with the conditions given in Mr. Fuller's paper in which he has two stations 9 miles apart. The difference in length of the two paths to A is about 30 kilometers and to B about 26 kilometers. For a wave length of 7,500 meters, the signals at A would be strong, since the difference in path is 8 half wave lengths, at B the signals would be weak, since the difference in path is nearly 7 half wave lengths. For a wave length of about 8,500 meters the difference in path to A would be just under 7 half wave lengths so that signals

[8]It is perhaps misleading to speak of angle of incidence when the dimensions of the reflecting surface are of the same order of magnitude as the wave length, the incident radiation is really scattered.

[9]Altho the diagram has been drawn with the two interfering rays in one plane, it is clear that the rays may be reflected from other directions not coplanar.

transmitted signal of approximately 1.5-3 seconds and I could hear a mushy kind of Doppler shift on my returned signal frequency.

Claims of very long delayed echo's (VLDE) on the order of hours a4nd even days have been reported since the beginning of radio. Time periods of this magnitude would point to the "seeming possibility" of a refracting ionosphere type medium outside of Earth's own ionosphere, possibly somewhere past Pluto in the Oort Cloud. However no evidence so far has been found of such a medium and 99% of reported VLDE's are "probably" hoaxes.

http://heim.ifi.uio.no:80/~sverre/LDE
http://www.qslnet.de/member/la3za/prop

20.) Sudden Stratospheric Warming (STRATWARM ALERT)-

Sudden Stratosphere Warming is a major temperature change of the Winter time Polar and middle atmosphere from the Tropopause, where the Troposphere transitions into the Stratosphere to the base D layer of the ionosphere, which is at Mesosphere level. The warming lasts for many days at a time and is characterized by a warming of the Stratosphere temperature by some tens of degrees (temperature inversion), in unison with adjacent Troposphere cooling.

Another way to explain Stratosphere Warming is a major disturbance of the Winter time Polar middle atmosphere from the lower Stratosphere to the Mesosphere, resulting from a breakdown of the single Arctic Circumpolar Vortex into two circulation cells. Air trapped in the vortexes is mixed by the new meridional flow and is exposed to sunlight. Solar Lyman Alpha ionizes the Nitric Oxide (NO) gasses, resulting in an increase in electron density and producing strong medium frequency signal absorption at D layer height.

A little related Troposphere level Meteorology:

Interrelated with the splitting and shifting of the Arctic Circumpolar Vortex, is a Troposphere level negative North Atlantic Oscillation (NAO) and Pacific-North America Anomaly (PNA), mid and upper air height anomaly pattern. This equates to a large high pressure ridge in Western North America extending northward all the way into the Yukon region of Canada and a deep trough in the Eastern North America, from the eastern U.S. extending down into the Yucatan region of Mexico, with a second ridge in the western North Atlantic Ocean. This pattern is also called a dual blocking ridge and taps Siberian Arctic air, sending it across the North Pole into the eastern 2/3's of Canada and the U.S. providing for very cold surface temperatures.

As the Stratosphere lies below the Ionosphere, which is at Mesosphere and Thermosphere height, you would not expect to see Stratosphere Warming effect medium frequency propagation in any way BUT medium frequency signals do propagate off of Troposphere temperature inversions and moisture discontinuities and a temperature inversion is involved with Stratosphere Warming. So it's probable that a medium frequency signal could do any number of things when scattering off of a temperature inversion at any height. Unfortunately though some otherwise very knowledgeable Physicists stubbornly resist this concept.

Curve, Figure, Number	Date, 1914	San Francisco Time	Difference in length of path of interfering waves.	Condition of intervening space
5	Mar. 8	3 p.m.— 3.54 p.m.	28 km.	all light
6	" 15	10.30 a.m.— 12 p.m.	21 "	" "
7	" 15	3 p.m.— 4 p.m.	35 "	" "
8	Apr. 1	3 a.m.— 4 a.m.	28 "	all dark
10	May 17	11.30 a.m.— 12 a.m.	15 "	all light
11	" 24	10.25 a.m.—11.25 a.m.	36 "	" "
12	" 24	11.25 a.m.— 12 a.m.	14 "	" "
13	June 13	2.45 a.m.— 3.30 a.m.	20 "	all dark
			average	
14	" 22	10.30 a.m.—11.15 a.m.	15 km.	all light
15	" 28	10.45 a.m.—11.30 a.m.	36 "	" "

There is, of course, a difference between the day and night records in that the variations at night, due to altering wave length, are usually greater than they are in the day time, thus showing that the interfering waves are more nearly equal in intensity at night than they are by day. This is clearly shown in Figure 13 of Mr. Fuller's paper. The morning records give large variations also, and it would appear that altho the intervening space is fully lit, night conditions of semi-transparency still supervene. One of the most interesting results mentioned at the end of Mr. Fuller's paper is that he finds that the character of the land or water between the stations appears to make very little difference in long distance transmission, i. e., that the signals over land are as strong as they are over water. This seems almost conclusive proof that the observed signals are due to rays which are almost entirely refracted and reflected. The result, of course, is at variance with observations with shorter wave lengths over smaller distances. In dealing with interference phenomena it may be assumed therefore that the two rays travel round the earth thru the narrow passage formed by the earth and the Heaviside layer, being refracted as they pass, as was explained by Dr. Eccles, and being also reflected from the lower surface of the Heaviside layer.

If one assumes a ray refracted so as to follow nearly the curvature of the earth, which strikes a reflecting surface as shown

In Figure 13 of his paper he obtains the following results—

Wave lengths for which minimum values of signal strength are found	Wave lengths for which maximum values of signal strength are found
5 km.	6 km.
7 "	8 "
10 "	—

If the two interfering rays travel along their two different paths in the same direction independently of wave length, it is evident that the difference in length of path must be an odd number of half wave lengths for 5 kilometers, 7 kilometers, and 10 kilometers waves, and an even number of half wave lengths for the 6 kilometers and 8 kilometers waves.

Let δ be the difference in length of path,

then $$\delta=\frac{5}{2}m=\frac{7}{2}(m-2)=\frac{10}{2}(m-4)$$

where m is any odd number.

In the same way $\delta=\frac{6}{2}(m-1)=\frac{8}{2}(m-3)$.

This gives a series of equations from which m and δ can be found, which give fairly consistent results. The average value obtained by solving them gives $m=7$ or 9 (the values of m found are 7.5, 8 and 9) and $\delta=17.5$ or 22.5 kilometers, a result very different from that found by the simple reflection theory.

From the other curves given in Mr. Fuller's paper, in which maximum and minimum points are shown with varying wave length, the difference in length of path of the two sets of interfering waves may be readily calculated. The results of these calculations are given on the following page. (All records are for transmission from San Francisco to Honolulu.)

There is no relation observable between the difference in length of path of the interfering rays and the state of the sky, i. e., whether it is all light or all dark, but the variation in the difference of path is evidence that the observed phenomena are due to reflections from irregularly placed surfaces and lends support to the "Heaviside Cloud" theory.

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You can almost always correlate the coldest weather occurrences with poor medium frequency signal propagation conditions.

Also Stratospheric Warming (STRATWARM) has a negative effect on medium frequency propagation, due to increasing medium frequency radio wave absorption by the D layer, via upward propagating Internal Buoyancy/Gravity Waves (IBGW's).

This phenomenon also occurs in Southern Hemisphere Winter but is less pronounced.

U. Of Berlin Germany Stratospheric Research Group Layer
http://www.geo.fu-berlin.de/en/met/ag/strat/index.html

21.) D Layer Mid Winter Absorption Anomaly-

A period of increased medium frequency radio wave absorption at high and mid latitudes occurring in mid winter and is associated with sudden stratospheric warming and the Quasi Biennial Oscillation (QBO). If you look in your radio logs for 160 meters you will notice that most of your good DX contacts are in the fall and spring. This is due to the D Layer Mid Winter Absorption Anomaly. (See definition #17. Sporadic-D (Ds) Absorption & Wave Guiding). (See definition #20. Sudden Stratospheric Warming (STRATWARM ALERT).

Weather In The Upper Atmosphere
http://www.albany.edu/faculty/rgk/atm101/weather.htm

22.) F3 Ionosphere Layer-

A PDF Article Via IPS Australia About The Long Suspected But Only Recently Verified F3 Ionosphere Layer
http://www.wcflunatall.com/F3layer.pdf

The F3 layer primarily exists only in the vicinity of the Earth's magnetic equator. This may represent part of an explanation for (TEP) Trans Equatorial Propagation.

23.) The Gray line/Gray line Propagation-

A general east-west transition between daytime and nighttime (twilight) where enhanced propagation conditions "may" occur. Near local sunrise the absorptive D layer has yet to become illuminated by the Sun, though the higher in altitude F/F2 layer has. Inversely near local sunset the absorptive D layer is losing illumination by the Sun, though the higher in altitude F/F2 layer still is. There is also a strengthening and weakening process in the E layer, as well as angle tilts and altitude changes in the D, E and F layers.

This process can allow for enhanced propagation conditions within the general north-south gray line corridor. It is most pronounced on 30, 40 and 60 meters and less so on 80 and 160 meters. Actually most gray line propagation on 160 meters and to a lesser extent on 80 meters is perpendicular (right angles) to the corridor. In my professional observation the gray line propagation enhancement process is still not totally understood and it's benefit exaggerated to almost mythical proportion.

ferences in length of path for the two rays at angles θ and θ' which interfere at the points distant D and $(D+a)$ from the sending station respectively must equal $\pm\frac{\lambda}{2}$.

Hence $$a\left(\frac{d\,[D\,(\sec\theta-1)]}{d\,(D)}\right)=\pm\frac{\lambda}{2}.$$

Reducing this quantity we arrive at the condition

$$\left(1-\sqrt{1+\left(\frac{n\,h}{D}\right)^2}\right)=\pm\frac{\lambda}{2\,a}\sqrt{1+\left(\frac{n\,h}{D}\right)^2}$$

But $$\sec\theta=\sqrt{1+\left(\frac{n\,h}{D}\right)^2},$$

then $$\sec\theta=\frac{1}{1\pm\frac{\lambda}{2\,a}}.$$

Putting now $\lambda=6$ km., $a=14.4$ km. (the values given in Mr. Fuller's paper), $\sec\theta=1.26$ and $\theta=37.6°$, since it is evident that the $-$ sign must be taken.

Substituting now for $\sec\theta$, its value found above,

$$\frac{n\,h}{D}=0.76.$$

If $D=3{,}700$ km. and $h=80$ km., D being the distance between San Francisco and Honolulu, and h the height usually assumed for the Heaviside layer, it follows that

$$n=\frac{0.76\times3{,}700}{80}=35 \text{ times},$$

or the rays reflected by the Heaviside layer must go up and down 35 times between it and the earth to give an interference band of this width. This is certainly not likely to happen without considerable loss of energy of the reflected ray, which would prevent sharpness of the interference band. Moreover, such reflections as these would give a difference in path for the two rays of

$$D\,(\sec\theta-1)=3{,}700\times0.26=960 \text{ km}.$$

THE HEAVISIDE CLOUD THEORY

Now the very interesting curves given by Mr. Fuller in which he shows that weakening and strengthening of the signal occurs as the wave length at the sending station is altered, indicate that the difference in length of path of the two interfering rays is much less than that calculated above.

theory, and that the other is reflected by the Heaviside layer and by the earth's surface.

Altho it is hardly to be expected that reflection will be regular, in the first instance it may be advisable to consider the conditions which govern the width of interference bands formed by regular reflections between plane surfaces. Let the two surfaces be represented by $O\,P$ and $Q\,R$ distant h kilometers from each other.

Let n be total number of successively reflected rays, and θ the angle at which the reflected ray strikes the Heaviside layer. It is easily seen that

$$\tan\theta = \frac{n\,h}{D} \qquad \text{(See Figure 2)}$$

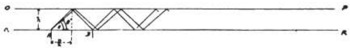

FIGURE 2

The difference in length of path for two rays going from A to B, one directly along the surface of the earth and the other reflected by the surface $O\,P$ is given by

$$2\left(\frac{D}{n}\sec\theta - \frac{D}{n}\right)$$

For the whole series of n reflections, this equals $D\,(\sec\theta - 1)$, and it is seen that this is dependent only on the value of θ and D. If one assumes a ray impinging on the reflecting layer at a slightly different angle, θ', the difference in length of path to a point distant $D+a$ from the sending station will be $(D+a)\,(\sec\theta' - 1)$. To get the distance between interference bands, differentiate $D\,(\sec\theta - 1)$ with respect to D, making the necessary substitution for $\sec\theta$,

$$\frac{d\,[D\,(\sec\theta - 1)]}{d\,(D)} = \frac{d\left(D\left\{\sqrt{1+\left(\frac{n\,h}{D}\right)^2} - 1\right\}\right)}{d\,(D)}$$

$$= \left(\sqrt{1+\left(\frac{n\,h}{D}\right)^2} - 1\right) - \left(\frac{n^2\,h^2}{D^2\sqrt{1+\left(\frac{n\,h}{D}\right)^2}}\right)$$

If a be half the width of an interference band, i. e., the distance from a dark to a light patch, the difference between the dif-

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(See definition #8.) E Valley/F Layer Propagation Ducting Mechanism/Chordal Hop Propagation).

24.) Plage-

A patchy H-alpha brightening on the solar disk commonly found in or near active regions of which can last for several days or so. A Plage is irregular in shape and variable in brightness and marks areas of nearly vertical emerging or reconnecting magnetic field lines. Often times a sunspot group will emerge from a Plage. (See definition #14. Sunspot Group).

Note! I make no claim of ownership of the images displayed on this website. Also I have attempted to keep the propagation theory explanations in simple to understand layman terms, because long complicated technical explanations can be boring and make one's eyes glaze over. Unfortunately though sometimes while trying to keep things simple, certain definitions, meanings and technical aspects can get watered down or even lost.

Thomas F. Giella W4HM
Retired Meteorologist & Plasma Physicist
Lakeland, FL, USA at
w4hm at tampabay dot rr dot com

of the atmosphere which act as reflectors and refractors for the waves that are used for the transmission of radio signals.

Other facts bearing on the presence of this layer have been dealt with by Dr. Eccles in a paper published by the Royal Society.[7] It will not be necessary to reproduce the argument he uses to prove its existence, that may be assumed. It is the object of this paper to discuss to what extent the Heaviside layer can explain the phenomena described by Mr. Fuller.

THEORY OF INTERFERENCE BANDS ON A SPHERICAL REFLECTOR

In the first place, the conditions governing the production of interference bands on a spherical surface with a surrounding envelope, also of spherical form, whose internal surface acts as a reflector, may be discussed. It is usually assumed that the height at which the Heaviside layer becomes sufficiently conducting to act as a reflector is about 50 miles (80 km.). This is shown to scale in Figure 1, the points A and B corresponding respectively with San Francisco and Honolulu. It is clear that the passage between this layer and the earth is very much in the nature of a narrow crevasse between two parallel surfaces or reflecting mirrors.

FIGURE 1

It is sufficient, as a first approximation, to consider, therefore the formation of interference bands by reflection from a pair of flat parallel surfaces. The distance between the bands of electromagnetic lightness and darkness is determined by the fact that the difference between the paths of the rays reaching these points by two alternative routes is half a wave length. If the difference in distance along the two paths is a multiple of a wave length the point is one of brightness; if it is an odd number of half wave lengths the point is dark.

It may be assumed in the first instance that one ray travels along the surface of the earth, as supposed in Sommerfeld's

[7] Eccles, "Proc. Roy. Soc.," A, Volume 87, pp. 79–99.

to that already available for the discussion of this subject, and it may be useful, therefore, to consider them in their bearing on the existence and probable nature of what, in this country, is generally called the "Heaviside layer."

Tho it is usually called by this name, Professor Fleming[4] observed recently that it was Sir James Dewar, who was one of the first to draw attention to its existence. In a lecture to the Royal Institution in 1902[5], when discussing the constitution of the atmosphere Dewar pointed out that there were really two parts to it: the lower part in which atmospheric currents circulated, and in which the constituents were similar to those of the atmosphere at lower levels, and the upper part in which the distribution of gases was governed by their density. In two lectures delivered recently to the Royal Institution[6], Professor Fleming has discussed the formation of this upper ionized layer and the causes which produce it. He points out that, in order to produce ionization in such a gas as oxygen, by light radiation, it is necessary to have a wave length of the order of 1,500 to 1,800 ångstrom units (10^{-7} mm.), that is, light which is far beyond the ultra violet end of the spectrum. If such light really produces any ionization, then it is to be expected that the ionization would be reduced at night; and, therefore, that signals might be expected to vary in strength at night, if these ionized gases are the cause of signal variation. Professor Fleming suggests, however, that at heights of the order of 60 miles (100 km.), where the ordinary constituents of the atmosphere disappear and are replaced by hydrogen and helium and possibly other lighter gases, the most likely agency in producing ionization is the solar dust projected from the sun and transmitted to the earth thru the agency of light pressure. This explanation of the production of an upper ionized layer of gas is verified by the fact that the time interval elapsing between the passage of a sun spot across the solar meridian and the corresponding magnetic storm, as shown by Arrhenius, is about 45 hours, a figure which agrees fairly closely with the time Professor Fleming calculates that a particle of 1,200 ångstrom units diameter would take to pass from the sun to the earth. Whatever the cause which produces this layer, there is little doubt that such a layer exists, not necessarily in the form of a shell concentric with the earth, with fairly flat surfaces, but more likely in the form of large masses of gases in the upper regions

[4] "Electrician," Volume 75, p. 348.
[5] "Proc. Royal Institution," Volume 17, p. 223.
[6] *Loc. cit.*

CHEN-PANG YEANG*

The study of long-distance radio-wave propagation, 1900-1919

GUGLIELMO MARCONI'S TESTS of the trans-Atlantic wireless telegraphy made sensational news at the turn of the 20th century. Since the early 1890s, the Italian-born inventor-entrepreneur had established radio communication links spanning as far as the English Channel but what he did in 1901 was unprecedented. He attempted to exchange telegraphic signals between Britain and North America without submarine cables or other mediation. Marconi's moment came on December 12. Sitting in a station on a hill in Newfoundland, Canada, Marconi and his assistant George Kemp heard regular sharp clicks from earphones connected to the receiving apparatus. They had heard a wireless message transmitted from the high antenna tower energized by a spark-gap circuit located at Poldhu, England. The New York Times quickly featured Marconi's story.[1]

* Dibner Institute for the History of Science and Technology, and Program in Science, Technology, and Society, Massachusetts Institute of Technology, 38 Memorial Drive, Cambridge, MA 02139 (cpyeang@mit.edu).

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The following abbreviations are used: *AP, Annalen der Physik;* DM, Deutches Museum Archiv, Munich; (http://www.lrz-muenchen.de/~Sommerfeld/ for the archives Sommerfeld documents); *Obit*, Royal Society of London, *Obituary notices of fellows*; *PRS*, Royal Society of London, *Proceedings*.

1. Orrien E. Dunlap, *Marconi, the man and his wireless* (New York, 1937), 87-102, and Degna Marconi, *My father Marconi* (New York, 1962), 111-120.

HSPS, Volume 33, Part 2, pages 369-404. ISSN 0890-9997.

The trans-Atlantic wireless test not only caught the attention of the general public, corporate capitalism, and the electrical industry for its technological implications, but also raised a curious scientific question. To establish a link across a distance as long as one sixth of the earth's perimeter, the wireless waves had to travel along a path conforming to the curved surface of the earth. Why do wireless waves, which behave much like optical and acoustic waves, not follow rectilinear trajectories? Why does the curvature of the earth not block them?

This paper shows how these problems were turned into mathematical representations, and how the empirical observations made by industrial practitioners evolved toward quantitative experimental data. It explores how engineering technologies affected experimental investigations, how traditions of applied mathematicians shaped numerical problems and approaches, and how theoretical tendencies of late-19th-century microphysics directed the formation of physical models. It also discusses how the problem of long-distance transmission emerged as a conjunction of distinct collective cultures, and how these cultures meshed with broader social contexts.

Two alternative theories of the peculiarly long transmission were proposed: the wave propagating along the surface results from diffraction by the body of the earth; and the wave bounces back and forth between the earth's surface and a conducting layer in the upper atmosphere. While theorists discussed these alternatives, experimenters worked on constructing empirical quantitative relations among the physical variables involved in long-distance transmission.

Three communities of researchers may be identified. European mathematical physicists and mathematicians worked on diffraction theories and developed mathematics to convert the diffracted fields into numerically tractable forms. Anglo-American electrical engineers and experimental physicists focused on atmospheric reflection and explored the conducting properties of the air. American wireless telegraphers established the empirical formula governing the relation between received wave intensity and distance for given wavelengths. It proved difficult to decide between the two theoretical models. The quantitative predictions of the diffraction theorists disagreed with the empirical formula. The reflection theorists could explain the bending of the waves and static noise qualitatively, but could not make quantitative predictions. The indeterminacy ended in 1919 when the English mathematician George Neville Watson developed a new mathematical technique for the diffraction theories and used it to demonstrate the superiority of the reflection approach.

The three different practices were significantly shaped by distinct intellectual traditions, purposes, and research styles. The long-distance radio experiments related to pragmatic instrumentality in wireless engineering: to test the validity of high-power transmitters and sensitive radio detectors for the first long-range radio station of the U.S. Navy. The mathematics of series or integral approximations used in the diffraction theories incorporated then recently developed complex-variable analysis in mathematics. The reflection model, which began as a speculation among electrical researchers, became part of the Maxwellian-microphysics agenda.

Proceedings of the Institute of Radio Engineers: 1916

THE HEAVISIDE LAYER*

By

E. W. Marchant, D. Sc., M. I. E. E.

(David Jardine Professor of Electrical Engineering, University of Liverpool)

The formulas which have been obtained for the strength of signals received at a station when a measured amount of high frequency power is sent into a distant transmitting antenna (as the result of investigations and measurements by Austin and others) are well known, and have been dealt with fully in Mr. Fuller's paper before the American Institute of Electrical Engineers.[1]

It is within the knowledge of all radio operators that signals vary widely in strength, often in the course of a few minutes; and such variations can most easily be explained by reflection and refraction from moving masses of "cloud" or ionic fog. The surface wave theory developed by Sommerfeld, while explaining transmission over long distances, round the curvature of the earth, does not explain these sudden changes. The fact that these changes occur more by night than by day provides further evidence that the reflection and refraction theory of which Dr. Eccles has been, in this country, the chief exponent, is the most likely one to explain observed phenomena.

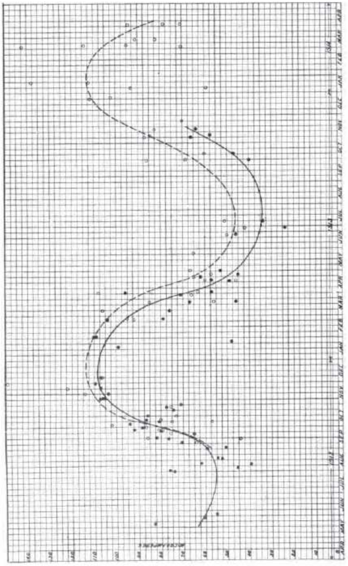
The experiments described by Balsillie[2] in which he found that dust storms occurring along the line of transmission affect signal strength, when the transmission is in the direction in which the wind is blowing, are of interest, as they indicate that the *atmosphere* immediately adjacent to the earth is a factor in the absorption of waves. The chief phenomena, however, which require further explanation are (*a*) the sudden variations in signal strength at night, and (*b*) that comparatively small changes in wave length may make relatively enormous changes in the strength of received signals. The experiments recently described by Mr. Fuller[3] have added much exact information

*Received by the Editor, April 18, 1916.

[1] "Proceedings of the A. I. E. E." Volume 34, p. 567.

[2] "Proceedings of British Association (Australia)," p. 514. See also the "Electrician."

[3] "Proc. A. I. E. E.," *loc. cit.*



STRENGTH OF SIGNALS RECEIVED AT WASHINGTON
o = SIGNAL FROM PHILADELPHIA
• = SIGNAL FROM NORFOLK

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These communities worked toward different goals, legitimized different methodologies, and gave priority to different technical and social concerns.

Diffraction theorists and the reflection modelers did not compete directly; their practices, and those of the experimenters, exhibited more complementary than competitive elements. Although the three communities were tied together by the same question (the possibility of long-distance radio-wave transmission), the most important aspect of their intertwined history was not the mutually exclusive and competitive answers they reached, but their contributions of different pieces of knowledge eventually subsumed in the solution.

The three communities' essential differences and the intellectual content of their interactions may be understood by analyzing their epistemic status—their judgments about what was known, what was important to know, and possible to know. Here reference to the teachings of Pierre Duhem and Sylvain Bromberg are in order. Duhem distinguished two aims of a physical theory: [to explain] a group of laws experimentally established, and "to *summarize* and *classify logically* a group of experimental laws without claiming to explain these laws."[2] Duhem's mathematical calculus for organizing scientific knowledge included quantitative and logical reasoning, numerical predictions, and recursive revision. Similarly, Bromberger distinguished theory as an intellectual device that could systematically generate answers to questions from theory as an answer to a why question.[3] Following Duhem's and Bromberger's theories of epistemic status, analyzing what is known, important to know, and possible to know amounts to deciding whether, for the historical actors, a piece of knowledge is explanatory or representational, an answer to a question or a part of a question-answering device.

The essential distinction between the diffraction theorists and the reflection theorists concerned the kinds of questions asked and the kinds of knowledge required, not the mutual exclusiveness of their physical models. The diffraction theorists developed rigorous mathematical theories to represent a physical model that aimed to account for only one wireless phenomenon—long-distance propagation. For this single phenomenon, they could mobilize quantitative reasoning and consolidate numerical predictions from mathematical theories. The reflection theorists constructed elaborate physical models to account for several significant wireless phenomena—not only long-distance transmission but also the diurnal and seasonal variations of signals and atmospheric noise. But their mathematical tools lagged much behind the diffraction theorists'. The diffraction theorists asked questions about mathematical tractability. The reflection theorists asked questions about the causes of various puzzling observations. Their theories were mainly explanations. But until a late stage they did not contain a systematic means for giving qualitative or quantitative predictions.

2. Pierre Duhem, *The aim and structure of physical theory* (Princeton, 1982), 7.
3. Sylvain Bromberger, "A theory about the theory of theory and about the theory of theories," in Bromberger, *On what we know we don't know: Explanation, theory, linguistics, and how questions shape them* (Chicago, 1992), 52-74.

The epistemic approach helps to understand the activities of the experimenters as well. The questions they asked were practical—they wanted to know the performances of transmitters and receivers under operating conditions in order that the U.S. Navy's first long-distance wireless would function properly. They were not motivated by theory-driven questions to conduct experiments. Likewise, their measured results served as reference for engineering specifications rather than as tests of theories. Because, however, the physics-trained experimenters believed that representing the measured results in terms of a mathematical formula, which was much more convenient than raw numbers for the theorists to work with, served engineering, they did provide material for checking theoretical predictions.

1. EMPIRICAL OBSERVATIONS

Guglielmo Marconi invented a transmitter and receiver for wireless telegraphy in the 1890s. Oliver Lodge in Britain, Alexander Popoff in Russia, Edouard Ducretet in France, and Ferdinand Braun in Germany made similar inventions about the same time.[4] The European and American governments, commercial and industrial enterprises, and inventors, engineers, and scientists quickly recognized the potential of these devices. Numerous sophisticated novel technologies of wireless telegraphy were developed between 1895 and 1920.

To the engineering communities, the primary concern with wireless telegraphy was the improvement of transmitters, receivers, and techniques of measurements.[5] They were not as successful in modeling the process of wave transmission as in engineering transmitters and receivers. They had too little information about wave propagation in the real world for which they intended the devices. To proceed, they needed to establish the empirical phenomena of wireless wave transmission. That task began only in the first few years of the 20th century.

The empirical problem may be stated as follows: under what environmental or instrumental conditions does the propagated electromagnetic energy experience a certain amount of change. The relevant major phenomena discovered before 1910 consisted of:

• Marconi's achievement of wireless communications over one sixth of the earth.

• The effect of the terrain. The maximum effective transmission distance of a wireless wave is the longer the greater the ground conductivity; thus a wave over sea usually propagates farther than one over land. The British naval officer Henry Bradwardine Jackson deduced the effect from experiments conducted on his own while serving on British warships between 1899 and 1902.[6]

4. Hugh G.J. Aitken, *Syntony and spark: The origins of radio* (New York, 1976), 198.
5. E.g., Jonathan Adolf Wilhelm Zenneck, *Wireless telegraphy* (New York, 1915); John Ambrose Fleming, *The principles of electric wave telegraphy and telephony* (London, 1916).
6. Henry B. Jackson, "On the phenomena affecting the transmission of electric waves over the surface of the sea and the earth," *PRS, 70* (1902), 254-272.

SUMMARY: The strength of received signals from two stations was measured at the Bureau of Standards over a period of about two years. The transmitting wave length was 1,000 meters, spark frequency, 1,000, and sending antenna current about 10 amperes for each of the transmitters. Their distances were respectively 185 and 235 kilometers. The curves giving variation in intensity of received signals are shown and discussed.

DISCUSSION

Robert H. Marriott: It will be found interesting and instructive to compare what Dr. Austin has found with the results I described in my paper on "Radio Range Variation" before the Institute, (PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, Volume 2, Number 1, page 37) and especially with chart 3, Figures 1 and 12 of that paper.

Alfred N. Goldsmith: It is evident from Dr. Austin's results that for the particular stations under consideration, the day of best transmission is close to January 1st, and the day of most difficult transmission to July 15th. The average ratio of received energy in winter to received energy in summer (for the extreme cases) is found to be 6.3. However, this last result is not very accurate, since the individual values of the ratio lie between 3.9 and 10.

was 69 ohms. The figure shows a well marked difference between the summer and winter intensities, but the great variation among the individual values makes it difficult to draw quantitative conclusions; observations on succeeding days in several instances differing from each other in a ratio of more than two to one, while the errors of observation are certainly less than 10 per cent. Rough curves have been drawn among the individual points of observation, indicating the general course of the changes. The Philadelphia values in general lie higher than the Norfolk values, with the exception of those taken in the Autumn of 1912 before certain changes were made in the Philadelphia antenna which appear to have increased its efficiency. No observations were taken in Norfolk after November, 1913, as changes in that station made it impossible properly to make comparison between the observations before and after that time. Notwithstanding the irregularities among the observations, a few facts appear fairly certain: The seasonal variations seem to be different in different years, the minimum of 1912 being higher than that of 1913. The rise in the curves in the Autumn of 1912 appears to be steeper than that of 1913, the practical maximum being attained by November 1st in 1912 and not until the middle of December in 1913. It has not been found possible definitely to connect the strength of signal with the changes in foliage conditions, altho it is possible that this is an important factor in the variations. Contrary to the ideas previously held, there seems to be no very marked connection between rainfall and the transmission of the signals. This was especially noticeable in the Autumn of 1912, when after a dry period, rain set in and fell heavily for four days. This, however, caused no certain increase in the strength of the received signals.

This preliminary series of observations shows that for a thoro study of the subject it will be necessary to observe at least twice a week, and preferably every day, for a long period of time. From these observations it will then be possible to derive average values from which the general course of the phenomena can be deduced with some degree of accuracy. It may then be possible by comparison with the curves of meteorological and magnetic phenomena to find relations which will help to explain the seasonal changes, and also the irregularities among the single observations.

Most of the observations have been taken by my assistant: H. J. Meneratti, Chief Electrician, U. S. N

• A wave goes further in dry than in humid air (Jackson).

• The maximum effective distance at night exceeds that in daytime (Marconi).[7]

• Noise, "static," or "stray wave" is more serious at night than in daytime (Jackson), during the summer than during the winter (Jackson), and at low than at high latitudes (Popoff, Feriyi, and Turpain).[8]

• The received energy generally increases with the length of the wave and the arrangement of the antenna.

• The radiation pattern of an antenna system can be different at different directions. A vertical aerial receives maximum energy when tilted along the transmission direction; several aerials with identical phase delay can give a strongly directional transmission (Marconi, Zenneck, Sigsfeld, Braun).[9]

Until 1905, the antenna consisted of a long vertical conducting wire connected at its lower end to a spark gap. The amplitude of received current is independent of the direction of the receiver's location with respect to the antenna, provided the receiver is on the ground. In 1906, Marconi suggested that a directional effect antenna could be obtained with a horizontal antenna.[10] The received current attains the maximum when the transmitter-receiver direction lies along the direction of the transmitter or the receiver antenna. Typically, reception is a minimum at angles of 110° or 250°. The minimum loci and the shape of the radiation pattern vary with antenna parameters. Figure 1 illustrates two of the radiation patterns Marconi measured.

Many of the empirical observations were qualitative descriptions that made either ontological assertions identifying physical factors relevant to the propagation of electromagnetic waves or quasi-quantitative comparative statements linking propagation with increase or decrease of a physical quantity. Quantitative descriptions of the empirical observations existed as tabulated data, not mathematical formulas. However far this phenomenological knowledge was from ideal scientific evidence, theorists had no choice but to use them as empirical evidence for their theories. Rigorous and controlled quantitative experiments on long-distance wave transmission remained to be done.

7. Dunlap (ref. 1), 122-127; Guglielmo Marconi, "A note on the effect of daylight upon the propagation of electromagnetic impulses over long distances," *PRS, 70* (1902), 344-347.
8. See Fleming (ref. 5), 851-852.
9. Guglielmo Marconi, "On methods whereby the radiation of electric waves may be mainly confined to certain directions, and whereby the receptivity of a receiver may be restricted to electric waves emanating from certain directions," *PRS, 77* (1906), 413-421; Ferdinand Braun, "On directed wireless telegraphy," *Electrician, 57* (1906), 222-224, 244-248. Cf. Friedrich Kurylo and Charles Susskind, *Ferdinand Braun: A life of the Nobel prizewinner and inventor of the cathode-ray oscilloscope* (Cambridge, 1981), 134, 143, 170.
10. Marconi (ref. 9).

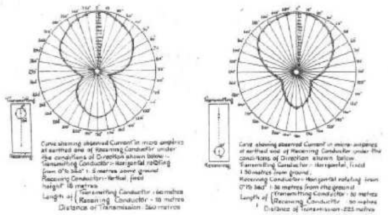

FIG. 1 The radiation patterns of Marconi's directive antenna. Left panel, the transmitter's antenna rotates from 0° to 360°; right panel, the receiver's antenna rotates from 0° to 360°, Marconi (ref. 9), figs. 2, 4.

2. SURFACE DIFFRACTION THEORIES

The British initiative

To the community of physicists in the late 19th century, the phenomenon of long-distance wireless wave transmission was not altogether unfamiliar. The physical picture associated with this phenomenon could be found in the physical optics of diffraction and in acoustic scattering theory. Lord Rayleigh had developed a set of analytic techniques to deal with the acoustic problem.[11]

Between 1901 and 1919, two groups of mathematical physicists and mathematicians developed Rayleigh's approach for application to radio-wave transmission. One was a British group at Cambridge University plus the French mathematician Henri Poincaré. The other group was led by the mathematical physicist Arnold Sommerfeld at the University of Munich and the German electrical engineer Jonathan Zenneck.

Hector Munro Macdonald received a bachelor's degree at the University of Aberdeen before moving to Cambridge University, where he became fourth Wrangler in the Mathematical Tripos of 1889. His research agenda was set by the Adams Prize problem of 1901: to describe the propagation of electromagnetic waves under a number of boundary conditions with simple geometry. Published in 1902 as *Electric waves*, Macdonald's prize-winning essay applied an electromagnetic theory based on an energy expression to study the effect of an antenna on its electrical oscillating frequencies, and to solve the diffraction field at the edge of a perfectly

11. John William Strutt, *The theory of sound* (New York, 1945).

SEASONAL VARIATION IN THE STRENGTH OF RADIOTELEGRAPHIC SIGNALS*

By

Louis W. Austin, Ph.D.

(*Director of the United States Naval Radiotelegraphic Laboratory*)

In 1912, experiments were begun at the Bureau of Standard on the measurement of the strength of the receiving antenna current produced by signals sent from the radio stations in the Philadelphia and Norfolk Navy Yards. The object of the experiments was the determination of the variation in the strength of the signals at different times of the year.

It had been known qualitatively that the winter signals in general were stronger than those of summer, especially when the transmission took place overland. The reason ordinarily given for this was the absorption of the waves during the summer, due to the vegetation.

The conditions of the experiments were as follows: The sending wave length was 1,000 meters, and the spark frequency was approximately 1,000 per second, the sending antenna current being kept not far from 10 amperes, and care being taken that waves of only one frequency were emitted. The height to the center of capacity of the Philadelphia antenna was 39 meters, and of the Norfolk antenna 52 meters. The antenna at the Bureau of Standards is a harp 55 meters high, having an effective height to the center of capacity of 30 meters. The capacity is 0.0014 microfarad. The distance from the Bureau of Standards to the Philadelphia station is 185 kilometers, and to the Norfolk station 235 kilometers. The method of measuring the received antenna current has been described in another place.†

The observations are shown in the accompanying figure. The ordinates represent microamperes of received current reduced to a constant sending antenna current of 10 amperes. The total receiving antenna resistance, including that of coupling,

* Delivered before The Institute of Radio Engineers, New York, December 2, 1914.

† Bulletin, Bureau of Standards 7, p. 295, 1910. Reprint No. 157.

conductingprism.[12] When the news of Marconi's trans-Atlantic transmission spread in 1901, Macdonald was ready to work out a theoretical account of the phenomenon based on diffraction model.

Macdonald's paper of 1903 begins with a simple model that included all the supposedly relevant physical characteristics of wireless wave transmission.[13] The transmission antenna appears as a vertically polarized point current source, the so-called "Hertzian dipole," above the ground. Macdonald treated the atmosphere as free space with uniform dielectric constant and permeability and zero conductivity, and the earth as a perfect conductor (figure 2). The model captured some reality; but also erred seriously in giving the atmosphere no role (different from free space) in wave transmission. All diffraction theorists after Macdonald began their theoretical work by imposing the assumption.[14]

To calculate the intensity of the electric and magnetic fields at any point on the earth, Macdonald solved Maxwell's equations for the electromagnetic fields. He wrote down the wave equation for the azimuthal component of the magnetic field intensity in spherical coordinates (the axis of the azimuth is the radius connecting the earth's center and the dipole's location). Following Rayleigh's *Theory of sound*, Macdonald expressed the solution as a series of Bessel-Hankel functions and Legendre polynomials.[15] He determined the coefficients of the terms in this series from the conditions that the field intensity be infinite at the location of the Hertzian dipole and the tangential component of the electric field at the surface of the perfect conducting earth should vanish.[16]

The diffraction theorists in the first twenty years of the 20th century agreed with all Macdonald's arguments up to this point. They disagreed about how to approximate the analytical solution in a numerically tractable form. Macdonald noticed that the problem had exactly the same form as one dealt with in Rayleigh's *Theory of sound*. Following Rayleigh, Macdonald exploited the asymptotic properties of Hankel functions to establish that when the wavelength λ is much smaller than the radius of the earth a, the field intensity obeys a simple relation. The ratio of the electric field at the sphere's surface at the separation angle θ (the angle between the oscillator P and the point of observation C as seen from the earth's center) to the electric field at $\theta=0°$ is $1\text{-}\cos\chi$, χ being the angle between the observer and the earth's center as seen from the dipole.[17]

This overly succinct result implies that the electric field produced by a Hertzian dipole does not vanish at any point on the earth, including the diametrically opposite point, $\chi = 0°$. It means that the earth never casts any shadow on the propa-

12. *Obit., 11* (1935), 553-555.
13. Hector Munro Macdonald, "The bending of electric waves round a conducting obstacle," *PRS, 71* (1903), 251-258.
14. Some of them later assigned the earth a finite conductivity and dielectric constant, but others continued to work on the perfect-conductor case.
15. Strutt (ref. 11), chapt. 17.
16. Ibid, 253.
17. Ibid, 255.

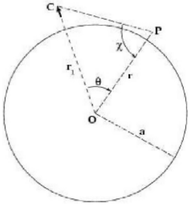

FIG. 2 Spherical boundary condition of the diffraction theory. The sphere represents the earth, the small arrow at C the transmission antenna modeled as a vertically polarized Hertzian dipole; the observer is at P.

gation of the electromagnetic field. The field can travel anywhere on the earth. Thus the magic of trans-Atlantic wireless transmission: the field diffracts across the surface of the earth. Macdonald considered this conclusion to be a complement to Rayleigh's discovery in acoustics.[18]

Unfortunately, Macdonald's approximation scheme had a serious problem, which Rayleigh pointed out. Rayleigh claimed that a shadowless wireless wave could not move around the earth since it would lack analogy to the optical case. The wavelength of the wireless wave (less than 50 kilometers) had about the same ratio to the radius of the earth as the wavelength of visible light had to one inch; but the light shining on a conducting ball one inch in radius does not creep around the ball to illuminate its rear surface. Furthermore, Rayleigh points out that Macdonald's asymptotic approximation did not in fact hold when the wavelength is much smaller than the radius of the sphere owing to a property of the Bessel functions that need not be detailed here.[19] Henri Poincaré also pointed out the difficulty with Macdonald's asymptotic approximation.[20]

In the following decade, the mathematical problem of how to approximate the exact solution of the diffracted field given by Macdonald was widely discussed among mathematicians and mathematical physicists, who proposed new approaches to the notorious Bessel functions. None of these efforts survived criticism. Discus-

18. Ibid, 328.
19. John William Strutt, "On the bending of waves around a spherical obstacle," *PRS, 72* (1904), 40-41.
20. Henri Poincaré, "Sur la diffraction des ondes electriques: Àpropos d'un article de M. Macdonald," *PRS, 72* (1904), 42-52.

H. E. HALLBORG: We should try more transmission experiments between stations lying north and south, so as to be able to compare ranges with those lying east and west. It has already been noted by ship stations that the transmission of signals in a north and south line is superior to that in an east and west line.

GUY HILL: Referring to the surface waves, Marconi has used wires on the ground for long distance reception, and some time ago Fessenden received messages over 600 miles on ground antennae.

A. E. KENNELLY: We may assume, in the present state of the theory of radio-telegraphic received signals, that the voltage of a signal received from a given steady wave-train is directly proportional to the maximum height of the receiving antenna above the plane of the equivalent perfect ground surface. The electric energy of the signal, however, is of course proportional to the received voltage and the received quantity. The quantity probably depends on the extent of wave surface area on the wave-front intercepted by the antenna. If this way of considering the matter is correct, a very low antenna of great length might give as strong a receiving signal as a high antenna of small width or surface area.

ALFRED N. GOLDSMITH: There seems to be a nonreciprocity of sending and receiving properties, on which Lord Rayleigh has already commented. A high antenna is necessary for transmission, but since reception of messages is largely accomplished on surface waves (at least for long distances) a low receiving antenna suffices.

CHARLES A. LE QUESNE, JR.: In a recent number of the Telephone and Telegraph Age I find a reference to some experiments by Austin Curtis on an effect of moonlight on reception of signals. The effects presented were similar to those for sunlight.

ALFRED N. GOLDSMITH: These experiments were originally disclosed in The London Electrician for March 21, 1913, (page 1104) and May 2, 1913, (page 143), and they have been considered by Dr. Eccles in the same periodical for March 28, 1913, (page 1144).

antennae, λ the wave length, and s, the distance between the stations.

$$I_2 = \frac{4.25 \, I_1 \, h_1 \, h_2}{s} \, \epsilon^{-\frac{\alpha s}{\sqrt{\lambda}}}$$

where α is a constant, equal approximately to 0.0015.

These experiments covered several types of antennae, and distances up to 1,000 miles (1,600 km.) with various antenna currents. The current for audibility (thru an equivalent resistance of 25 ohms) was taken as 10 microamperes. It appears that we need only 5 microamperes, or with the heterodyne receiver less than 2.5 microamperes. Making this change in the equation above, the results had in the recent Arlington-Salem tests offer good substantiation of the relation. With a sending antenna effectively 450 feet (138 meters) high, and a receiving antenna of 130 feet (40 meters), groups of thirty-word messages have been consistently received by daylight up to a distance of 2,383 miles (3,830 km.). From this it can be shown by a graphical solution of Austin-Cohen equation that the daylight range of an Arlington-type station to a similar station is 2,920 miles (4,700 km.) at a wave length of 4,000 meters; and rises to 3,400 miles (5,500 km.) at a wave length of 10,000 meters. (Further details of these heterodyne experiments, and the Arlington-Salem tests are given in the latter portion of the next paper in this issue of the Proceedings. Editor.)

I wish to endorse Professor Kennelly's suggestions. I trust that the observations will cover all parts of the twenty-four hour day, and that transmitting station records, as recommended by Mr. Weagant, may be secured.

LLOYD ESPENSCHIED: Such experiments as just proposed can be best carried on by the Navy. They would materially add to the efficiency of the Weather Bureau's work, if properly planned.

CAPT. F. J. BEHR (Coast Artillery Corps, U. S. A.): This subject is one of great interest to us; particularly the relative advantages of "damped" and "undamped" waves. These meetings of THE INSTITUTE OF RADIO ENGINEERS are doing yeoman service in calling attention to these points and the proper method of investigating them.

sion of the problem was dominated by Cambridge-trained people—and by Henri Poincaré.

Poincaré tried to work out an adequate and rigorous approximate solution for the mathematical problem formulated by Macdonald. He worked at it from 1909 until his death in 1912, publishing nine papers in all, including a 100-page monograph published in 1910.[21] Poincaré's strategy was to convert the infinite series obtained by analytically solving the wave equation into a definite integral and to employ Cauchy's residue theorem to evaluate it. Like Macdonald, Poincaré expressed the analytical solution of the wave equation in terms of a series of spherical harmonics constituted of Bessel functions and Legendre polynomials. In the case of a dipole on the ground, the infinite series can be converted into a sum of integrals associated with the poles of the spherical harmonics. When the size of the conductor is much larger than the wavelength, the term corresponding to the pole with the smallest imaginary part dominates the other terms. Poincaré proved that the dominant-pole contribution to the field intensity on the spherical surface is proportional to $\exp[-\rho(ka)^{1/3}\theta]$, where θ is the angle defined in figure 2, $k=2\pi/\lambda$ is the earth's radius and ρ is an unspecified constant. The field intensity produced by a Hertzian dipole on a spherical conductor has the form of exponential decay with respect to the separation angle.[22]

Poincaré's work involved esoteric theories of Bessel functions and complicated mathematical manipulations. But its conclusion had a clear and straightforward physical meaning: the diffraction field on a conducting sphere decays exponentially: the larger the wavelength, the longer the transmission distance. Four years after Poincaré published his important formula, a debate broke out over whether the field's decay rate varied with $\lambda^{1/3}$, as required by his theory, or with $\lambda^{1/2}$, as revealed from experiment. But Poincaré's result also was incomplete. It did not specify the numerical values of the decay rate γ and the amplitude constant. Without these values, the mathematical theory of diffraction could not produce quantitative results strictly comparable to the experimental data. The task of obtaining the missing numerical value of the decay rate fell to John William Nicholson.

Nicholson, Cambridge Wrangler began to publish on the diffraction problem in 1910. He opened with a criticism of Poincaré's method.[23] Poincaré had not carried out the asymptotic approximation of the Bessel functions correctly, and his procedure for converting the infinite series to an integral was not adequately rigorous. Nonetheless, like Poincaré Nicholson converted the series into an integral and obtained its approximate value by the contribution from the dominant pole. He examined the pole structures of the functions and concluded that for $ka>>1$, the magnetic field intensity is dominated by the contribution from the zero of the de-

21. Henri Poincaré, "Sur la diffractiondes ondes hertziennes," Circolo matematico di palermo, *Rendiconti, 29* (1910), 169-259.
22. Ibid, 201.
23. John William Nicholson, "On the bending of electric waves round the earth," *Philosophical magazine, 19* (1910), 276.

rivative of the Hankel function with the smallest imaginary part. The imaginary part of this zero has the form of $\rho(ka)^{1/3}$. Thus the approximate field is proportional to $\exp[-\rho(ka)^{1/3}\theta]$.

This conclusion is the same as Poincaré's. In addition, Nicholson solved for the numerical value of the attenuation coefficient ρ and obtained the value 0.696. Having this numerical information, Nicholson constructed tables providing quantitative predictions of the diffracted electromagnetic waves around the earth.

No quantitative experimental data on wireless wave transmission were available when Nicholson finished his calculation. Still he could make a definitive and surprising statement: "diffraction must be a relatively insignificant agency in the success of experiments such as those of Marconi."[24] Nicholson's confidence came from a dramatic discrepancy between the numerical scale of the diffraction theory and that of Marconi's experiment. The exponential decay at $0.696(ka)^{1/3}$ made the diffracted field diminish much faster than it should have done if diffraction was responsible for long-distance wave transmission. Although Nicholson continued to work on the diffraction theory for a few years, he no longer believed that it could explain long-distance transmission. He thought that reflections from the upper atmosphere offered a more plausible theory.

Nicholson's conclusion did not destroy the diffraction theory. His mathematical solution to Macdonald's predicament was not the final one. Other mathematicians developed different methods that generated numerical results different from his. Also, while the British-French diffraction theorists all stuck to the assumption that the earth can be modeled as a perfect conductor, which guides the diffracted field around the earth, the German diffraction theorists did not focus only on this case.

German follow-up

In Germany, a group of diffraction theorists worked on the problem of wireless-wave transmission over ground. They believed that finite ground conductivity played a role in several wireless phenomena. They assumed that a "surface wave" would rise above the ground and creep along the ground surface. The finite ground conductivity could modify the polarization of the wave. The German diffraction theorists during the 1900s and the 1910s included an electrical engineer, Jonathan Zenneck, at Braunschweig, the theoretical physicist Arnold Sommerfeld, and his protégés at the University of Munich.

In 1889, while pursuing his doctoral degree at the University of Tübingen, Zenneck became assistant of Ferdinand Braun, a pioneer of radio research in Germany. During their work together (1892 to 1906) Braun's research group competed fiercely with Marconi's team. In 1899, Braun launched experiments on long-distance wireless telegraphy in the Cuxhaven region near Hamburg. Zenneck was

24. John Nicholson, "On the bending of electric waves round a large sphere: III," *Philosophical magazine, 21* (1911), 67-68.

their use for a stated amount of energy. But it is as yet an obscure point.

JOHN L. HOGAN, JR.: The point that Mr. Hill suggests regarding the prominence of reflection (and interference) effects with sustained waves is well substantiated by some observations presented by Dr. de Forest before this INSTITUTE. (Proceeding of the Institute of Radio Engineers, Vol. 1, Number 1, page 37.) He shows that if continuous waves pass from a transmitting station to a receiving station by two different routes, one of which is direct and the other of which is caused by reflection of waves which strike elevated cloud layers, very marked interference effects will be produced at certain frequencies. That is, at definite wave lengths the signals will be either markedly weakened or strengthened. Change of wave length may bring the signals to normal strength.

It is possible that these selective absorption effects are phenomena based on slow resonance, and that therefore they should be more marked with sustained than with damped waves. Instances of marked reflective amplification may be responsible for the transmission of long-distance signals which have brought forward the contention that the range to be attained by the use of sustained waves is greater for equal output than with damped waves. I have discussed this claim with Dr. Austin while in Washington, and he appeared very sceptical concerning it. We felt that we had not enough data to warrant acceptance of it and that there should be no great difference in the transmission of sustained waves as compared with those of low decrement.

It seems to be a wonderful confirmation of Professor Kennelly's hypothesis that even such observations as those taken between Clifden and Glace Bay (where signals were graded in strength by simple aural classification as "very strong," "strong," "moderate," "weak," and "very weak"), are in such good accord with the theoretical conclusions.

In connection with abnormal daylight absorption treated by Dr. Kennelly, it is interesting to note that the value and relation for normal daylight absorption have been partially confirmed.

In 1911, Drs. Austin and Cohen, on the basis of experimental work performed from Brant Rock, gave the following law for the received antenna current I_2 in terms of I_1, the transmitting antenna current, h_1 and h_2, the heights of transmitting and receiving by the reflection of the waves from the upper layers of the atmosphere rather than in any diminution of absorption. This implies a stratified structure of an ionized atmosphere at night, this structure being broken up by convection currents of air and changing illumination during the day.

Observations at Brant Rock and at Arlington show that, tho the difference between the strength of signals by night and by day is much less at long wave lengths than at short, still there is no approach to actual equality in strength of day and night signals even for very long waves. Thus, with Clifden sending at 7,000 meters, at Brant Rock the received current thru 25 ohms resistance was from 35 to 55 micro-amperes by day, rising to 100 micro-amperes by night (for autumn and winter). In summer, the day signals were generally inaudible, varying between 7 and 12 micro-amperes. The night signals were much louder in this case also.

ROBERT H. MARRIOTT: The Standardisation Committee of the INSTITUTE will consider the shunted-telephone method of recording the strength of signals, as well as other methods intended for the same purpose, in order that Professor Kennelly's suggestion of the coöperation of amateur and commercial stations in scientific investigation of transmission may be put into practise shortly.

ROY A. WEAGANT: It is quite certain that much of the value of data obtained by amateurs on the strength of signals of certain commercial stations will be lost unless the commercial stations can be induced to keep a definite record of their radiation at various times. The current value in the antenna, the quality of the note, and the wave length are necessary for such a record. This is not usually done.

GUY HILL: According to your theory of reflection from conducting upper layers in the atmosphere, might not continuous ("undamped") waves be reflected more perfectly than damped wave trains? This question has a bearing on an effect we wish to explain, namely the apparent greater range achieved by given amounts of energy when in the form of continuous radiation. More observations on this point are needed.

A. E. KENNELLY: I think that if a steady stream of waves were emitted, they might show these reflections more markedly; and possibly greater ranges might also be attained by

deeply involved in the Cuxhaven project. By 1905, Zenneck had become an authoritative figure in the community of telegraphy engineer. In 1906, he became a professor at the Braunschweig Technical University.[25]

Zenneck's first work of interest here concerned wave propagation along an infinite planar interface between the air and a conductor (figure 3).[26] The novelty of Zenneck's approach in comparison with the British theorists did not lie only in the geometry. In contrast to previous work, he did not use any information about the dipole oscillator to solve the overall field generated by the source and shaped by the boundary condition. He supposed a particular form for the electric and magnetic fields and confirmed that it satisfied Maxwell's equations and the boundary condition. This form was a plane wave with field components containing a factor $\exp[i(\omega t+sx)]$, where ω is the angular frequency and s is the wave number in the horizontal direction. Plugging these expressions into Maxwell's equations and the boundary condition, he found that the field quantities above the surface are pro portional to $\exp[i(\nu t+sx-r_0z)]$, and those below the surface to $\exp[i(\nu t+sx+r_1z)]$, where $r_0=(k_0^2-s^2)^{1/2}$ and $r_1=(k_1^2-s^2)^{1/2}$, and k_0 ands k_1 are the wave numbers in the air and on the ground, respectively. The values of s, r_1, and r_0, all obtained by solving simple algebraic equations, are determined by the dielectric constants and conductivities of the air and the ground. They were complex numbers.

The physical implications of Zenneck's field solution are extraordinary. First, unlike the optical plane waves in free space, Zenneck's wave not only propagates but also attenuates along both the x and z directions. In addition, the polarization of Zenneck's wave is determined by the ground conductivity and dielectric constant. In contrast to free-space plane waves, the polarization of Zenneck's waves cannot be chosen freely.

When the ground conductivity is finite (in the scale of earth, stone, or sand conductivity), the polarization direction of Zenneck's wave inclines along the direction from which the wave comes. Zenneck pointed out that Marconi's experimental results on the directive antenna agreed with this finding. Marconi discovered that the receiving antenna receives maximum power when the aerial inclines along the line of sight between the transmitter and the receiver. According to Zenneck's theory, the finite ground conductivity causes the direction of polarization of the propagating wireless wave to incline toward the direction of propagation; the antenna has maximum efficiency to convert the field into an oscillating current when it aligns with the polarization direction of the field (figure 4).

The attenuation of Zenneck's wave along the propagation direction reaches its maximum at a finite ground conductivity. When the conductivity is either zero or infinite, the attenuation is zero. A ground with high resistance (a dielectric material) could support long-distance propagation. Zenneck also showed that the at-

25. Kurylo and Susskind (ref. 9), 73-74, 130-173.
26. Jonathan A.W. Zenneck, "Über die Fortpflanzung ebener elektromagnetischer Wellen längs einer ebenen Leiterfläche und ihre Beziehung zur drahtlosen Telegraphie," *AP, 23* (1907), 846-866.

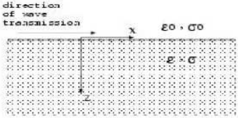

FIG. 3 Zenneck's boundary condition.

tenuation decreases with wavelength and is much more serious along the vertical than along the propagation direction. The field intensity decreases to $1/e$ of the original intensity at $z=0$ in some centimeters along the vertical and in some kilometers along the horizontal. Most of the energy is concentrated near the air-ground boundary; Zenneck's wave is a "surface wave."

Zenneck's work provided a novel insight. Unlike the British and French diffraction theorists, who held that the shape of the earth enabled long-distance wave propagation, Zenneck suggested that the ground resistance also played a critical role. Nonetheless, his paper of 1907 could not be considered as a complete work. "Zenneck's wave" is only one possible solution of the Maxwell's equations and the boundary conditions, not necessarily the solution describing physical reality. In contrast to the British diffraction theory, Zenneck's approach did not specify the source that generated his wave; we not only have no idea how to generate it, we do not know whether it can be generated at all! Enter Arnold Sommerfeld.

Sommerfeld had worked on optical diffraction before he took up radio waves. His novel approach of converting the solution of a differential equation with a proper boundary condition into a closed-form complex integral suitable for numerical evaluation would become a hallmark of his work.[27] He published his first paper on the Hertzian waves in 1899.[28] It studied the propagation of electromagnetic waves along a conducting wire. Sommerfeld demonstrated that as current flows in the wire, the Hertzian wave it produces also propagates along the wire. Once electrical phenomena were conceived in terms of waves in the aether, there was no essential difference between the wired and the wireless. Since the energy transfer associated with the flow of an electric current in a wire could be understood as the propagation of an aetherial wave along the wire, it was reasonable to understand a wave propagating above ground in terms of a flow of energy guided by the ground.

27. Paul Forman, "Arnold Sommerfeld," in *Dictionary of scientific biography, 12* (New York, 1975), 526-529; Arnold Sommerfeld, "Autobiographische Skizze," in Sommerfeld, *Gesammelte Schriften, 4* (Braunschweig, 1968), 673-682.

28. Arnold Sommerfeld, "Über die Fortpflanzung elektrodynamischer Wellen längs eines Drahtes," *AP, 67* (1899), 233-290.

(22) J. A. Fleming, Nature, Vol. 90, Oct. 31 and Nov. 7, 1912, pages 262 and 292, respectively.

(23) J. Zenneck, Leitfaden der Drahtlosen Telegraphie, Stuttgart, 1913.

(24) J. E. Ives, Philosophical Magazine, May, 1913.

(25) L. W. Austin, Journal Washington Academy of Sciences, June 4th, 1913.

Dr. L. W. AUSTIN (by letter): An idea, held some time ago, that the difference between the strength of signals by day and those by night was due to the ionization of the air around the sending antenna, caused by the ultra-violet light from the sun, has been entirely abandoned.

An alternative explanation, that the increased strength of signals at night was due to diminished conductivity in the upper conducting layers of the atmosphere at night, seems improbable in view of data in the possession of the U. S. Navy Department.

This data shows that: (1) In certain regions and at certain wave lengths the ground absorption is greater than over equal stretches of salt water in the ratio of as much as twenty to one. Yet signals are sometimes received in such regions at night with the same strength as if there were no absorption at all. The sunlight can hardly affect ground absorption. (2) When working with sustained waves from arc radio-telegraph sets, the strength of signals may be great on certain wave lengths and very weak at other slightly different wave lengths. Thus a change of two or three per cent. in wave length produces enormous changes in intensity of signals. The probable explanation of this effect is, in accordance with Dr. de Forest's suggestion, (Proc. Inst. Radio Engineers, Vol. I, No. 1, page 37, 1913) that interference between a set of waves travelling along the earth and another set which have been reflected from conducting layers of the upper atmosphere takes place. There is no doubt as to the existence of this effect. The probable reasons for the failure to observe it with spark sets is partly because of the greater changes of wave lengths employed with such apparatus, and partly because the shortness of the wave trains does not permit the direct and reflected waves to overlap and interfere for any considerable number of wave lengths.

The most probable explanation of the increased strength of night signals is to be found in an increase of energy received

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(11) H. Poincaré, Comptes Rendus, Vol. 154, 1912, page 795, or Jahrbuch der Drahtlosen Telegraphic, etc., Vol. 3, 1910, page 445.
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(20) W. H. Eccles, Proceedings Royal Society, Vol. 87A, 1912, page 79.
(21) M. Dieckmann, Experimentelle Untersuchungen aus dem Grenzgebiet zwischen Drahtloser Telegraphie und Luftelektrizität, Berlin, 1912.

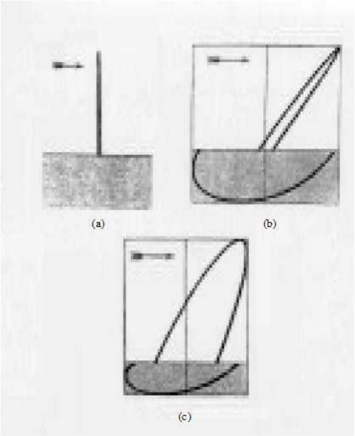

FIG. 4 The polarization diagrams of Zenneck's waves. (a) large ground conductivity; (b) small ground conductivity and dielectric constant; (c) moderate ground conductivity and small ground dielectric constant; The arrows denote the direction of wave transmission. Zenneck (ref. 26), figs. 4-6.

Sommerfeld recognized that he could resolve the questions how or whether Zenneck's surface wave could be produced by the mathematical techniques he had developed in the mid-1890s to tackle diffraction problems and wired waves. In 1909 Sommerfeld showed that Zenneck's "surface wave" could be generated by a vertically polarized Hertzian dipole oscillator located above the flat conducting surface.[29]

29. Arnold Sommerfeld, "Über die Ausbreitung der Wellen in der drahtlosen Telegraphie," *AP, 28* (1909), 665-736.

Sommerfeld's problem has the same geometry condition as Zenneck's: an infinite flat interface separating the conducting material below and the air above. But different from Zenneck, he put a vertical Hertzian dipole on the ground as the source of waves. To solve the problem with his Hertzian radiator, Sommerfeld expanded the Hertzian potential in terms of a set of basis functions more convenient for mathematical manipulations than Macdonald's. However, Sommerfeld's expansion is not a discrete sum of spherical harmonics with various half-integer orders. As was typical of his mathematical approach in the 1890s, it was an integral expansion involving only the Bessel function of order 0. The different choices of expansion led to an essential difference between the British-French and the German theories of diffraction. Sommerfeld noticed that any cylindrical wave in the form of $CJ_0(q\,r)\exp[(q^2-k^2)^{1/2}z]$, is a solution of the wave equation where q is a free parameter and J_0, is the 0th order Bessel function. Sommerfeld's solution of the Hertzian potential has the form of an integral expansion of cylindrical waves over q.

To evaluate this integral, Sommerfeld used Cauchy's residue theorem to convert the integral over the entire real axis into a contour integral over the entire complex plane. The integral came out as the sum of three terms; one of which had the same form as Zenneck's surface wave. Furthermore, the other terms became insignificant at long distance. In short, Sommerfeld proved that Zenneck's surface wave is the asymptotic solution of the diffracted field produced by a vertically polarized Hertzian dipole sitting just above the flat boundary surface.

The German diffraction theory differed from the British-French rival by indirectly showing that not only the geometric shape of the boundary surface but also the resistance of the ground affect the transmission distance. Moreover, Sommerfeld's approach to the diffraction problems created a unique tradition of practices. Expanding the field with respect to an integral of cylindrical waves differed significantly from the common technique that expanded the field over a sum of discrete-order spherical harmonics. Sommerfeld knew that his approach engendered many problems, which he gave to his students at the University of Munich. Herman William March wrote a thesis in 1911 extending Sommerfeld's integral approach to the diffracted wave along a spherical conductor. Witold von Rybczynski wrote on a similar topic in 1913.

3. ATMOSPHERIC REFLECTION HYPOTHESES

A few very important phenomena could not be explained by a surface wave that depends solely upon the characteristics of the ground. The moisture effect, the daylight effect, and "stray rays" all strongly suggested that the propagation of an electromagnetic wave has to do with air as well as ground. This consideration lay behind the theory that extended wave transmission arises from reflection of electromagnetic waves by an electrically conducting layer in the upper atmosphere. Around 1902, Oliver Heaviside, Arthur Edwin Kennelly, André Blondel, Henri

(a) Long waves, because their concentration factor is larger, that is, they follow the earth more closely. In fact, in

(b) Any conditions where surface waves predominate, e. g., over water.

The increased dielectric constant of moisture laden air may account in part for certain well-defined interference effects, as explained by Dr. Lee de Forest [19].

Dr. W. H. Eccles [20] gives a theory of wave propagation in ionised air which, under certain conditions, leads to conclusions directly conflicting with those of Fleming. Thus, according to Eccles, as a result of ionisation of the upper layers of the atmosphere, the wave front may be tilted forward so as to follow the earth's surface more closely; in fact, ionisation might thus assist long distance transmission. There are, then, two opposing effects, the relative preponderance of which determines whether the wave front is tilted forward or backward.

(a) It is tilted backward if, because of ionisation there is a deposition of water on the ionic nuclei, with a consequent increase in the dielectric constant.

(b) It is tilted forward if the presence of ions of molecular dimensions increases the velocity of the waves.

Further experiment on these points is highly desirable.

It will, however, be noted, that regardless of whether effect (a) or (b) predominates, Professor Kennelly's explanation of the sunrise and sunset effects as due to reflection at the boundary surface between ionised and un-ionised air still holds. Effect (a) would provide a more nearly complete reflection.

It has been further suggested that the antenna may be actually discharged by ultra-violet light in sunlight falling on it (Hallwachs effect). This, and other interesting points relative to the influence of atmospheric conditions on transmission and reception are fully treated in a recent publication by M. Dieckmann [21]. The attention of the experimenter in this field is directed particularly to Professor Fleming's valuable paper before the British Association [22] and to the chapter on electric wave transmission in Professor Zenneck's "Leitfaden der Drahtlosen Telegraphie" [23] to both of which sources I desire to acknowledge my indebtedness for suggesting some of the material given in this discussion.

A complete theory of propagation of electromagnetic waves on a sphere of material of *finite* conductivity has not yet been developed.

There is another source of loss of energy in transmission which is generally not considered, namely, the loss thru ground currents in the immediate neighbourhood of the antenna. Inasmuch as considerable absorption of energy undoubtedly takes place in this vicinity, some interest is attached to conclusions drawn by Brylinski [16] relative to the resistance to alternating current of a homogeneous plane conductor of indefinite extent, the current flow being parallel to the plane. (It has been shown experimentally that this is very nearly the case for actual transmitting stations). Brylinski shows that the resistance increases with the specific resistance of the material, with the frequency of the current, and with the damping of the current. Remembering that the nearest approach to an ideal Hertzian doublet, radiating without loss in the surrounding medium would be attained by having a perfect conducting mass extending thru the equatorial plane of the doublet, and that this implies that the ground resistance to an infinite distance is zero, we find that long distance transmission is best attained by the use of sea water grounds, long waves, and continuous radiation of energy. The first two of these conclusions are in accord with the facts, the third point is one requiring further investigation.

Returning to the effect of atmospheric ionisation on transmission, an ingenious explanation of daylight absorption has been suggested by J. A. Fleming [17], [18]. If the upper layers of the atmosphere are strongly ionised by sunlight, the ions produced may act as nuclei for the condensation of water vapor. As a result of the presence of the water drops, and the high dielectric constant of water (namely, 80) the upper layers of air have a higher dielectric constant after exposure to sunlight. Fleming experimentally found that the dielectric constant of steam-laden air varied between 1.004 and 1.026. Therefore the electric waves will travel more slowly in the upper layers of air than in the lower, and the wave front will be tilted backward relative to the direction of transmission. In consequence of this tilting back of the wave surface, the entire wave may pass directly over the receiving station. The effect is quite similar to diminishing the concentration factor. On Fleming's hypothesis, daylight absorption should be least for

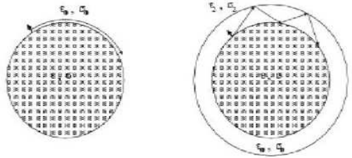

FIG. 5 The surface-diffraction model (left panel) versus the atmospheric-reflection model (right panel); the thicker arrow gives the direction of the Hertzian oscillator, the lighter arrows the direction of wave propagation.

Poincaré, and Charles-Edouard Guillaume all considered the possibility of atmospheric reflection.[30] But only Heaviside and Kennelly published their ideas.

Oliver Heaviside, a self-educated theorist unaffiliated with any academic institute, developed a mathematical model for telegraph-signal transmission, a new formulation of Maxwell's theory, and the technique of operational calculus for solving linear ordinary differential equations.[31] He never studied wireless telegraphy seriously. But his work on wired signal transmission played a significant heuristic role in his thought on the transmission of wireless waves.

In 1901, Heaviside was studying the electromagnetic field patterns produced by an electrical signal transmitted through a coaxial cable. He obtained the electromagnetic field by solving Maxwell's equations for the boundary condition specified. Additionally, he made various geometric metamorphoses of the coaxial cable to other mathematically tractable structures, for example, transformation of the cylindrical condition to a point source sitting on top of a large hemisphere surrounded by another hemisphere.[32] He found that this structure can support the transmission of waves along the curved surfaces and conjectured that the same mechanism accounted for Marconi's wireless signals across the Atlantic Ocean.

He published this idea in 1902, in a short paragraph in an introductory article on telegraphy in the *Encyclopedia Britannica*.[33] In it Heaviside observed that, because both the sea and the land have non-vanishing conductivities, wireless waves could travel along the earth's surface in the same manner as electromagnetic waves

30. Alexander Russell, "The Kennelly-Heaviside layer," *Nature* (24 Oct 1925), 609.
31. Paul Nahin, *Oliver Heaviside, sage in solitude: The life, work, and times of an electrical genius of the Victorian age* (New York, 1987); Ido Yavetz, *From obscurity to enigma: The work of Oliver Heaviside, 1872-1889* (Basel, 1995).
32. Nahin (ref. 31), 279-281.
33. Oliver Heaviside, "The theory of electric telegraphy," *Encyclopedia Britannica* (10th edn., 1902), *33* (1902), 215.

travel along a conducting telegraph wire. He added the possibility that traveling waves are bounded not only by the earth's surface but also by a conducting layer in the upper atmosphere. That was all. He did not discuss the source of the conducting layer, empirical evidence for it, or the behavior of waves propagating between the concentric spherical conductors.

The other man holding the hypothesis of an atmospheric reflection layer was Arthur Edwin Kennelly. Born in India, he left the University of London, where he was a student, to become a full-time telegrapher. After working in the Eastern Telegraph Company for years, he joined Thomas Edison's West Orange laboratory in 1887. The experience transformed him from an operation engineer to a researcher on new electrical technologies. He became a professor of electrical engineering at Harvard University in 1902, and stayed there until 1913.[34] His principal interests were electric circuits and power systems and his contribution to wireless telegraphy was comparatively minor. His primary contribution was popularizing the theories and technologies of wireless telegraphy to the public by providing simple physical explanations of the phenomena encountered in wireless practices. He emphasized physical intuition rather than complicated mathematical theory.

In 1902 Kennelly published a paper with a model similar to Heaviside's.[35] Unlike Heaviside, however, Kennelly explained the existence of the atmospheric conducting layer. The explanation rested on J.J. Thomson's discovery that the air has an electric conductivity when thinned. The more dilute the air, the higher the conductivity. Kennelly evoked the standard dependence of atmospheric pressure on height and Thomson's extrapolated experimental formula to deduce that at the height of 80 kilometers the air conductivity is 20 times that of sea water! After securing the causal explanation of the atmospheric conducting layer, Kennelly argued that if the propagation space is confined by the atmospheric conducting layer and the earth surface, then the wave's energy density diverges as fast as a cylindrical wave's. In the absence of an atmospheric conducting layer, the energy density diverges as fast as a spherical wave's. The argument concerning energy divergence plus the atmospheric reflection model account for a higher field intensity over a given distance.

Kennelly's paper in 1902 gave a causal explanation of the existence of the conducting layer and a more exact estimate of its height. But he did not connect the hypothesis with observed phenomena. Nor did he devise a quantitative theory of wave transmission from Maxwell's equations and the given boundary condition, as the diffraction theorists had done.

34. Karl Willy Wagner, "Arthur Edwin Kennelly, zu seinem 70. Geburtstage," *Elektrische Nachrichten Technik, 8:12* (1931), 1.
35. Arthur E. Kennelly, "On the elevation of the electrically-conducting strata of the earth's atmosphere," *Electrical world and engineer*, 15 Mar 1902; reprinted in "Kennelly-Heaviside ionized layer—a classic of science," *Science news letter, 17* (18 Jan 1930), 45.

papers relate to the superiority of long wave transmission, and transmission over water. A further aspect of the problem is considered in them, namely the effect of the curvature of the conducting sheet or ground.

It will be remembered that Sommerfeld regarded this conducting sheet as plane, and it would certainly seem that the transmission of electromagnetic waves over an earth quadrant despite the curvature requires explanation. The papers just cited supply this explanation. They show that

(a) For a spherical, perfectly conducting ground, the energy of the wave decreases not as $\frac{1}{S}$ but as $\frac{1}{S}\sqrt{\frac{\theta}{\sin\theta}}$ (6)

where θ is the angular separation of the points considered measured along a great circle of the earth (neglecting "scattering").

It follows, therefore, that the amplitude at any distance from the antenna will be greater than for a plane ground, and may even rise to considerable values at the antipodes. There is, however, a second consideration, namely, the failure of the energy to fully follow the earth's surface and its consequent re-radiation or "scattering." It results in the introduction of what I shall call the "concentration factor."*

The theory shows that for a spherical, perfectly conducting ground

(b) The energy of the wave, taking account of scattering or re-radiation of energy from the surface wave, is obtained by multiplying the value obtained under statement (a) above by the concentration factor:

$$\epsilon^{-0.0019\, s \sqrt[3]{\frac{s}{\lambda}}} \qquad (7)$$

where λ is the wave length (wave length and distance expressed in kilometers).

The calculated values of the concentration factor for a distance of 5,000 km. is 0.0025 for a wave length of 4,000 meters and 0.0086 for a wave length of 8,000 meters. The advantage of using long waves is again apparent.

The expression for the energy of the wave obtained according to statement (b) above is in reasonable agreement with the results obtained experimentally by Dr. Louis W. Austin [15].

*Usually called "Zerstreuungs Faktor," or "scattering factor."

media (that is, in space, and in the partially conducting sheet).

The relative importance of the space and surface waves is found to be determined by the value of ρ. The value of ρ for sea water is 0.03, for pure water 30, for wet earth 6.5, and for dry soil 300 (for a wave length of 2,000 meters at a distance of 2,500 km.) It is seen that the numerical distance increases with the real distance, diminishes with increased wave length, and is less for equal distances over sea water than over land. Furthermore, Sommerfeld's analysis shows that the assumption of perfect conductivity of the ground is allowable only for short distances over sea water. The distance from the antenna at which the surface or space waves predominate is determined as follows:

(a) For small values of the numerical distance, the space waves predominate.

(b) For larger values of the numerical distance, surface waves predominate.

(c) For very large values of the numerical distance, the space waves may again predominate, but this last effect may be neutralized by the effect of the curvature of the earth, and is probably not important in practise.

The surface wave is the more desirable one for long distance reception because it decreases far more slowly with distance than the space wave. The numerical distance should therefore be kept small so that the surface waves soon predominate. This may be secured by the following means:

(a) Increasing the wave length.

(b) Increasing the conductivity of the ground.

(c). Increasing the dielectric constant of the ground.

These conclusions are well borne out in practise. Sommerfeld has also suggested that daylight absorption is due to higher conductivity of the air causing an increase in U_1, and thereby increasing the numerical distance. In support of this, he mentions that Ebert found that the conductivity of air at a height of 2,500 meters was 23 times greater than at the earth's surface. It is, however, the opinion of other investigators, notably Messrs. Zenneck and Pierce, that the ionisation of the air due to sunlight is entirely insufficient to account for the magnitude of the observed effects.

Sommerfeld's work has been carried further by H. March (10), H. Poincaré (11), (12), J. W. Nicholson (13), and W. V. Rybczynski (14). The practical conclusions to be drawn from all these

Naval Wireless Telegraphic Laboratory

The experiments done by Louis Austin's team at the U.S. Naval Wireless Telegraphic Laboratory in 1910 were thought to be the only high-quality evidence for long-distance wireless-wave transmission. The mathematical formula synthesized from the experimental results, known as the "Austin-Cohen formula," turned out to be the empirical law governing the relationship between the field intensity and the large transmission distance. Nevertheless, the broad acceptance of the empirical formula made people overlook the fact that the Navy's "experiments" were actually organized not for scientifically investigating long-distance wave transmission phenomena, but for testing the equipment of the Navy's recently installed high-power wireless-telegraphy station.

In 1899 the Bureau of Equipment of the U.S. Navy established a Radio Division to look into replacing flag-and-light signaling with wireless. The plan failed owing to cultural gaps and the associated organizational inertia. Experienced seamen rejected the new gadgets without performance records. Engineering officers living in a conservative military culture clashed with the wireless inventors who preferred flexibility and novelty. The Bureau of Equipment did not have enough power to overcome the opposition. The Navy ended up on-board radio sets rarely used by the combat units and without a system of standardized training in operational and maintenance procedures.[36]

The opposition had much to say for its position. The wireless technology of the early 20th century was unreliable. The mainstream transmitter (spark-gap discharger) suffered from its highly damped oscillation. The mainstream receiver (coherer) could not follow faithfully the continuous variation of a signal and performed unstably. To incorporate the radio into operation, the Navy required reliable data and reliable instruments for which they could develop standard operational-maintenance procedures and systematic procurement schemes. It needed a research establishment for equipment tests, accurate measurements, and technical evaluation of wireless technologies.

The head of the Radio Division, Cleland Davis, and the director of the U.S. National Bureau of Standards Samuel Wesley Stratton, agreed to station the laboratory be stationed within the existing organizational structure of the Bureau. The Naval Wireless Telegraphic Laboratory thus was born.[37] Its first head, Louis Winslow Austin, a physicist then working at the Bureau, had obtained a doctoral degree at

36. Susan Douglas, "Technological innovation and organizational change: The Navy's adoption of radio, 1899-1919," in Merritt Roe Smith, ed., *Military enterprise and technology change: Perspectives on the American experience* (Cambridge, 1985), 117-173; Linwood S. Howeth, *History of communications-electronics in the United States Navy* (Washington, D.C., 1963), chapts. 12, 13.

37. Louis W. Austin, "The work of the U.S. Naval Radio-Telegraphic Laboratory," American Society of Naval Engineers *Journal, 24* (1912), 122-141.

the University of Strassburg. After graduation, he worked at the Reichsanstalt, the German model for the Bureau of Standards, which he joined on his return to the U.S. in 1904. He was transferred to the Navy Department in 1908 in order to head the Wireless Telegraphic Laboratory. He started with an assistant, George H. Clark, and a few part-time technicians.

In 1908, the Navy issued a tender for its first high-power wireless station in Arlington, Virginia. It specified that the transmitter should be capable of sending messages at all times and at all seasons to a radius of 3000 miles in any navigable direction. The National Electric Signaling Company (NESCO) obtained the contract in 1909. The transmitter would be similar to the 100 kilowatt Fessenden synchronous rotary spark discharger then installed at NESCO's experimental wireless station at Brant Rock, Massachusetts. Both the Navy and NESCO knew that this machine could not meet the long-distance specification in the contract. Nonetheless, the Navy awarded the contract with NESCO in the belief that the Fessenden discharger was the best available. To legitimate the compromise, the Navy required further technical tests and measurements of the existing system at Brant Rock while the construction for the Arlington station proceeded.[38] The task of testing and measuring the 100-kw rotary spark discharger at the Brant Rock station was assigned to the Naval Wireless Telegraphic Laboratory. During the summer and autumn of 1909, the electricians of the Laboratory conducted preliminary measurements on the wireless sets at Brant Rock and on communications from there to the scout cruisers *Birmingham* and *Salem*.[39]

From subsequent field tests done in July, 1910 Austin synthesized the first empirical formula governing the relation between distance and radiation intensity for long-range wave transmission. That realized the major aim of the tests: to evaluate the communication qualities of particular wireless sets, namely the Fessenden rotary-spark transmitters, not to produce an empirical law for the science of wave propagation. Austin paid attention to particular instrumentality rather than general regularity.

The experiments of 1910 were not the first attempts to obtain quantitative relations between received antenna current and distance. William Duddell and J.E. Taylor in Britain and Camille Tissot in France did similar experiments in 1904 and 1906. Within a range of 50 miles, they discovered that the current is inversely proportional to distance.[40] Austin's tests ran to 1000 miles. *Birmingham* sailed about 1200 miles south from Brant Rock, *Salem* about 450 miles southeast; through the voyages the wireless sets at Brant Rock and on the cruisers regularly transmitted and received signals from one another, both day and night. The whole experimen-

38. Hugh G.J. Aitken, *The continuous wave: Technology and American radio, 1900-1932* (Princeton, 1985), 88.
39. Austin (ref. 52), 125, 147-153, and Louis W. Austin, "Some quantitative experiments in long-distance radiotelegraphy," Bureau of Standards *Bulletin, 7:3* (1911), 315-363.
40. William Duddell and J.E. Taylor, "Wireless telegraphy measurements," *Electrician, 55* (1905), 258-261, and Camille Tissot, "Note on the use of the bolometer as a detector of electric waves," *Electrician, 56* (1906), 848-849.

part in radio telegraphy are A. Blondel [5], E. Lecher [6], and K. Uller [7], [8]. However, it remained for A. Sommerfeld in 1909 [9] to give a broad theoretical treatment of the spread of electromagnetic waves over a partially conducting sheet placed, as before, in the equatorial plane of the oscillator; the sheet being plane. Because of their importance, Sommerfeld's explanations and his conclusions will be considered in some detail.

He first discusses the fundamental energy distinction between space and surface waves. Space waves, such as electromagnetic (Hertzian) waves and sound waves, spread three-dimensionally. Their energy (per unit area of wave front) is therefore proportional to the inverse square of the distance from the source. Surface waves, such as ripples on water, electric waves on wires, and elastic waves of surface distortion in solids, decay according to a different law of energy diminution. Thus, for waves spreading circularly over water, and neglecting dissipative absorption in the medium, the energy varies inversely with the distance; not as the inverse square.

Sommerfeld defines a quantity U in his paper as follows:*

$$U^2 = \frac{K \mu n^2 + j \mu \sigma n}{c^2} \tag{3}$$

where K is the dielectric constant, μ is the permeability,
σ is the conductivity, j is $\sqrt{-1}$,
n is the frequency, c is the velocity of light.

From U_1 and U_2, the values of U for air and the conducting sheet respectively, he builds up a new quantity ρ, which he calls the "numerical distance." If S is the actual distance, ρ is defined by the following equation:

$$\rho = \frac{U_1^4}{U_2^4} \cdot \frac{U_1^2 - U_2^2}{U_1^2} \cdot \frac{U_1 s}{2} \tag{4}$$

Sommerfeld sets up the partial differential equation for his problem, introduces the necessary boundary conditions, and, after a series of elaborate analytical transformations, arrives at the following value for Π, the vector potential at any point:

$$\Pi = P + Q_1 + Q_2 \tag{5}$$

Herein P represents that portion of Π. which is due to a true surface wave, and Q_1 and Q_2 represent space waves in the two

*The quantity U is Sommerfeld's "k". The notation here employed is, where possible, that recommended by the Standardisation Committee of THE INSTITUTE OF RADIO ENGINEERS.

(b) The electric and magnetic field intensities are in phase.

It will be noted that these conditions apply only when the equatorial plane is a *perfect* conductor. This is nearly the case for sea water, but not at all for dry land. J. Zenneck considered this problem in detail for the case of an imperfect conducting plane. (2) For the case of the partial conductor he found

(a) The lines of magnetic force are parallel to the plane, the lines of electric force are inclined in the direction of motion of the wave.

(b) The electric force has a horizontal component which is nearly in phase with the magnetic force.

(c) The vertical component of the electric force and the horizontal component of the electric force are out of phase with each other.

There is a resultant rotary electric field at the surface of the plane.

Zenneck gives the following values for the field forces at a distance from an antenna of height h, of form factor α, in which flows a current I_m, and from which are radiated waves of length λ:

$$\text{Electric Force} = 4\pi \frac{\alpha h}{\lambda} I_m \frac{\varepsilon^{-\beta s}}{s} 3.(10)^{10} \text{ C. G. S. Units} \quad (1)$$

$$\text{Magnetic Force} = 4\pi \frac{\alpha h}{\lambda} I_m \frac{\varepsilon^{-\beta s}}{s} \quad (2)$$

where β is a constant. It will be seen that the values of these forces are dependant on the wave length.

The effects of the conductivity of the ground plane and of underground water or rock have been exhaustively studied by F. Hack (3) and P. Epstein (4) has given figures for the electric lines of force of actual waves (of length of 2,000 meters) passing over soil of high conductivity, and at considerable distances from the antenna.

Of particular interest in these latter papers is the proof of the existence of a varying horizontal component of the electric force on the wave front. Such electric forces exist on wires along which guided or surface electric waves are passing, and the question naturally arises whether we are not dealing with surface waves if the case of terrestrial radio transmission. Among the earlier investigators of such guided waves and of their probable

tal process, including instrument calibration and maintenance, on-site measurements, and data analysis, was executed by electricians hired by the Naval Wireless Telegraphic Laboratory and engineers of NESCO.[41]

Austin carefully documented the instrument specifications in the report he wrote for the Bureau's *Bulletin*. The transmitters were Fessenden synchronous rotary-spark dischargers, powered at 100 kw at the Brant Rock station and 2 kw on the cruisers. The broadcasts occurred at 1000 meters and 3750 meters. When the separation between the transmitter and the receiver exceeded 100 miles, operators used charcopyrite zinkite rectifiers with galvanometers, and shunted telephone circuits, to detect the antenna current. Both kinds of sensors had high sensitivity for weak current.

During the voyage the electricians noticed several unusual phenomena. After the departure of the ships, the signals became too weak for detection by the crystal-rectifier detector. Except for a few signals taken in the first two days, all the data were taken by the shunted telephone. In addition, the electricians observed that the signals received at night were significantly more erratic than those received during the day. The signal level at night was usually stronger, but it had more fluctuation and experienced more disturbance. The nine-day experimental campaign produced five tables of measured data (for example, see figure 6).

The Austin-Cohen formula

Austin at first tried to fit the daytime data with Duddell's formula that made received antenna current inversely proportional to distance. The inverse law gave much higher values than the measured data beyond 200 miles. Then he tried the ad hoc assumption that the received current experiences an additional exponential factor owing to atmospheric absorption. The NESCO engineer Louis Cohen discovered that a fixed damping coefficient A could reproduce all the data for the same wavelength; to capture the data better for both wavelengths, he set $A = \alpha\lambda^{-1/2}$. Thus the exponential factor is $\exp[\alpha\lambda^{-1/2}d]/d$. They specified that $\alpha = 0.0015$, when the distance d and wavelength λ are expressed in kilometers.[42]

The Laboratory also sought an empirical law governing the transmitted antenna current and the heights of the transmitting and receiving antennas. Experiments conducted between Brant Rock and Washington, D.C. after the sea voyage in mid-July 1910 showed that the receiving antenna's current was proportional to the transmitting antenna current and to the heights of both antennas, and inversely proportional to the wavelength (regardless of the exponential decay factor). Combining these relations, Austin obtained the famous empirical "Austin-Cohen formula:"

41. Austin (ref. 39), 320-330.
42. Ibid, 326-327.

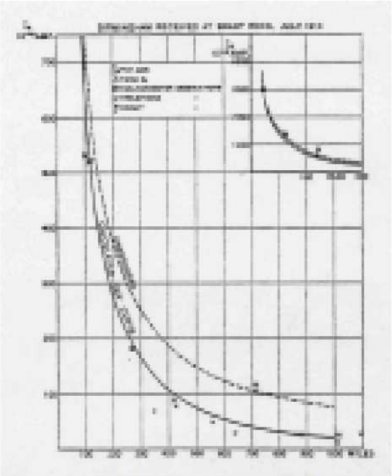

FIG. 6 Birmingham's signal as and received at Brant Rock (July 1910); 3750 meters. The vertical axis represents the received antenna current, the horizontal axis the distance. The solid curve is calculated from the Austin-Cohen formula, the dashed curve from the inverse law "N" denotes data from night-time measurements. Austin (ref. 39), fig. 4.

where I_r is the current received through an antenna with an equivalent resistance of 25 ohm; I_s, the transmitting antenna current; h_1, the height of the transmitting antenna; h_2, the height of the receiving antenna; λ the wavelength; d the distance; and $\alpha=0.0015$; all the lengths being in kilometers and the current in amperes. According to Austin, the formula is "an equation which will cover the normal day received current over salt water through 25 ohm for two stations with flat-top

up this question experimentally, and should endeavour to lay a firm foundation for a theory of long-distance radio-telegraphy by accumulating information on the important question of the electric conductivity and ionisation of our atmosphere at various heights above the earth's surface. Something might be done by the use of a Gerdieu's ionimeter in dirigible balloons or in aeroplanes.

University College, London; June 24th, 1913.

ALFRED N. GOLDSMITH: There are a number of effects in the transmission and reception of signals by radio communication which are as yet only partly explained. Those most closely related to the present paper may be classified as follows:

(1) The superiority of transmission over water as compared with transmission over land.

(2) The superiority (under certain conditions) of transmission on high wave lengths as compared with transmission on short wave lengths.

(3) The clinging of electromagnetic waves to the earth's surface, in spite of the considerable curvature of the globe.

(4) The superiority of transmission by night as compared with transmission by day.

(5) The "daylight effect," or change in intensity of received signals at or near sunrise and sunset.

Before classifying the proposed explanations of these effects, we shall consider briefly the bibliography of the propagation of electro-magnetic waves thru space and over the surfaces of more or less perfect conductors. The classical papers of Hertz and his immediate followers have rendered wave transmission thru space alone thoroly clear. The next problem in order of complexity is the radiation from a Hertzian doublet (dumb-bell oscillator) thru the equatorial plane of which a perfect conductor of indefinite extent stretches. Such a plane conductor may be regarded as a first approximation to the "ground" of a radio-telegraphic station.

M. Abraham, in 1901, gave the mathematical solution of this case [1] and its physical interpretation. Considering the wave at a distance from the oscillator, he found that

(a) The lines of electric force were perpendicular to the conducting plane, the lines of magnetic force parallel to it.

In order that we may test our theories of atmospheric action on long electric waves, we require the prolonged collection of statistics as to the variation of the atmospheric stray signals over long distances. This work would be greatly assisted by the establishment of numerous stations sending out time and weather signals over large areas. Such a system will come into operation to some extent on July 1st, 1913, when time and weather signals will be sent out from many radio-telegraphic stations at regularly appointed hours. If these signals are made with constant antenna currents, they will afford the means of testing the transparency of the atmosphere to electric waves over large distances, and assigning to the received waves a numerical value as regards intensity. I am now engaged in working out an improved method of measuring the intensity of the signals as received on any given antenna, which, I think, will be an improvement on the shunted telephone method now used. If we suppose that intelligible signals could be made at any place without intermission day or night, and all the year round, and of exactly the same strength at the transmitter, they would be received 1,000 miles away with different strengths at different times of the day and year and probably of a cycle of years. Before we can find an adequate theory to explain this variation, we must tabulate the variation and express it by curves like the variation of terrestrial magnetic force or the frequency of sun spots.

There is an increasing body of evidence to connect the variation with atmospheric ionisation. One of the most useful inventions, in this connection, would be some automatic device for registering atmospheric ionisation, which could be sent up to various heights in an unmanned balloon and then recovered again like a self-registering barograph or thermometer. If we could in this way determine the ionisation at various heights and various times, we should lay a firm basis for a true theory. As yet we know very little with absolute certainty about the ionisation in the atmospheric region which begins at about 7 miles elevation, and is variously called the *stratosphere* or *isothermal* region. In it the temperature gradient is constant, or nearly so, in an upward direction. If the ionisation is to be measured by atmospheric conductivity, then we need, above all, some solid information on this subject.

I suggest, therefore, that THE INSTITUTE OF RADIO ENGINEERS (in the United States particularly) should take

antennas of any height, with any value of sending current and any wave length, provided the sending station is so coupled as to give but one wave length." It had the further limitation that it had been tested on only the Fessenden rotary spark charger. The coefficient 4.25 in equation (1) is particularly dependent on the instrument. Austin pointed out it applied strictly only to the antennas used in the experiments of 1910.[43]

The Austin-Cohen formula became the most important, and perhaps the only quantitative, empirical basis for all theories of long-distance wireless wave transmission. Before its publication in 1911, scientists worried whether their theories were consistent with physical intuition or wireless know-how, after 1911, they worried whether their numerical results fit Austin's quantitative data or the Austin-Cohen formula. That altered the epistemic situation significantly.

5. DIFFRACTION THEORIES AGAIN

The fit between diffraction theories and the Austin-Cohen formula was far from satisfactory. The theorists adopted several strategies to save the day. The German physicist Witold von Rybczynski showed that his calculations agreed with selected data from Austin's report better than the Austin-Cohen formula did. The English physicist Augustus Edward Hugh Love questioned whether the detector in Austin's experiments had functioned properly. Meanwhile, the experimenters strengthened their position by confirming the Austin-Cohen formula. The test campaign made by the U.S. Naval Radio Telegraphic Laboratory in 1913, which was planned to choose between the rotary-spark discharger and the arc oscillator as the future standard transmission technology, gave an opportunity to produce more measured data. The Austin-Cohen formula survived the tests.

$$I_r = 4.25 \frac{{}_s h_1 h_2}{d\lambda} \exp\left[\frac{-\alpha d}{\sqrt{\lambda}}\right] \qquad (1)$$

The Germans

Sommerfeld assigned the problem of wireless-wave diffraction along the earth surface to an American doctoral student, Hermann William March, who completed the project in 1911.[44] March expressed the fields as the spatial derivatives of a Hertzian potential and the general solution of the wave equation as an expansion in spherical harmonics. The British theorists took such an expansion as a sum over a discrete index. In contrast, March expanded the solution as an integral over a continuous index. He matched the integral with the spherical boundary condition to determine the functional form of the integrand, which turned out to be inversely

43. Ibid, 340-341.
44. Hermann William March, "Über die Ausbreitung der Wellen der drahtlosen Telegraphie auf der Erdkugel," *AP, 37* (1912), 29-50.

proportional to the derivative of the Hankel function with argument *ka*. To evaluate the integral, March developed the Hankel function for large *ka* asymptotically in the same way as Macdonald had done. Then the integral could be calculated analytically. In March's final result, the Hertzian potential is proportional to $\exp[-ika\theta]/(\theta\sin\theta)^{1/2}$ for large *ka* (θ is the usual angle of separation between the transmitter and the receiver). March's solution did not have any exponential decay with respect to θ like $\exp[-\rho(ka)^{1/3}\theta]$; the exponent $\exp[-ika\theta]$ is a sinusoidal function of θ.

March's result, though fresh, had the defect of decaying much more slowly with distance than British theorists predicted and wireless practitioners observed. March's mathematical problem was identical to Macdonald's: in integrating the derivative of a Hankel function for large *ka*, the asymptotic expansion cannot be performed in the usual way. The publication of a new version of this error energized Poincaré, who pointed out the illegitimate approximation in a letter to Sommerfeld.[45] In a short published note on the matter, Poincaré observed that March's predictions disagreed with Austin's experimental data.[46]

Sommerfeld put Rybczinski in the problem. Following Poincaré, Rybczinski took the dominant contribution of the integral from the pole with the smallest imaginary part.[47] He replaced March's integral with another similar in functional form; but the value of Rybczinski's integrand at the projected point of the dominant pole on the real axis equalled that of Poincaré's integrand at the same point. He thus retained the virtues of both March's and Poincaré's approximations: the new integrand was more precise than March's in the region that gives the dominant contribution, and much easier to integrate analytically than Poincaré's. Rybczinski obtained a radiation intensity proportional to $\exp[-0.33(ka)^{1/3}\theta]/(\theta\sin\theta)^{1/2}$.

Rybczinski showed more persuasively than March that the diffraction theory could produce an exponentially damped wave along a large spherical conductor. Rybczinski's factor $\exp[-0.33(ka)^{1/3}\theta]$ differed from Nicholson's factor $\exp[-0.7(ka)^{1/3}\theta]$, and both formulas disagreed with Austin-Cohen's formula in their dependence on wavelength. The diffraction theories stuck with decay rates inversely proportional to $\lambda^{1/3}$, whereas the empirical regularity required $\lambda^{1/2}$. Nicholson's formula decays significantly faster than Rybczinski's, the Austin-Cohen formula significantly slower. As we know, Rybczinski justified his form by appealing to a selected set of data from Austin's paper of 1911 (seven daytime and four nighttime data points for λ= 3750 meters between 400 and 1000 miles). For these cases, Nicholson's predictions were too low, the Austin-Cohen's too high.

Rybczinski's theory met with approval by some wireless telegraphers, especially the German school. They did not think that he had given a complete physical

45. Henri Poincaré to Arnold Sommerfeld, 1 Jan 1912 (DM, HS 1977-28/A,266).

46. Henri Poincaré, "Sur la diffraction des ondes hertziennes," Académie des Sciences, Paris, *Comptes rendus, 154* (1912), 795-797.

47. Witold von Rybczinski, "Über die Ausbreitung der Wellen in der drahtlosen Telegraphie auf der Erdkugel," *AP, 41* (1913), 191-208.

probably be willing to assist by furnishing a continuous record of the current and voltage in their sending antenna.

SUMMARY: The influence of solar radiation on radio transmission is discussed. The changes of intensity of signals near sunrise and sunset are explained by reflecting effects which may be expected at the boundary surface or "shadow wall" between darkness (air of small conductivity) and illumination (ionised air of marked conductivity). The theory and recorded observations are found to be in reasonable agreement.

It is proposed that amateur radio telegraphists shall co-operate with THE INSTITUTE OF RADIO ENGINEERS in gathering data on the strength of received signals under various conditions.

DISCUSSION.

DR. J. A. FLEMING (by letter): The subject of Dr. Kennelly's Paper is one which continues to attract great attention from radio-telegraphists on account of its practical importance. Unfortunately, it is a large scale effect, and one not very amenable to laboratory experiments. Much, however, may be done by systematic observations of stray atmospheric waves and on the signals sent out from large stations.

At the British Association Meeting last year, at Dundee, I had the honor of opening a discussion on "Some of the Unsolved Problems of Radiotelegraphy," and at the conclusion of that paper made the suggestion that the British Association should appoint a Radio Telegraphic Committee to bring conjoint investigation to bear on some of these questions. That suggestion was adopted, and the Committee appointed with Sir Oliver Lodge as Chairman. The Committee has already held one meeting. I hope that, as one result, an attempt will be made to organize systematic observations on the number and intensity of atmospheric stray waves during the hours of day and night, and over large areas. This is a work in which we may enlist the assistance of amateurs, and it has the advantage that it is entirely receptive work, and involves no production of waves or disturbance of the ether. Much of the amateur work hitherto done has been merely playing at radio-telegraphy, and has had no other result except to disturb commercial work.

that the theory is more than a working hypothesis. It is a suggestion to be judged according to such further evidence as may be accumulated. The information at present available is insufficient to demonstrate any theory of the subject. The records indicate that the phenomena are complicated. It may be that there are meteorological disturbances of the upper air which superpose their effects upon a normal diurnal regime. Our knowledge of the atmosphere by direct exploration with manned balloons is limited to an elevation of about 11 km. By means of small "sounding balloons," carrying up self-registering instruments, we obtain occasional records of pressure and temperature up to about 30 km. Above this level, we have no immediate prospect of securing observations by direct exploration. Nevertheless, the twilight limit of atmosphere, or the height at which the air can reflect twilight, is taken at 75 km. Auroral discharges in air, and shooting stars in air, are located much higher.

It would seem as tho information concerning the upper atmosphere might be obtainable thru concerted observations of radio telegraphic signals. The apparatus required for this purpose is simple and inexpensive. It would consist essentially of a receiving aerial, a detector and receiving instruments, with some means of estimating the strength of received signals at different hours of the day and night. The radio telegraphic amateurs might here render valuable service, by co-ordinating their efforts in observing signals regularly. There is no part of the world where an amateur, who is in the range of some large fixed station might not help in this work. It is to be expected that the accumulation of amateur observations in this way would be useful not only to radio telegraphy, but also to the general sciences of meteorology and solar physics. THE INSTITUTE OF RADIO ENGINEERS might aid greatly in this work, by enlisting observers using printed instructions for executing observations, collecting, collating, condensing and publishing the results. Fifty observing stations, grouped at various azimuths and distances around a single powerful radio sending station, would be none too many for the proper checking up of the measurements. In this way, the energy and enthusiasm of any number of amateur radio-telegraphists could be utilized to advantage. Once the system was inaugurated, the large sending station would

picture of long-distance wireless-wave transmission. Trans-Atlantic radio communications was still not fully explained. But at a minimum Rybczinski's theory gave an approximately correct picture of wave propagation along the earth without atmospheric reflection. Sommerfeld wrote to Wilhelm Wien in November, 1913. that Rybczinski's theory was analytically right and gave a rate of attenuation that matched experiment to some extent. But (Sommerfeld continued) reflection from conducting layers in the upper atmosphere probably played the major role for very long-distance transmission.[48]

Rybczinski's work did not fare as well outside as inside the Sommerfeld school. His ad hoc procedure of approximation lacked mathematical rigor. He did not select the most reliable data. His seven points, taken from the voyage of 1909, were obtained with instruments still under adjustment and under severe weather conditions. And four of his data points came from measurements at night time, when wireless signals are notoriously unstable. In a paper written in 1914, Austin criticized Rybczinski's data points for these reasons.[49]

A new experiment

The results from the test voyages of 1910 did not significantly hinder the promise of the Fessenden rotary-spark discharger. The Arlington station went on line in February, 1913. The Laboratory tested the transmission equipment. The U.S.S. *Salem* proceeded to Gibraltar, 6400 km Washington, D.C.[50] A critical task of the voyage was to compare the signal from the Fessenden rotary-spark transmitter with that from a new technology—the arc transmitter.

The arc transmitter used the negative resistance created by an electric arc in a low-density gas. Because the value of the negative resistance was precise, the electric arc could be used to design an oscillating circuit with a sharp resonance spectrum. The acceptance test for the Arlington station offered a good opportunity to carry out systematic measurements of the arc transmitter's operational conditions. *Salem* simultaneously received signals from the 100 kw Fessenden transmitter. The round trip to Gibraltar took about six weeks. The arc out-performed the spark.[51] Austin: "At distance over 1000 miles the arc waves appear to begin to show advantages over the spark waves."[52]

The Gibraltar voyage also offered an opportunity to test the Austin-Cohen formula under a set of physical conditions different from those of the 1910 tests: a

48. Arnold Sommerfeld to Wilhelm Wien, 29 Nov 1913 (DM, NL 56, 010).
49. Louis W. Austin,"Quantitative experiments in radiotelegraphic transmission," Bureau of Standards, *Bulletin, 11* (1914), 69-86.
50. Howeth (ref. 36), 178-183.
51. Austin (ref. 49); John L. Hogan, "Quantitative results of recent radio-telegraphic tests between Arlington, VA., and U.S.S. 'Salem'," Electrician, 63 (1913), 720-723.
52. Austin to the Chief of the Bureau of Steam Engineering, 3 Apr 1913, in RG 19, Bureau of Ships, E 988, 841(24), Box 1926, National Archives, Washington, D.C.

new (arc) transmitter, a different set of wavelengths (3800 and 2000 meters), and a much longer maximum distance (3500 miles).

Austin and John L. Hogan, an engineer at NESCO, found that the day-time data in 1913 agreed well with the empirical formula. Hogan called the agreement "exceptionally close."[53] Austin went further. He compared Rybczinski's formula, the Austin-Cohen formula, and the new experimental data. Most data points fell closer to the Austin-Cohen formula than to Rybczinski's. Austin again: "There can be no doubt from these results that the theoretical equation [Rybczinski's] gives values too low to be reconciled with the observations, but that they are in very fair agreement with the semi-empirical equation."[54]

Still, something might be retained from the diffraction approach. Austin wrote Zenneck:[55]

> I am becoming quite convinced that the theoretical transmission formula, given in your book, represents approximately the weakest signals observed; while our Navy formula gives a fairly good average. Although I have taken a great many observations, I am still somewhat doubtful regarding the power to which the wave length should be raised in the exponential term. The observations are exceedingly discordant, apparently due to selective reflection.

The British

In January, 1914, Macdonald proposed a new method to approximate the infinite series of his diffraction theory.[56] He introduced a new series, much easier to sum up, that approximated the original series quite well where the spherical harmonic of $n+1/2$ equals ka. Macdonald argued that the new sum well approximated the old one because the dominant contribution of the sum came from this neighborhood. There he replaced the Hankel functions of order $n+1/2$ and its derivatives by Hankel functions of order 1/3 and 2/3. He evaluated the integral via Cauchy's residue theorem. When ka is large, the pole of the Hankel function of order 2/3 with minimum imaginary part dominates. Macdonald found that the resultant field intensity had an exponential decay in the form of $\exp[-\beta(ka)^{1/3}\sin(\theta/2)]$. The functional form of Macdonald's exponential decay differed from both Nicholson's and Rybczinski's factors, $\exp[-\rho(ka)^{1/3}\theta]$.

Enter Augustus Edward Hough Love, still another Cambridge-trained mathematician (second Wrangler, 1885). At the time he contributed to the theory of wireless telegraphy he was a professor of Natural Philosophy at Oxford.[57] In a paper published in 1915, Love gave a comprehensive overview of the research

53. Hogan (ref. 51), 721.
54. Austin (ref. 49), 77-79.
55. Austin to Zenneck, 14 Sep 1916 (DM, NL 053).
56. Hector M. Macdonald, "The transmission of electric waves around the earth's surface," PRS, 90 (1914), 50-61.
57. *Obit.*, *3* (1939-41), 469-470.

black dots. There is a reinforcement after the dip, and perhaps also before it. On the other hand, at sunset, no dip is indicated, such as the foregoing theory would indicate.

Figure 7 is taken from observations by Messrs. Dolbear and Proctor (8) in March, 1911. Here Glace Bay is again the sending station; while there were two independent receiving stations, one at Somerville, and the other at Revere; both suburbs of Boston. The diagram, taken from the published article, purports to give the general average of all the observations made at both receiving stations, at a period of the year near the vernal equinox. It will be seen that there is a dip both at mid-sunrise and at mid-sunset, with reinforcements both before and after each dip. There is a nocturnal maximum and a daylight reduction. The results set forth in this particular diagram are in closer accordance with the hypothesis here put forward than almost any others, but no explanation was offered or theory advanced in the article, by its writers.

Figure 8 gives some observations reported from Madrid, and Barcelona in Spain, and also Ceuta, in Africa, nearly opposite to Gibraltar. Here the nocturnal maximum is very short. There is a sunrise and sunset dip, with reinforcement before and after.

Figure 9 gives a published series of observations reported from Clifden, Ireland, as to the diurnal strength of signals from Glace Bay, N. S. One column gives the diurnal chart for each day in April, 1911. Here the agreement with the theory is not so good. There is usually, but not always, a dip at mid-sunrise and mid-sunset. Sometimes the sunrise dip is missing, and sometimes the sunset dip. There is often a reinforcement in the signals before and after a dip; but in many instances such a reinforcement is not indicated.

The records appear to have been made in all cases by shunting the receiving telephone with non-inductive resistance down to the point of inaudibility. The strength of signals is then estimated from the conductance of the limiting shunt.

It appears, therefore, that there is sufficient warrant from the observations at hand in giving the theory here suggested for the sunset and sunrise dips further consideration. It is not claimed

(8) The Effects of Sunlight on the Transmission of Wireless Signals, by B. L. Dolbear and J. A. Proctor, Electrical World, N. Y., Vol. 58, No. 6, Aug. 5th, 1911, pages 321-323.

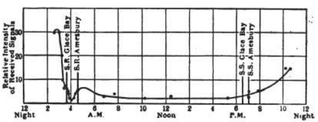

Fig. 6. Observations taken by Mr. Pickard on the relative intensity of signals received at different hours of day and night.

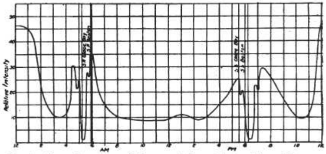

Fig. 7. General average of all curves taken at Somerville and Revere March, 1911.

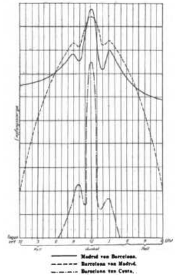

Figure 8

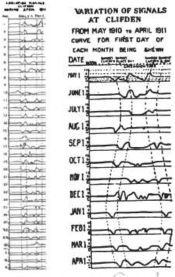

Figure 9

status of long-distance wireless-wave transmission; computed the numerical values of the diffraction series with an approach different from all previous ones; compared his calculations with the values obtained from Macodnald's new formula, found them in agreement, and declared Macdonald's theory the best of the lot; and reinterpreted the long-distance experimental data by correcting the asserted relation between the audibility factor, the results from the shunt-telephone measurements, and the antennacurrent.[58] That improved the fit with his (and hence Macdonald's) predictions.

Love's method of approximation was numerical. Like Nicholson and Macdonald, Love approximated the terms in the neighborhood of $n+1/2 = ka$. Then he computes the numerical values of a sufficient number of terms, added them up, and compared the numerical results with those he obtained from Macdonald's method at several separation angles.[59]

The Austin-Cohen formula made the field intensity proportional to $[1/\theta]\exp[-9.6\lambda^{-1/2}\theta]$, which was quite different from all the diffraction formulae, including Macdonald's.[60] Love saved the phenomena by reinterpreting the measured data. Love noticed that Hogan used a "law of device" to convert the data from the measured audibility factor to the antenna current (he made the audibility factor proportional to the square of the antenna current). However, from Austin's 1911 report, this device law did not always hold. Austin's measurements for calibration for weak signals suggested that the audibility factor was proportional to the antenna current. Considering that most data were taken when signals were weak, Love argued that the proper device law was the direct proportion. He modified Hogan's data accordingly and thus gave empirical support to the diffraction theory.

Were Love's conclusions justified? No! His numerical method was based on assumptions about infinite series identical to Macdonald's; it was not a surprise that the two methods gave similar predictions. The real issue, whether the underlying assumptions employed for the purpose of approximation were legitimate, remained unsettled. Moreover, Love's reinterpretation of the data was prblematic. He relied on regularities measured in 1911. Austin reported the same experimental results as Hogan did in 1913, but he did not discover any significant deviation of the measured data from the Austin-Cohen formula.

6. ATMOSPHERIC REFLECTION AGAIN

Atmospheric reflection produced much less literature after 1911 than surface diffraction theories. The wireless communities found it convenient to interpret radio phenomena in terms of atmospheric effects, but much more difficult to elaborate a reflection model via experimental or theoretical means. Still, atmospheric

58. Augustus E.H. Love, "The transmission of electric waves over the surface of the earth," Royal Society of London, *Philosophical transactions A, 215* (1915), 105-131.
59. Ibid, 116-123.
60. Ibid, 127.

reflection theorists managed to go one step further than Heaviside and Kennelly. They wished to understand why static noise is greater at night, and why the transmission efficiency of the wireless signals experiences a diurnal change. Having different research agendas and satisfied with qualitative explanations they did not compete directly with the mathematical physicists working on diffraction theories. Rather, they drew on the intellectual tradition of microphysics, which studied electromagnetic wave propagations in various media in order to reveal the internal molecular structures of materials.[61]

William Henry Eccles, who earned a bachelor's degree in physics from the University of London in physics in 1898, joined Marconi's research team on wireless telegraphy in 1899. It was as a professor at the University of London, where he moved in 1910, that he taught the general wireless communities the empirical ground of the atmospheric-reflection hypothesis.[62]

Eccles discovered that if static was detected at one station, then it was very likely to be detected simultaneously at others some distance away. He deduced that the effect involved a long-distance mechanism, perhaps the discharge of atmospheric electricity at hundreds or thousands of miles away from the receiver stations.[63] In a paper published in 1912, he attempted to explain the cause of diurnal variations of the static intensity. Since trans-Atlantic telegraphic signals and static can be transmitted over long distances, they might propagate in a similar manner.[64] A correct physical model for long-distance wave propagation might explain the data on trans-Atlantic wireless telegraphy and on static.

In Eccles's model, the earth is surrounded by a permanent conducting (Heaviside) layer in the upper atmosphere, and another, concentric layer between the Heaviside and the earth. This new layer corresponds to a region of air with gradually changing physical properties. The ultraviolet component of sunlight ionizes the air in this region.[65] Since sunlight alternates with penetration into this region, the number of charged particles per unit volume in it increases with height.

Eccles evoked a simple microphysical model to describe wave propagation in this medium. When an electric field is applied, the ions move; Eccles deduced the average induced ionized current from Newton's second law of motion. Incorporating the induced current into Maxwell's equations, he expressed the refractive index of the medium in terms of the ions' number density, mass, and charge. From this simple Maxwellian theory, Eccles demonstrated that the phase velocity of an electromagnetic wave increases with the number density of ions.

61. Jed Buchwald, *From Maxwell to microphysics: Aspects of electromagnetic theory in the last quarter of the nineteenth century* (Chicago, 1985).

62. *Obit., 17* (1971), 195-196.

63. William H. Eccles and H. Morris Airey, "Note on the electrical waves occurring in nature," *PRS, 85* (1911), 145-150.

64. William H. Eccles, "On the diurnal variations of the electric waves occurring in nature, and on the propagation of electric waves round the bend of the earth," *PRS, 87* (1912), 79-99.

65. Ibid, 88-89.

(5) When both stations are in full sunlight, their signals are subjected to daylight attenuation, by diffused conduction in the upper air.

(6) When the sunset wall gets behind the eastern station, as at 17, 17', the wall will temporarily serve as a reflector behind the latter, and strengthen the signals.

(7) When the sunset wall intervenes between the stations, the wall will act as an intercepting barrier, reflecting waves back, and markedly, weakening the signals.

(8) When the sunset wall gets behind the western station, there will again be a temporary increase of signals by reflection. After this the conditions should approach those of permanent shadow, or night time.

In one revolution of the earth, therefore, we should expect to find maximum strength on full night shadow, a lowered strength in full daylight, and a marked weakening of the signals, with the wall between the stations, either at mid-sunrise, or at mid-sunset. [6] Each of these dips in the strength of signals should be both preceded and followed by a brief interval of stronger signals, due to partial reflection, in the same way as a rough or imperfect sheet reflector behind a lamp intensifies its rays.

On the other hand stations on the same parallel of longitude should have no dip on signals on the equinoxes: but should have a dip at sunrise and sunset with the sun near the solstice. (December and June.)

Stations north and south might expect a longer signaling range than those east and west owing to the aid of partial reflections along the shadow wall.

We may now compare the foregoing deductions with recorded observations. Figure 6 is taken from observations by Mr. G. W. Pickard in 1909, [7] as published in Figure 97 of Prof. G. W. Pierce's book on Wireless Telegraphy. It will be observed that there is a marked dip in the intensity of signals received at Amesbury, near Boston, Massachusetts, when sunrise was about midway between Amesbury and the sending station at Glace Bay, Nova Scotia. Both of these stations are indicated in Figure 4 by

(6) This provisional theory of the sunrise and sunset dips was first put forward by the writer at the Radio-Telegraphic Discussion of the Dundee meeting of the British Association, September, 1912.

(7) "Principles of Wireless Telegraphy," G. W. Pierce, New York, 1910, page 135.

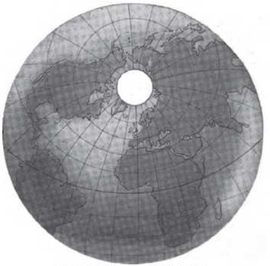

Figure 4. Projection of the Globe

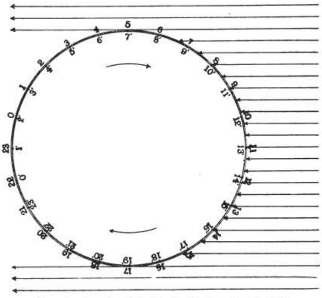

Figure 5. Rotation of the Earth with Regard to Sunlight as Viewed from South Pole.

Eccles explained three distinct wireless phenomena on his model: the possibility of wave transmission along the surface of the earth, the radiation directivity of Marconi's tilted aerial, and the diurnal variation of static. The theory of ionic refraction suggested that the larger the density of ions, the higher the phase velocity. From Eccles's physical model, the ion density increases with height, as, therefore, does the wave's phase velocity. According to Snell's law, an upgoing radio wave would be gradually drawn downward by the refraction in the gradually varying medium. The wave path would curve. If its curvature equalled that of the earth, the wave could run naturally along the surface without any action of the ground material. Unfortunately the quantitative prediction from ionic refraction disagreed with the Austin-Cohen formula.[66]

Eccles' theory suggested that the amount of refraction decreases with frequency. When the frequency falls low enough, the curvature of the refracted wave path becomes larger than the earth's curvature. In this case, the wave path is obliquely incident to the ground and the direction of wave polarization no longer remains vertical. To match the polarization to the maximum extent, the receiving antenna must be tilted toward the direction of transmitter. Thus Eccles reached the same conclusion as Zenneck's without using the "surface wave."

The ionized layer results from sunlight and thus does not exist at night. In England, the major source of long-distance static comes from Africa, where thunderstorms and other electrically disturbing weather processes are more severe. In the daytime, long-distance static is controlled by refraction in the ionized layer in the middle and lower atmosphere. During the night, long-distance static is directed by reflection from the conducting Heaviside layer in the upper atmosphere. The waves refracted through the absorptive ionized atmosphere suffer more energy dissipation than the waves reflected by a conducting surface. Hence static during the daytime is weaker than that at night.

Eccles's atmospheric refraction theory contained an essential difference from Heaviside's. In Heaviside's model, radio waves are guided by the concentric spheres of the earth and the permanent conducting layer in the upper atmosphere in accordance with the conductivities of the air and the ground. In Eccles's model, radio waves are directed by the refractive condition of the ionized atmosphere and do not respond to the condition of the ground. For Eccles, ionic refraction alone explains the bending of the wave propagating direction.[67]

Eccle's work of 1912 brought the atmospheric reflection theory from a tentative hypothesis to a sophisticated model. Heaviside and Kennelly attended to only one fact. In contrast, Eccles covered several apparently unrelated phenomena—long-distance wave transmission, tilted polarization, and diurnal variation of static. Eccles's model was essentially a theory of the qualitative behavior of wireless phenomena. Only partial and preliminary results were achieved by efforts to de-

66. Ibid, 91.
67. Eccles to Heaviside, 27 Nov 1912, Heaviside Papers, UK0108 SC MSS 005/I/6/10, Institute of Electrical Engineers Archives, London.

scribe the wave-propagation characteristics mathematically, and these were not consistent with the empirical regularity (the Austin-Cohen formula).

The English physicist John Ambrose Fleming followed up Eccles's work by trying to account for the diurnal variations of wireless signals. But the static patterns seemed too complex for a consistent explanation. In the annual meeting of the British Association for the Advancement of Science (BA) in 1912, Fleming had organized a discussion on "The scientific theory and outstanding problems of wireless telegraphy" and suggested that the BA form a committee to guide and formulate research on them. The committee was formed and planned systematic observations on atmospheric stray rays. It did not achieve significant results.[68]

Kennelly attended Fleming's radio-telegraphic session at the BA meeting in 1912. Kennelly agreed that the boundary between the sunshine and the shadow regions formed a reflecting surface critical to the diurnal variation observed in wireless telegraphy. He proposed a model for the variation of wireless signals around twilight. Two wireless stations sit in an east-west direction and the transitional band moves gradually toward the east station. Before the band crosses when both stations are on the same side of the blocking curtain formed at the transitional band, it does not affect signal transmission between them. When the band moves behind the east station (shortly before the east station's sunrise), the blocking curtain functions as a reflecting surface to bounce the overshoot waves from the west station back to the east station. Hence the received signal strength there is intensified. After sunrise at the east station, the band moves between the stations, wave transmission is blocked, and the received signal strength diminishes significantly. When the sunrise just passes the west station, the band functions again as a reflecting surface behind the west station to enhance the received signal strength there. As the band moves farther away, the reflective enhancement also wanes. The same pattern happens around sunset. Kennelly's mechanism predicts that a wireless signal transmitted along an east-west direction has a maximum just before the twilight of the east station and right after the twilight of the west station, and a minimum in between. The pattern of the signal variation predicted from Kennelly's model agreed with observations made at wireless stations at Nova Scotia and Amesbury, Massachusetts.[69]

These investigations typified the work of the atmospheric-reflection theorists. They paid much more attention to the diurnal variation of wireless energy than to mathematical relation between the signal intensity and the distance, and they emphasized qualitative characteristics rather than quantitative information in the experimental data. Their theoretical work involved sophisticated model-building and simple mathematical theories of wave propagation based on microphysics.

Toward 1920, several young experimental physicists well trained in applied mathematics began to appreciate the physical importance of the ionic-atmosphere

68. Fleming (ref. 5), 860.
69. Arthur E. Kennelly, "The daylight effect in radio telegraphy," Institute of Radio Engineers, *Proceedings, 1:3* (1913), 12.

toward G in the diagram. All that can be asserted definitely is that there is a greater probability of a transition layer, or partially reflecting layer, being formed between sunshine and shadow at sunrise and sunset, than at any place in the sunlit region of daylight. The ionised layer boundary cannot coincide with the shadow boundary AB, but will lag behind it, and will rise more nearly vertically, owing to the effects of atmospheric absorption, and of building up with time. We may call this hypothetical transition layer, or boundary between daylight and darkness, the "shadow wall" accompanying sunrise or sunset.

In Figure 4 we have a stereographic projection of part of the northern hemisphere. The lines of longitude at hourly intervals may be considered as representing the positions occupied by either the sunrise or sunset shadow walls, at successive hourly intervals at the equinox, when the sun appears on the equator. The shadow, considered as an imperfect electromagnetic mirror, may only extend upwards say from the 30 km. level to the 130 km. level; or may only occupy a height of say 100 km. in all; but, if it exists, it extends northwards and southwards for thousands of kilometers. In summer, the wall would slant from S. E. to N. W., and in winter from S. W. to N. E., across the globe.

If the boundary surface between day and night; or the shadow wall, possesses roughly reflecting or scattering influence on electromagnetic waves, we should expect to find the following series of phenomena in relation to two stations east and west, on or near the same parallel of latitude, as indicated in Figure 5; where the observer is supposed to be at the earth's south pole looking at the rotating pole beneath him.

(1) When both stations are in full shadow, as at 20, 20′; 21, 21′; 22, 22′; 23, 23′; 0, 0′; 1, 1′; 2, 2′; 3, 3′; 4, 4′; the signals exchanged should be normal, in the absence of thunderstorms or meteorological disturbances.

(2) When, shortly before dawn, at the eastern station, the shadow wall gets behind that station, it should act as a partial reflector to that station, and intensify the signals.

(3) When the shadow wall advances to a point between the stations, as at 6, 6′, the wall should act as a partial barrier between them and weaken the signals.

(4) When the wall reaches a point a little beyond the western station, as at 7, 7′, it should act as a temporary reflector to the latter, and temporarily strengthen the signals.

vation bb′, 50 km. above the sea level GG′, the air pressure and density are 0.05 per cent of those on the sea, while 99.95% of the air lies below this level. Again, at an elevation of approximately 60 km., the density has fallen to 0.01%, and 99.99% of the total atmosphere lies beneath. In each 10 km., the air pressure is falling to one-fifth. A vertical sunbeam, reaching the level BB′, has passed thru 0.01% of the total atmosphere. The successive levels AA′, BB′, are lines of equal penetration, and there should be equal intensities of ionisation over each such level; but there should not be any layer of sudden transition.

Figure 2 represents the same atmosphere conditions as in Figure 1; except that the sun's rays are supposed to be entering the atmosphere at an inclination of 60° with the zenith, as indicated by the arrows on either side. Along these inclined paths, the sunbeam will encounter approximately twice as much air between any two given elevations as in Figure 1. Consequently, at the 50 km. elevation, the sunbeams have traversed 0.1% of a vertical atmosphere, instead of only 0.05%. The levels AA′, BB′, CC′ of 0.001%, 0.01% and 0.1% respectively are all raised about 5 km. with respect to those on Figure 1. Otherwise, there is very little change between the conditions of penetration by rays from an overhead sun at the equator, and those from the sun at either 8 A. M. or 4 P. M. There should be no sudden transition layer or surface of discontinuity in ionisation, in either case.

When, however, the sun's rays are striking tangentially over a place on the globe as in Figure 3, there tends to be a transition along the line AB, between air in the shadow and air in the sunshine. If the condition represented is that of sunrise, then the air still in shadow is presumably air that has become neutralized during night, with a relatively low conductivity. The illuminated air on the other hand is rapidly becoming ionised and more conductive. While, therefore, we cannot expect the moving shadow plane to be a sharply defined surface separating ionised from neutral air, we might reasonably expect a roughly defined bounding surface, such as might produce some diffuse reflection of electromagnetic waves. No attempt is made to indicate the lines of equal penetration or ionisation, owing to the complexity of the actions. It is known that there is a very appreciable refraction of the beams of light. We should also expect absorption to take place at different elevations, and inoisation to increase to some extent with time. The shadow boundary AB steadily advances

model. They tried to bring together the work of all three communities. One of them was Balthasar van der Pol, who worked at the Cavendish Laboratory between 1917 and 1919. In 1918, he tackled the discrepancies among different diffraction formulas (Nicholson, Rybczinski, Macdonald). He reasoned that if he could show that one of them was mathematically rigorous, he could demonstrate that diffraction could not account for the Austin-Cohen formula. The mathematics required was too difficult to him. He turned to a Cambridge-trained mathematician, George Neville Watson, for help.

7. WATSON'S WORK

Like Macdonald, Nicholson, and Love, Watson excelled at the Cambridge training in mathematics, becoming Senior Wrangler, Smith's Prize man, and a Fellow of Trinity College. In 1918, he took up the professorship of mathematics at the University of Birmingham. Unlike the diffraction theorists, Watson was almost detached from physics at Cambridge. He specialized in complex-variable theory applied to Bessel functions. He was also interested in theories of approximation, numbers and computability.[70] He was just the man to solve van der Pol's problem.

Papers of 1918 and 1919

In 1918, Watson gave a rigorous mathematical proof that the field intensity diffracted along the curvature of a large conducting sphere has an exponential factor whose decay rate is proportional to $\lambda^{-1/3}$ rather than $\lambda^{-1/2}$ (as required by the Austin-Cohen formula). In 1919, he showed that the field intensity diffracted in a space bounded by a large conducting sphere and a conducting surface exterior and concentric to the sphere has the $\lambda^{-1/2}$ dependence.[71] The atmospheric reflection theory can explain the empirical regularity.

Watson found the rigorous solution of the diffraction problem without the mathematical problems of previous diffraction theories by working on the Hertzian potential instead of the magnetic field intensity. True to the Cambridge approach, he expanded the Hertzian potential in terms of a discrete sum of spherical harmonics instead of an integral. The result was an infinite series different from Macdonald's, but with a similar angular dependence and pole structure.

Watson's great innovation was to convert the series expansion of the Hertzian potential into an integral expansion without infinities. He interpreted all terms in the diffraction series as residues of a complex function associated with poles on the real axis and so expressed the diffraction series as a contour integral in the complex plane. This procedure, later known as "Watson's transformation," con-

70. *Obit., 12* (1966), 521-522.
71. George N. Watson, "The diffraction of electric waves by the earth," Royal Society of London, Proceedings, 95 (1918-1919), 83-99; and "The transmission of electric waves round the earth," ibid., 546-563.

verted the Hertzian potential from a series to a complex integral. This integral as evaluated by Cauchy's residue theorem contained an exponential decay $\exp[-23.94\lambda^{-1/3}\theta]$, quite close to Nicholson's $\exp[-23.8\lambda^{-1/3}\theta]$.[72] Watson confirmed that the intensity of the field diffracted along the earth's surface was significantly weaker than the Austin-Cohen formula required. The exponential decay of the one contains $\lambda^{-1/3}$, of the other to $\lambda^{1/2}$. The diffraction theory was mathematically consistent, but empirically inadequate.

Watson located the problem in the physical model. All the diffraction theorists assumed that the earth's surface alone diffracts the field radiated by the dipole oscillator. Since the surface diffraction alone cannot account for the empirical observations, the upper reflective regions of the atmosphere might play the dominant role at long distances. Could diffraction theory incorporate the physical assumption of an atmospheric reflective layer? Watson took up the question in his paper of 1919. He took the earth to be a conducting sphere on which the Hertzian dipole sits, and the atmospheric reflective layer to be concentric with the earth.[73]

To evaluate the Hertzian potential in this new boundary condition, Watson expanded the Hertzian potential in a series of spherical harmonics, applied "Watson's transformation" to convert the series into a complex integral, analyzed the pole structure of the integrand, and evaluated the integral in terms of these poles. He discovered that when both the inner and outer conductors are perfect, the field intensity is a superposition of oscillatory modes periodic with the distance, that is, that the field does not decay at all! When both the inner and outer conductors are good but imperfect, the field has an exponential decay proportional to $\lambda^{-1/2}$. By adjusting the conductivity of the ionized layer, Watson could match the numerical value of the decay rate of his theory and the Austin-Cohen formula.

Reception

Watson established a conjunction of mathematical representations, explanatory models, and experiments in the study of long-distance wave transmission. He applied the complex-variable techniques of the diffraction theories to the physical model entertained by the atmospheric-reflection theorists to derive quantitative results consistent with the empirical formula obtained from long-distance experiments. By connecting the mathematical representation with the formulated experimental data, Watson gave the atmospheric-reflection theory the promise of becoming a question-answering device operated and using standard mathematical techniques. When it left his hands, Watson's theory lacked verisimilitude. The physical model of a homogeneous and sharp conducting boundary was an over idealization. Watson did not incorporate a vertical atmospheric profile with gradually varying refractive indices. His theory could not incorporate Eccles's ion-refraction theory in a profound way. Nor was Watson's theory able to marshal em-

72. Watson, "diffraction" (ref. 71), 97.
73. Watson, "transmission" (ref. 71), 547.

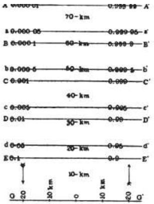

Figure 1. Air-Density and Penetration at Different Atmospheric Levels. Sun's Rays Vertical

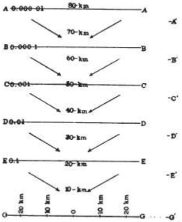

Figure 2. Penetration of Inclined Solar Rays at Different Atmospheric Levels

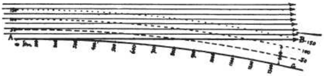

Figure 3. Diagram representing the Surface of the Globe with Three Atmospheric Levels 50, 100 and 150 Km. above the sea. Rays of Sunlight following Parallel Straight Lines are Tangential to the Globe at A and are Penetrating the Atmosphere above the Line AB which Marks the Bounding Surface between Light and Shadow. The Sun's Parallax and Atmospheric Refraction are

low, we should expect that surface to behave electrically like an inverted sea. Electro-magnetic waves, reaching this surface from below, would not penetrate it appreciably, but would be reflectively guided over it, as they are guided over the salt-water ocean below, and the waves would then spread over the surface of the globe in two dimensions only, like the growth of a stone-throw ripple in a pond, instead of in three dimensions, like the growth of a soap bubble. This would much reduce the natural three-dimensional attenuation, and increase the intensity of signals received at long distances. It has been suggested that some of the abnormally long signalling ranges occassionally reached at night may be due to the presence of such a reflecting layer (2). If, on the other hand, the conducting layer exists, but is not sharply defined, the conductivity gradually increasing to a maximum as we approach from above or below, we might expect marked conductive dissipation with little or no reflection; so that long-distance signals might be weakened instead of strengthened, owing to the presence of the conducting layer.

Whatever the facts may be concerning the action of the air near the 70 km. level, it seems likely that, during full daylight, the solar ionisation cannot develop any sharp transition layers or reflecting boundaries in the atmosphere. That is, the daylight effect should tend to increase the attenuation of electromagnetic waves.

In order to form a definite conception of the relations between air-pressure and elevation above the sea, Figure 1 has been prepared on certain assumptions; namely, that the temperature of the air is uniformly -35° C. for the sea-level up to a height of 12 miles or 19.3 km. where the observed air-pressure is (3) 1⅞ inches (4.76 cm., or 0.0625 of normal sea level pressure). Up to this level, the "height of the homogeneous atmosphere" (4) is taken as 7 km. Above this level, the temperature has been assumed constant at -60° C. and the height of the homogeneous atmosphere uniform at 6.23 km. No correction has been made for changing chemical composition of the atmosphere at different elevations. (5) Thus premised, Figure 1 indicates that at the ele-

(2) "On the Elevation of the Electrically-Conducting Strata of the Earth's Atmosphere," by A. E. Kennelly, Electrical World and Engineer, Vol. 39, No. 11, March 15th, 1902, page 473.

(3) A. L. Rotch, "The Conquest of the Air," New York, 1909.

(4) J. Clerk Maxwell, "Theory of Heat," London, 1875.

(5) W J. Humphreys, "On the Physics of the Atmosphere," Jour. Franklin Inst., March, 1913.

pirical evidence beyond the Austin-Cohen formula, for example, the diurnal variation of static.

Appreciation of Watson's contributions came slowly. The first few published papers to mention his work all emphasized the mathematical rather than the empirical implication. Van der Pol stressed Watson's mathematical contribution to clarifying the controversy involving different approximation methods for wave diffraction above a spherical conductor, rather than Watson's theoretical prediction of the Austin-Cohen formula.[74] Macdonald commented on Watson's work without addressing empirical adequacy at all. He concentrated on extending Watson's approach to the general case where single-frequency time-dependence does not hold.[75] Sommerfeld's student Otto Laporte used Watson's results to reconcile the British representation of the diffracted field in terms of a series with the German representation in terms of an integral, not for their own sake.[76]

Most scientists who elaborated the atmospheric-reflection model in the 1920s, studied wave propagation through ionic media. They downplayed Watson's old-fashioned model (the sharply defined "Kennelly-Heaviside layer") and counter-intuitive approach (the complex-variable theory of diffraction). In a classic paper on the subject written in 1924, Joseph Larmor mentioned Watson only at the end of a list of diffraction theorists beginning with Macdonald, and then as the man who demonstrated that surface diffraction cannot account for long-distance wave transmission around the earth.[77] Among these initial responses to Watson's papers, one thing stands out: after Watson had proved the mathematical rigor of Nicholson's predictions, no one attempted to reconcile the experimental data with the surface diffraction theory. Watson's paper in 1918 tilled the diffraction theory as a physical model for long-distance wave transmission.

Watson's fortunes improved in the late 1920s. In 1928, G.W. Kenrick of the University of Pennsylvania reinvestigated the mathematical and empirical significance of Watson's theory. Kenrick pointed out that much work had recently been done to explain short wave transmission by reflection and refraction of electric waves, but "less attention has been given to modifications produced in the classical Hertzian solution for the field at a distant point due to an oscillating doublet."[78] He called for a reexamination of Watson's work in the interest of short-wave analysis. Kenrick calculated the electromagnetic field radiated by a Hertzian dipole

74. Balthasar van der Pol, "On the propagation of electromagnetic waves round the earth," *Philosophical magazine, 38* (1919), 365-380.

75. Hector M. Macdonald, "The transmission of electric waves around the earth's surface," *PRS, 98* (1920), 216-222, 409-410; 108 (1925), 52-76. "On the determination of the directions of the forces in wireless waves at the earth's surface," *PRS, 107* (1925), 587-601.

76. Otto Laporte, "Zur Theorie der Ausbreitung elektromagnetischer Wellen auf der Erdkugel," *AP, 70* (1923), 595-616.

77. Joseph Larmor, "Why wireless electric rays can bend round the earth," *Philosophical magazine, 48* (1924), 1026-1036.

78. Gleason Willis Kenrick, "Radio transmission formulae," *Physical review, 31* (1928), 1040-1050, on 1040.

using the same boundary condition that Watson had. Instead of working on the residue waves, he computed the multiple reflected rays bouncing through the space between the earth and the atmospheric layer, and summed all the reflective terms. He thus reproduced Watson's mathematical formula and hence the Austin-Cohen formula. Watson's work became significant not only for disproving the diffraction model but also for its quantitative predictions of observed phenomena.

The radio scientists and engineers of the 1930s worked intensely on wave propagation under various scenarios specified by atmospheric and terrestrial conditions. A theory of pure refraction without taking into account the effect of the earth was no longer adequate. Their theoretical exercise dealt with wave diffraction above a ground with different possible geometric and material specifications in a heterogeneous atmosphere. "Watson's transformation" proved a very useful technique for analyzing these problems. In 1937, a Harvard professor of physics, Harry R. Mimno reviewed the literature on the physics of the ionosphere.[79] He highlighted the significance of the discrepancy between the $\lambda^{-1/3}$ dependence predicted by all the diffraction theorists before Watson and the $\lambda^{-1/2}$ dependence given by the Austin-Cohen formula, and he stressed Watson's contribution in providing a theoretical account of the empirical $\lambda^{-1/2}$ dependence. Van der Pol's student H. Bremmer wrote that "the pioneering work clearing the way for further investigations was done by Watson in 1918. By a transformation with the aid of an integral in the complex plane, this author succeeded in transforming the rigorous series of zonal harmonics into a new series converging rapidly enough to be of use in the radio problem. As a matter of fact, almost all of the later literature is based upon this transformation of Watson."[80]

Often in the history of science two mutually exclusive theories compete for the answers to the same set of questions. In the case considered here, two mutually exclusive theories address different types of questions. The essential difference between the surface diffraction theories and the atmospheric reflection theories was their distinct epistemic status rather than their different physical models. The surface diffraction theorists began by investigating the possibility of long-distance radio-wave transmission. To answer this question, they constructed a straightforward physical model and attempted to develop a rigorous mathematical solution of the problem described by the physical model. But they soon discovered a mathematical difficulty in obtaining an accurate approximate solution. They switched to a mathematical question—what is an accurate approximation of the diffracted field intensity above a large conducting sphere? Almost all their effort involved proper approximations of the analytic form of the diffracted field.

The atmospheric-reflection theorists asked for causal explanations for a broader realm of wireless phenomena, including long-distance transmission, diurnal variation of signal strength, static, the effect of weather fluctuation, and the directive

79. Harry R. Mimno, "The physics of the ionosphere," Review of modern *physics, 9:1* (1937), 1-43.
80. H. Bremmer, *Terrestrial radio waves: Theory of propagation* (New York, 1949), 7.

Commencing, say, at zero, with sufficient height; it might increase to a maximum at a moderate height, and then dwindle down to a minimum near the earth's surface. If the sunlight ionisation, instead of varying gradually in this way terminated suddenly, so that, at some particular elevation a bounding surface formed with non-conducting air on one side, and conducting air on the other; then this boundary surface might be expected to develop strong reflecting properties, on the principle that wave disturbances are subject to reflection at surfaces of discontinuity. Thus clouds, or diffused masses of water vapor, reflect both sound and light. A travelling compression wave, or sound wave in air, reflects light. Any change in a medium for wave transmission, occurring at a surface, is known to set up a reflection. If the change is sudden and well-marked, so that the bounding surface is sharp, the reflection will be definite and powerful. If the change is gradual, and by easy transition; so that the bounding surface is not clearly defined, the reflection will be diffusely scattered and weak.

Consequently, if the ionisation of the air developed a sharp transition layer, or succession of layers, we might expect reflection to occur at and from such layers, with a lessening of attenuation; whereas, if the ionisation were gradually varying from layer to layer, with no clearly marked transition, there would be mere dissipation of energy by conduction or scattering without any gain by reflection, thereby increasing the attenuation.

It was pointed out by Dr. J. J. Thomson [(1)] that rarefied air at a pressure of 0.01 mm. of mercury in a glass chamber devoid of metallic electrodes, conducts electricity in the laboratory as well as an aqueous solution of sulfuric acid. At an elevation of about 70 km. (43.5 miles) above the sea level, and a uniform temperature of -60° C., such an air density may be expected to exist. If this free rarefied air conducts electricity in response to the feeble electric intensities of radio telegraphy, as well as it does in vacuum tubes to the more powerful intensities used in the laboratory; then, whether the sun is shining on this or not, we should expect a conductivity in it of the same order of magnitude as in ocean water. If such a conducting layer developed suddenly at a certain elevation, so that a definite bounding surface separated the conducting air above from non-conducting air be-

(1) J. J. Thomson, "Recent Researches in Electricity and Magnetism," 1893, page 101.

beyond, the violet, when the sun's rays fall perpendicularly as at the tropical noon-day. At morning or evening, when the sun's rays pass aslant thru much greater distances of air before reaching the ground, the violet, and even the blue rays largely disappear, leaving a predominance of red in the light that remains, and thus producing the ruddy hues of dawn or evening landscapes.

If the upper regions of the atmosphere are appreciably ionised by full and sustained solar radiation during daylight hours we may consider that these regions are thereby rendered partially conducting. That is to say, instead of being a perfect insulator, like free space or un-ionised air, ionised air has a certain small conductivity. This would involve a loss of energy in any electromagnetic waves traversing it, which, in turn, would involve additional attenuation of such waves. Moreover, if the ionisation-conductivity were not uniform but developed in clouds or patches, there would be scattering as well as absorption of energy.

It seems therefore possible to explain the weakening effect of broad sunlight upon radio-transmission signals by attributing conductivity, distributed either uniformly or non-uniformly thru the sunlit upper atmosphere, where the ultra-violet waves are likely to be more intense than in the region near the ground. We have no direct evidence, however, as to whether such ionisation-conductivity is quantitatively sufficient to account for the observed effects. It has been pointed out by Zenneck that the observed conductivity of air near the earth's surface for continuous current is far too small to account for the effects in question; but we have no experimental evidence as to what the conductivity may be at high atmospheric levels to alternating electric intensities.

If we assume, for simplicity, a tropical sun sending its rays perpendicularly down thru normally distributed air towards the earth, the degree of ionisation should be uniform over any surface situated at a uniform level. That is, the ultra-violet radiation would be most intense at a great height, and gradually weaken by absorption as it penetrated downwards. On the other hand, the number of air molecules per c.c.; i. e., the air density, would be relatively very small at a great height, and would increase exponentially with the downward penetration. In any one horizontal layer of air, the number of free ions might be assumed uniform.

antenna pattern. To answer these questions, they constructed elaborate physical models. They were partially successful in offering reasonable causal explanations to observed wireless phenomena. But they failed to develop a mathematical theory for systematic quantitative predictions before 1910, succeeded to a very limited extent after Eccles, and only began to make steady progress after Watson. The reflection theorists had difficulty in formulating answers to numerical-prediction questions. Thus the diffraction theorists and the reflection theorists carried out different agendas: the former tried to resolve a mathematical problem of approximation, the latter aimed to explain newly discovered phenomena. This fact explains why atmospheric-reflection theories rarely engaged in any public debate with the surface-diffraction theorists, why some mathematical physicists kept working on diffraction theories regardless of their dubious empirical adequacy, and why an experimenter strongly supporting the reflection models still gave credit to the diffraction models. The diffraction theories and the reflection theories were not competing worldviews.

From the epistemic viewpoint, long-distance wave-transmission research left unexpected legacies to all the participating communities. They started from what they wanted to know, and found what they did not expect to learn. The diffraction theorists found that approximation can be a critical issue in physical problems in which the analytic solution cannot give meaningful quantitative information and direct numerical computation is intractable. The new condition that the wavelength was much shorter than the scatterer's dimension forced them to develop a repertoire of advanced mathematical techniques other than those developed for acoustic scattering for dealing with the approximations of series or integrals. Sommerfeld's integral and Watson's transformation initiated studies of mathematical questions that would become classical problems in mathematical physics: a vertical or horizontal dipole oscillator above or below a homogeneous or layered horizontal plane, a vertical or horizontal dipole oscillator above or below a homogeneous or heterogeneous sphere within a homogeneous or a concentrically layered medium, and so on. These problems did not necessarily correspond to real physical situations. But the mathematicians contentedly investigated the complex-variable techniques to solve the problems for their own sake. The mathematical theory of complex series and integrals prospered from 1930s to 1950s largely owing to the heritage of the German and the British diffraction theorists in the 1900s and 1910s.[81]

The atmospheric-reflection theorists started from the puzzles associated with radio operations, but ended up with a new science of the atmosphere. Their models of the ionosphere were connected with contemporary electron theories of matter. Thus the study of atmospheric effects on radio became incorporated into one of the largest intellectual movements of physics in the early 20th century: the rise of atomic and molecular physics. The radio scientists benefitted from this incorpora-

81. Alfredo Baños, *Dipole radiation in the presence of a conducting half-space* (Oxford, 1966).

tion: they developed various Maxwellian theories of electromagnetic wave propagation in ionized media. Moreover, the reflection theorists discovered that the radio could be an experimental means to explore atmospheric phenomena. Edward Appleton's experiments of the 1920s, which won him a Nobel Prize, gained "direct" evidence about the physical condition of the ionosphere from radio-interference methods. Meteorology and planetary science became accessible not only through the traditional means of natural history, but also through experiments made possible by efforts of the reflection theorists.[82]

The original goal of the American wireless experimenters was to test equipment for the first long-distance radio station of the U.S. Navy. They had a practical engineering problem to solve, but in pursuing it made an important contribution to pure science. The Navy's questionable decision to settle with NESCO's transmitter, the missionary agenda of the Bureau of Standards, and Austin's technical training in German experimental science incorporated meticulous instrumental design systematic operational procedure, and mathematical representation of the data into the investigation. The outcome of their experiments was an empirical law that served as the only quantitative check on theories of long-distance radio-wave transmission in the 1910s. The U.S. Navy did not gain directly from scientific studies of wave transmission, but from the experimental results: it learned that the arc transmitter performed better than the spark-gap transmitter at long distances. The Austin-Cohen formula provided a primary guide for wireless engineers to design long-distance long-wave wireless stations throughout the 1910s. Engineers relied on this simple mathematical relation to select the wavelength and antenna height of a transmitting station for a signal-strength requirement at a given distance. The other face of the empirical law was an engineering formula.

These drastically diverse post-developments enforce the lesson that our three technical communities, working against with different intellectual backgrounds and toward different goals, created a unified study of long-distance radio-wave transmission. They did so by contributing different elements: one offered empirical evidence, another a physical model, and a third a mathematical tool. This episode might be interpreted as confirmation of Peter Galison's estimates of the strength of the constraints on a scientist or engineer within his own communal tradition or of Andrew Pickering's emphasis on the importance of the contingencies a scientist or engineer might confront.[83] More significantly, it warns us not to assume that the intellectual work of different technical communities apparently concerned with the same general phenomena were alternative answers to the same questions. They might have had their eyes on different, and different kinds of questions.

82. Peter Galison and Alexi Assmus, "Artificial clouds, real particles," in David Gooding, Trevor Pinch, and Simon Schaffer, eds., *The use of experiment: Studies in the natural sciences* (Cambridge, 1989), 225-274.

83. Peter Galison, "Context and constraints," and Andrew Pickering,"Beyond constraint: The temporality of practice and the historicity of knowledge," in Jed Buchwald, ed., *Scientific practice: Theories and stories of doing physics* (Chicago, 1995), 13-55.

THE DAYLIGHT EFFECT IN RADIO TELEGRAPHY.

By A. E. Kennelly.

(Professor of Electrical Engineering, Harvard University.)

It is now generally admitted that the range of radio-transmission of signals is materially influenced by solar radiation; not only in regard to false signals or "X's"; but also in regard to the attenuation of the transmitted electro-magnetic waves.

This attenuating influence of solar radiation on the transmitted waves ordinarily consists of (1) a nearly steady action during the daytime, together with (2) certain marked disturbances occurring near sunrise, or sunset, or both.

In regard to the first or steady effect, we may consider that during the day, whatever the weather may be; i. e., the conditions of wind, temperature, pressure, cloudiness or precipitation in the first few kilometers of air nearest to the ground surface, the sun's rays are steadily falling upon the upper layers of the air; where the air density is relatively very low. It is known from physical laboratory experiments, that ultra-violet light, passing thru attenuated air, ionises it; or decomposes electrically neutral air molecules into positive and negative constituents, the energy of decomposition being absorbed from the radiation. If the ultra-violet radiation is then withdrawn, these constitutents attract each other and recombine, perhaps converting the energy of recombinaion into heat energy or molecular oscillations. For a given intensity of received radiation of assigned wave-length in the ultra-violet region of the spectrum, we may suppose that there exists, in the final state, a certain corresponding number of free electrons per unit of air-volume. It is also reasonable to consider that after the ultra-violet rays in the sunlight have penetrated deeply into the air, they become: (1) scattered and diffusely reflected by the air-molecules, thereby giving us the blue color of the clear sky, and (2) absorbed in decomposition and ionisation of the air-molecules. Consequently, but little ultra-violet light from the sun reaches the ground, after passing thru the atmosphere. The solar spectrum at the ground, or ocean level, may be considered as terminating near to and only a little

CHEN-PANG YEANG

The study of long-distance radio-wave propagation, 1900-1919

ABSTRACT:

At the beginning of the 20th century, scientists and engineers were puzzled by the fact that the long wireless waves could propagate along the earth's curvature without being blocked by the earth. Two explanatory theories were suggested: that the waves are diffracted along the earth's surface and that the waves are reflected back and forth between the earth and a conducting atmosphere. The surface diffraction theory, first proposed by Hector Munro Macdonald in 1901, was continuously elaborated by the British and German mathematical physicists. But its predictions were not consistent with the empirical Austin-Cohen formula obtained from the U.S. Navy's long-distance experiments. The atmospheric reflection theory, first proposed by Arthur Kennelly and Oliver Heaviside in 1901/2, was more commonly believed to be the correct physical model. Yet it had problems yielding quantitative predictions because of its lack of mathematical development. In 1919, the English mathematician, George Neville Watson, developed a mathematical theory of atmospheric reflection that generated predictions consistent with the Austin-Cohen formula based on the analytic techniques established by the surface diffraction theorists.

the one that occurs most commonly—the phenomena vary greatly from day to day—is that one appearing when the sun is setting at a place about half-way between the stations. The minimum is fairly well marked in the sunrise curve shown in fig. 8. The reflections that are so pronounced a feature of Marconi's long-distance observations are not nearly so evident over short distances, according to the author's experience. But fig. 9 shows

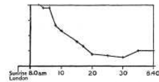

Fig. 8.—Intensity of Signals, January 25, 1912.

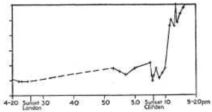

Fig. 9.—Intensity of Signals, January 20, 1912.

a case where the variations soon after sunset at Clifden were very decided. The curve does not do full justice to the phenomena, however. As a matter of fact the chief variations were so rapid and so wide that there was not time to measure them; indeed, on occasion, the changes in intensity are startling in their amplitude and swiftness.

It will be noticed that all the curves exhibit a great difference between the strength of the night signals and that of the day signals, although the distance is only 440 miles. Yet it is known that the same signals are heard at Glace Bay as strongly in the day as in the night. We gather from this that the daytime trajectory of the radiation passes well above places relatively near to the sending station and descends again, after overtaking the curvature of the earth, at the greater distance. It is well to recall here that in his recent experiments on the reception of signals from Clifden at distances up to 6000 miles, Marconi found the signals readable only at night at greater distances than 4000 miles—which seems to indicate that the trajectories of the rays in the daytime are such as to bring down within the distance named practically all the radiation starting, at all elevations, from the antenna.

The author desires to tender his thanks to the Government Grant Committee of the Royal Society for a grant in aid of the observations described in this communication.

through the atmosphere can give rise to somewhat regular reflections, so that when it passes over and behind the sending station it changes from being a hindrance to being a help in signalling. This view contains nothing that is fundamentally inadmissible. But the reflecting process was observed to be better with short waves than with long; perhaps the following considerations may in some degree account for this. First, it is known from general electromagnetic principles that when a wave crosses layers of changing refractive index there is a reflected wave propagated backwards, and this reflected wave is the more intense the greater the change in index. Second, let us assume that the surfaces of equal ionisation rise from the day level to the night level in a long slope extending over, perhaps, a hundred miles from east to west through the twilight belt, being rather broken of course, by irregularities in the changing ionisation. On account of the broken character of the belt reflection from the sloping surfaces will be irregular. But it will be more irregular for the more refrangible radiation, that is to say, will be more irregular for waves of low frequency than for waves of higher frequency. Perhaps with this may be conjoined the fact that the frictional absorption suffered by the longer wave is greater than that suffered by the shorter.

The phenomena just discussed are to some extent noticeable over relatively short distances. The following curves are drawn from observations of the intensity of signals from Clifden as heard at the author's laboratory in London, the measurements being made by balancing the intensity of the Clifden signals against the adjustable intensity of locally produced artificial signals of about the same acoustic frequency. On the curves the intensities are plotted in arbitrary units as ordinates, with the times of measurement as abscissæ. The observation had to be snatched, so to speak, at the moments when the station happened to despatch a message, and the points of observation are therefore often rather irregularly distributed. Fig. 7 shows two remarkable minima, which are produced, presumably, by the presence of the ionic curtain between the stations. Of these two minima,

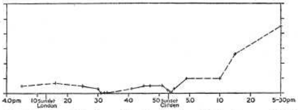

Fig. 7.—Intensity of Signals reaching London from Clifden, January 12, 1912.

ELECTRICAL WORLD AND ENGINEER.
MARCH 15, 1902. 473

On the Elevation of the Electrically-Conducting Strata of the Earth's Atmosphere.

By A. E. Kennelly.

According to the measurements of Professor J. J. Thomson ("Recent Researches in Electricity and Magnetism," p. 101), air at a pressure of 1-100 mm. of mercury has a conductivity for alternating currents approximately equal to that of a 25 per cent aqueous solution of sulphuric acid. The latter is known to be roughly 1 mho-per-centimeter, so that a centimeter cube would have a resistance of about one ohm. Consequently, air at ordinary temperatures, and at a rarefaction 76,000 times greater than that at sea level, has a conductivity some 20 times greater than that of ocean water, although about 600,000 times less than that of copper.

If we apply the ordinary formula for finding the elevation corresponding to a given air-rarefaction, we find that if the air had a uniform temperature of 0 deg. C., the height of this stratum of air with a rarefaction of 76,000, would be

18.39 log 76,000 kilometers above the sea.
or 89.77 kilometers,
or 55.77 miles.

If the air had a uniform temperature of —50 degs. C. this elevation would be reduced 18.3 per cent, or to 73.3 kilometers (45.5 miles). The temperature of the earth's atmosphere has only been measured within a range of a very few kilometers above the surface of the sea, and consequently the materials are not at hand for any precise calculation of the height of electrically conducting strata. It may be safe to infer, however, that at an elevation of about 80 kilometers, or 50 miles, a rarefaction exists which, at ordinary temperatures, accompanies a conductivity to low-frequency alternating currents about 20 times as great as that of ocean water.

There is well-known evidence that the waves of wireless telegraphy, propagated through the ether and atmosphere over the surface of the ocean, are reflected by that electrically-conducting surface. On waves that are transmitted but a few miles the upper conducting strata of the atmosphere may have but little influence. On waves that are transmitted, however, to distances that are large by comparison with 50 miles, it seems likely that the waves may also find an upper reflecting surface in the conducting rarefied strata of the air. It seems reasonable to infer that electromagnetic disturbances emitted from a wireless sending antennæ spread horizontally outwards, and also upwards, until the conducting strata of the atmosphere are encountered, after which the waves will move horizontally outwards in a 50-mile layer between the electrically-reflecting surface of the ocean beneath, and an electrically-reflecting surface, or successive series of surfaces, in the rarefied air above.

If this reasoning is correct, the curvature of the earth plays no significant part in the phenomena, and beyond a radius of, say, 100 miles from the transmitter, the waves are propagated with uniform attenuation cylindrically, as though in two-dimensional space. The problem of long-distance wireless wave transmission would then be reduced to the relatively simple condition of propagation in a plane, beyond a certain radius from the transmitting station. Outside this radius the voluminal energy of the waves would diminish in simple proportion to the distance, neglecting absorption losses at the upper and lower reflecting surfaces, so that at twice the distance the energy per square meter of wave front would be halved. In the absence of such an upper reflecting surface, the attenuation would be considerably greater. As soon as long-distance wireless waves come under the sway of accurate measurement, we may hope to find, from the observed attenuations, data for computing the electrical conditions of the upper atmosphere. If the attenuation is found to be nearly in simple proportion to the distance, it would seem that the existence of the upper reflecting-surface could be regarded as demonstrated.

two hours. It then begins to strengthen, and finally reaches a maximum—sometimes a very high one—at the time of sunset at Glace Bay. During the night the signals are very variable in strength, varying from very weak to very strong. Shortly before sunrise at Clifden the signals grow stronger, and reach a high maximum shortly after sunrise; they now dwindle to a marked minimum about two hours after, and then they return gradually to their normal day strength. The ratio of the intensity of the signals during the twilight maximum to the average intensity throughout the day is much greater for a wave 5000 metres long (frequency 60,000 per second) than for a wave 7000 metres long (frequency 43,000 per second), and the long wave signals are uniformly stronger during the day than those of the shorter wave.

Some of these observed facts can be understood by the aid of the hypothesis of ionic refraction. We have only to lay down the principle that the aggregate curvature of the trajectory of the longer waves is nearer to the curvature of the earth than that of the shorter waves, or, in other words, that the daylight trajectory of the longer waves is more suited than that of the shorter waves to the distance between the Irish and Canadian stations. Again, the minimum that occurs at about two hours after sunset at Clifden is readily explained by the conception, already discussed, that in the twilight regions the recombination of ions has consequences equivalent to a somewhat opaque curtain hanging from the top to the bottom of the middle atmosphere. Moreover, at two hours after sunset at Clifden the sun is setting at a place between the stations about 650 miles from Glace Bay. At this place the horizontal plane of Glace Bay passes between 50 and 60 miles overhead. If now we assume that the height of the curtain of irregularly ionised air is of the order 50 miles, thus making no allowance whatever for the bending of the rays from Glace Bay in their progress below that level, we see that the signals transmitted to Clifden are weakest when the curtain comes on the horizon of the sending station. If, on the other hand, we allow for the likelihood of the rays following considerably bent paths even in the lower middle atmosphere, we must take Marconi's results as showing that the ionic curtain reaches effectively to much lower atmospheric levels than 50 miles. All of this applies, *mutatis mutandis*, to the morning minimum produced by the sunrise belt passing between the stations.

In regard to the remaining point quoted from Dr. Marconi, namely, the strong maximum in signals to Clifden at about sunset at Glace Bay, and before sunrise at Clifden, there is more difficulty in finding an explanation. It would seem that the heterogeneous ionisation following the twilight

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carried on with radiation that had started at considerable upward inclination, and would therefore be accomplished with difficulty. The wave-fronts arriving at the receiving station would also be tilted forward considerably, and consequently the horizontal component of the electric field of the waves might approach the magnitude of the vertical component. In this case an inclined antenna would be a better receiver than a vertical one.

In various parts of the world it has been found that stations on the opposite sides of a mountain chain can communicate in the night with ease, though only with great difficulty, if at all, in the day. This is especially the case if a short wave is in use, and such a pair of stations can sometimes establish day communication by adopting a longer wave-length. It is, in fact, now common knowledge that for communication across hilly country in the daytime, a long wave—a thousand metres or more—should be used. The explanation is obvious on the hypotheses developed above. The rays, starting with sufficient elevation from a sending station in the plains, travel in straight lines through the lower atmosphere past the mountain tops, and then, reaching the middle atmosphere, are deflected downward by refraction in the ionised air. Short waves are refracted much less than long waves, and are therefore not bent so fully into the lower atmosphere as are the long waves. Indeed, the short waves may be entirely lost, and the long waves be bent down abundantly and come to earth again on the far side of the mountains. In the night, however, the ionisation of the middle atmosphere has disappeared, the Heaviside layer is open, and waves of all frequencies are reflected down to earth again. Another fact that emphasises the existence of elevated trajectories is afforded by the experiences of the Alpine receiving stations. These stations commonly receive signals from great distances in all directions—from stations in all parts of Europe and from ships on the Atlantic—so that it has been said that "the Alps attract signals." Stations in the plains do not get these distant signals nearly so often. The fact is that the high mountain stations have, of course, a much better chance of lying on the trajectories of the waves, or, as suggested by Larmor, in a slightly different connection, of "tapping a stronger stratum of radiation."

Recently, in an evening discourse at the Royal Institution, Marconi has described* the striking effects of sunrise and sunset on the strength of signals received from across the Atlantic Ocean. He stated that the intensity of the signals received at Clifden, Ireland, from Glace Bay, Canada, remains fairly steady during the day, but shortly after sunset at Clifden it becomes gradually weaker, and reaches a minimum in about

* June 2, 1911.

RADIOTELEGRAPHY.[1]

[With 1 plate.]

By Commendatore G. Marconi, LL.D., D.Sc.

The practical application of electric waves to the purposes of wireless telegraphic transmission over long distances has continued to extend to a remarkable degree during the last few years, and many of the difficulties, which at the outset appeared almost insurmountable, have been gradually overcome, chiefly through the improved knowledge which we have obtained in regard to the subject generally and to the principles involved.

The experiments which I have been fortunate enough to be able to carry out, on a much larger scale than can be done in ordinary laboratories, have made possible the investigation of phenomena often novel and certainly unexpected.

Although we have—or believe we have—all the data necessary for the satisfactory production and reception of electric waves, we are yet far from possessing any very exact knowledge concerning the conditions governing the transmission of these waves through space, especially over what may be termed long distances. Although it is now perfectly easy to design, construct, and operate stations capable of satisfactory commercial working over distances up to 2,500 miles, no really clear explanation has yet been given of many absolutely authenticated facts concerning these waves. Some of these hitherto apparent anomalies I shall mention briefly in passing.

Why is it that when using short waves the distances covered at night are usually enormously greater than those traversed in the day time, while when using much longer waves the range of transmission by day and night is about equal and sometimes even greater by day?

What explanation has been given of the fact that the night distances obtainable in a north-southerly direction are so much greater than those which can be effected in an east-westerly one?

Why is it that mountains and land generally should greatly obstruct the propagation of short waves when sunlight is present and not during the hours of darkness?

[1] Reprinted by permission from author's separate of Proceedings of the Royal Institution. Read before Royal Institution of Great Britain at weekly evening meeting, Friday, June 2, 1911.

The general principles on which practical radiotelegraphy is based are now so well known that I need only refer to them in the briefest possible manner.

Wireless telegraphy, which was made possible by the fields of research thrown open by the work of Faraday, Maxwell, and Hertz, is operated by electric waves, which are created by alternating currents of very high frequency, induced in suitably placed elevated wires or capacity areas. These waves are received or picked up at a distant station on other elevated conductors tuned to the period of the waves, and the latter are revealed to our senses by means of appropriate detectors.

My original system as used in 1896 consisted of the arrangement shown diagrammatically in figure 1, where an elevated or vertical wire was employed. This wire sometimes terminated in a capacity or was connected to earth through a spark gap.

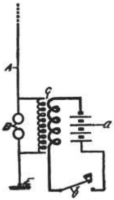


FIG. 1.

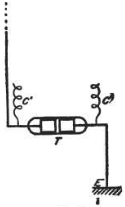


FIG. 2.

By using an induction coil or other source of sufficiently high tension electricity sparks were made to jump across the gap; this gave rise to oscillations of high frequency in the elevated conductor and earth, with the result that energy in the form of electric waves was radiated through space.

At the receiving station (fig. 2) these waves induced oscillatory currents in a conductor containing a detector, in the form of a coherer, which was usually placed between the elevated conductor and earth.

Although this arrangement was extraordinarily efficient in regard to the radiation of electrical energy, it had numerous drawbacks.

The electrical capacity of the system was very small, with the result that the small amount of energy in the aerial was thrown into space in an exceedingly short period of time. In other words, the energy, instead of giving rise to a train of waves, was all dissipated after only a few oscillations, and, consequently, anything approaching good tuning between the transmitter and receiver was found to be unobtainable in practice.

reach the earth again in appreciable amount. This would probably not have happened with longer waves.

As for the night signals, both long and short waves are propagated through the lower and middle atmosphere in straight lines to great heights and reflected at the Heaviside layer, and then they descend to earth again, having suffered comparatively little absorption. The waves may be imagined to creep round this electrical vault of the atmosphere in a manner somewhat analogous to the creeping of sound round a whispering gallery, being plentifully scattered downward in their progress by the irregularities in the reflecting surface, or, to put it another way, we may imagine that a transmitting station "lights up the sky," in an electrical sense, for many degrees below its horizon.

Since in the observations quoted the daylight signals were perceptible at 700 miles, where the horizontal plane of the sender crosses the observer's vertical at a height of 60 miles, we may conclude that the trajectory of the radiation directed horizontally from the sender does not reach higher than 30 miles in the daytime. It may be mentioned at this point that Marconi originally suggested that the phenomenon might be due to a possible discharging action of sunlight on the sending antenna, and J. J. Thomson considered it rather due to the absorption of energy by the ionised air in the immediate neighbourhood of the antenna, but both these explanations ought to make the contrast between day and night signals the same for short distances as for long, which is not the case.

The above considerations suggest that there should exist a best frequency for signalling over great distances. Now the radiation from a Hertzian oscillator is most intense in its equatorial plane, and therefore, from a vertical linear earthed antenna, is most intense in the horizontal plane of the sending station. Hence we conclude that the best frequency is that for which, in a given ionic condition of the atmosphere, the trajectory of the radiation which starts nearly horizontally returns to the earth's surface near the receiving station. Marconi has stated* that a wave-length of 5000 metres is almost always better than one of 4000 metres for Transatlantic signalling—though, he remarks, the shorter wave-length is better than the longer occasionally. In this connection it may be pointed out that, if the transmission of signals be attempted with an exceedingly long wave-length, the aggregate curvature produced by the ionic refraction in the day might be sharper than the curvature of the earth. This would cause the nearly horizontal radiation to be turned down to the earth within a relatively short distance from the radiator. In that case reception at a distance would be

* Nobel Lecture, December, 1909.

exhibit a different frequency; or, in other words, there should be a distinct best frequency at which to adjust the receiving apparatus at each of these stations. This is on account of the difference of trajectory that difference of frequency brings. There is but little experimental evidence bearing on this point, though what there is favours the assumptions; but clearly if dispersion do occur in the sunlit middle atmosphere, and do not occur at night, the weakness of the day strays is fully accounted for without invoking the assistance of absorption.

Though the hypothesis of propagation round the earth by refraction in the ionised middle atmosphere has now been applied to the problem that prompted it, namely, the explanation of the minimum phenomenon of natural electric waves, yet it seems desirable to enquire how the hypothesis comports itself towards the known facts and properties of the artificial electric waves used in signalling.

The two assumptions on which the discussion has so far been built are, first, that there exists in the atmosphere a permanently conducting upper layer which is somewhat sharply defined, and which therefore reflects waves of every frequency—we may call it Heaviside's reflecting layer; and, second, that in the day (and only to a slight and erratic extent in the night) the atmosphere below this reflecting layer is ionised in nearly horizontal strata, the ionisation diminishing as the earth's surface is approached, with the result that electric waves are given a bent trajectory and the Heaviside layer put out of action. In using these assumptions in what follows, the atmosphere will be supposed at rest.

One of the most important of the facts known concerning the transmission of artificial waves is the difference between day and night signals discovered by Marconi* in 1902 during a voyage from England to New York. He found that there was little difference between day and night signals at distances less than 500 miles from the sending station, but that the day signals were unreadable at distances of 800 miles and more, while the night signals were readable up to distances of 2000 miles. This is possibly due to the same causes as the weakening of the day strays relatively to the night strays, but is most probably due to the failure of the heterogeneously ionised air to bend the waves sufficiently to fit the convexity of the earth. Thus, in explaining the daylight effect observed first by Marconi in 1902, it is only necessary to suppose that the relatively short waves then in use travelled to great heights in the atmosphere on account of the smallness of the curvature of their trajectory, and were not refracted sufficiently to

* Marconi, 'Roy. Soc. Proc.,' June, 1902.

Many mechanical analogies could be quoted which show that in order to obtain syntony the operating energy must be supplied in the form of a sufficient number of small oscillations or impulses properly timed. Acoustics furnish us with numerous examples of this fact, such as the resonance produced by the well-known tuning fork experiment.

Other illustrations of this principle may be given; e. g., if we have to set a heavy pendulum in motion by means of small thrusts or impulses, the latter must be timed to the period of the pendulum, as otherwise its oscillations would not acquire any appreciable amplitude.

In 1900 I first adopted the arrangement which is now in general use, and which consists (as shown in fig. 3) of the inductive association of the elevated radiating wire with a condenser circuit which may be used to store up a considerable amount of electrical energy and impart it at a slow rate to the radiating wire.

As is now well known, the oscillations in a condenser circuit can be made to persist for what is electrically a long period of time, and it can be arranged moreover that by means of suitable aerials or antennæ these oscillations are radiated into space in the form of a series of waves, which through their cumulative effect are eminently suitable for enabling good tuning and syntony to be obtained between the transmitter and receiver.

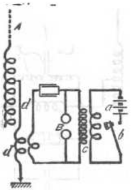


Fig. 3.

The circuits, consisting of the condenser circuit and the elevated aerial or radiating circuit, were more or less closely coupled to each other. By adjusting the inductance in the elevated conductor, and by the employment of the right value of capacity or inductance required in the condenser circuit, the two circuits were brought into electrical resonance, a condition which I first pointed out as being essential in order to obtain efficient radiation and good tuning.

The receiver (as shown in fig. 4) also consists of an elevated conductor or aerial connected to earth or capacity through an oscillating transformer. The latter also contains the condenser and detector, the circuits being made to have approximately the same electrical time period as that of the transmitter circuits.

At the long distance station situated at Clifden, in Ireland, the arrangement which has given the best results is based substantially upon my syntonic system of 1900, to which have been added numerous improvements.

An important innovation from a practical point of view was the adoption at Clifden and Glace Bay of air condensers, composed of insulated metallic plates suspended in air at ordinary pressure. In this manner we greatly reduce the loss of energy which would take place in consequence of dielectric hysteresis were a glass or solid dielectric employed. A very considerable economy in working also results from the absence of dielectric breakages, for, should the potential be so raised as to even produce a discharge from plate to plate across the condenser, this does not permanently affect the value of the dielectric, as air is self-healing and one of the few commodities which can be replaced at a minimum of cost.

Various arrangements have been tried and tested for obtaining continuous or very prolonged trains of waves, but it has been my experience that, when utilizing the best receivers at present available, it is neither economical nor efficient to attempt to make the waves too continuous. Much better results are obtained when groups of waves (fig. 5) are emitted at regular intervals in such manner that their cumulative effect produces a clear musical note in the receiver, which is tuned not only to the periodicity of the electric waves transmitted but also to their group frequency.

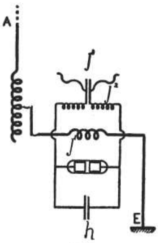


FIG. 4.

In this manner the receiver may be doubly tuned, with the result that a far greater selectivity can be obtained than by the employment of wave tuning alone.

In fact, it is quite easy to pick up simultaneously different messages transmitted on the same wave length, but syntonized to different group frequencies.

As far as wave tuning goes, very good results—almost as good as are obtainable by means of continuous oscillations—can be achieved with groups of waves, the decrement of which is in each group 0.03 or 0.04, which means that about 30 or 40 useful oscillations are radiated before their amplitude has become too small to perceptibly affect the receiver.

The condenser circuit at Clifden has a decrement of from 0.015 to 0.03 for fairly long waves.

This persistency of the oscillations has been obtained by the employment of the system shown in figure 6, which I first described in a patent taken out in September, 1907. This method eliminates

is sometimes a complete zero lasting for only two minutes or less. Assuming that in this case the source of the natural electric waves and the receiving station lie both on the great circle of twilight, we deduce that the twilight band is at least 30 miles wide, this being the distance the earth rotates eastward in two minutes. In addition, the same assumption would indicate that the principal source of the strays during November, 1909 and 1911, lay in the direction of the eastern portion of the Atlas Mountains.

Again, the observations have shown that the chief twilight minima occur about 10 minutes before sunrise and about 10 minutes after sunset during the same periods. This fact is accounted for by the consideration that the time of sunrise in the middle atmosphere is a little earlier and the time of sunset a little later than at the surface of the earth. In this connection it should be noticed that the electrically effective sunrise at a point in the middle atmosphere, as measured by the ionising power of the sunlight reaching the point, is not coincident in time with the sunrise at the same point as indicated by mere luminosity, that is, with the geometrical sunrise. The rays heralding the sunrise in the latter and ordinary sense must possess very little ionising power, for the reason that in passing the earth tangentially they have traversed so long a path in the lower atmosphere as to have lost their ionising radiation. Thus an observation of the time interval of the stray minimum before geometrical sunrise and after sunset does not determine the height of the electrically disturbed regions. Besides this, the exact time of the stray minimum will be affected to some extent by the obliquity of the ionic curtain to the line of propagation of the waves.

During the day the electric waves travel in the relatively narrow shell of dielectric between some stratum in the middle atmosphere and the surface of the earth. At night they travel in the much wider shell of dielectric between the assumed high conducting layer and the earth. In England, in winter, the day strays are much weaker than the night strays. From this we might conclude either that the aggregate absorption in the thin shell of dielectric is greater than in the deeper night shell, or that the ionisation of the middle atmosphere during the day is sufficiently non-uniform to hinder the propagation of the waves. But another factor must be recognised. The electric disturbance produced by a lightning discharge is doubtless impulsive in character, and is probably either a solitary wave or a very short train of waves. The study of the refraction of such disturbances leads to some well-known theoretical difficulties, but if we assume that the wave undergoes dispersion during its progress through the ionised middle atmosphere, then the disturbance arriving at a given receiving station should exhibit a fairly definite frequency, and that arriving at a station at a different distance should still atmosphere be drawn round the globe they will be nearest the earth at places where the sun is on the meridian, and will rise away from the earth somewhat sharply at places where the sun is rising or setting. The regions in which the change from the day level to the night level takes place form a great circular band round the globe and inclined to the meridians at an angle depending on the season. This region of the atmosphere, since it is perpetually moving with the sun, will be in a highly disturbed electrical condition. Formation of ions is actively proceeding in one half of the great circle and recombination in the other, and these processes doubtless take place somewhat irregularly even in a still atmosphere—with the result that patches or banks of ionised air, analogous to the banks of fog met at sea—will transiently constitute this band in the middle atmosphere. The effect of such patches of variously ionised air on electric waves propagated through the region is, in view of the connection between the velocity of the waves and the concentration of the ions, certain to be difficult. The scattering by repeated refractions will tend to make the region impenetrable to waves directed through it. Hence it may be expected that the regularity of the propagation through the steadily ionised horizontal strata of the daytime will be greatly disturbed by the twilight transitional banks and patches, with the ultimate consequence that the sounds heard in the receiving apparatus will be greatly weakened.

The author's experience up to the present indicates that the existence or non-existence of clouds in the vicinity of the receiving station has but little influence on the intensity and character of the stray minima, or, for that matter (provided the day is not brilliantly clear), on signals received from any distance and any point of the compass. Whence we may conclude that the irregularly ionised band is situated above the ordinary cloud level. The twilight transitional region may therefore be regarded as a sort of curtain enringing the earth and occupying the middle atmosphere and not the lower. Thus it can affect only the trajectories of waves travelling from great distances. The weakening of such long-distance waves will probably be greater or less according as they have to penetrate the curtain more or less obliquely. In the case of the natural electric waves received by an antenna in England during the autumn and winter the origin of the waves must in general lie to the south. It is reasonable to suppose that tropical Africa will supply most of them. In that case, the twilight transitional band must have a very great and a relatively short-lived influence on the intensity of the strays heard in the telephones, for the path of the waves from the suggested source to the receiving station is nearly coincident with the twilight band. These suppositions accord precisely with the observed facts. The minimum

almost completely the spark gap and its consequent resistance, which, as is well known, is the principal cause of the damping or decay of the waves in the usual transmitting circuit.

The apparatus shown in figure 6 consists of a metal disk *a*, having copper studs firmly fixed at regular intervals in its periphery and placed transversely to its plane. This disk is caused to rotate very rapidly between two other disks, *b*, by means of a rapidly revolving electric motor or steam turbine. These side disks are also made to slowly turn round in a plane at right angles to that of the middle disk. The connections are as illustrated in the figure. The studs are of such length as to just touch the side disks in passing, and thereby bridge the gap between the latter.

With the frequency employed at Clifden, namely, 45,000, when a potential of 15,000 volts is used on the condenser, the spark gap is practically closed during the time in which one complete oscillation only is taking place, when the peripherical speed of the disk is about 600 feet a second. The result is that the primary circuit can continue oscillating without material loss by resistance in the spark gap. Of course the number of oscillations which can take place is governed by the breadth or thickness of the side disks, the primary circuit being abruptly opened as soon as the studs attached to the middle disk leave the side disks.

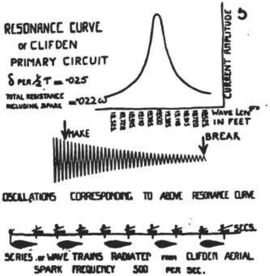


Fig. 5.

This sudden opening of the primary circuit tends to immediately quench any oscillations which may still persist in the condenser circuit; and this fact carries with it a further and not inconsiderable advantage, for if the coupling of the condenser circuit to the aerial is of a suitable value the energy of the primary will have practically all passed to the aerial circuit during the period of time in which the

primary condenser circuit is closed by the stud filling the gap between the side disks; but after this the opening of the gap at the disks prevents the energy returning to the condenser circuit from the aerial, as would happen were the ordinary spark gap employed. In this manner the usual reaction which would take place between the aerial and the condenser circuit can be obviated, with the result that with this type of discharger and with a suitable degree of coupling the energy is radiated from the aerial in the form of a pure wave, the loss from the spark gap resistance being reduced to a minimum.

I am able to show a resonance curve taken at Clifden which was obtained from the oscillations in the primary alone (fig. 5).

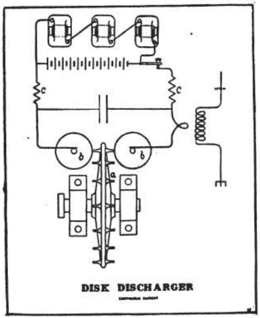


FIG. 6.

An interesting feature of the Clifden plant, especially from a practical and engineering point of view, is the regular employment of high-tension direct current for charging the condenser. Continuous current at a potential which is capable of being raised to 20,000 volts is obtained by means of special direct-current generators; these machines charge a storage battery consisting of 6,000 cells, all connected in series, and it may be pointed out that this battery is the largest of its kind in existence. The capacity of each cell is 40 ampere-hours. When employing the cells alone the working voltage is from 11,000 to 12,000 volts, and when both the direct-current generators and the battery are used together the potential may be raised to 15,000 volts through utilizing the gassing voltage of the storage cells.

For a considerable portion of the day the storage battery alone is employed, with a result that for 16 hours out of the 24 no running

0·01. This in turn indicates that the number of ions per cubic centimetre should be about 160,000 when the wave-length is 2000 metres, and about 16,000 when the wave-length is 6000 metres. Such ionic concentrations are not improbable.

It may be objected that there has as yet been no experimental corroboration of this concentration of the energy of the waves into a comparatively thin stratum near the surface of the earth. But as a fact no measurements have as yet been carried out over great distances on the variation of intensity of signals with distance and under unvarying atmospheric conditions; and clearly the measurements that have been made over short distances—which all support the inverse square law as was to be expected—cannot have any bearing on refractions that take place in high layers. When measurements of intensity over distances of 1000 to 2000 miles become available it may be expected that the inverse square law will hold for a distance of three or four hundred miles, and after that a law indicating rather less divergence may hold for several hundred miles more, if the frequency is low enough for the ionic refraction to produce bending at least as great as the convexity of the globe.*

We now proceed to the explanation of the stray minima described earlier. In the first place it is evident that if the surfaces of equal ionisation in a

* Since the above was written, an account by L. W. Austin ('Washington Bureau of Standards Bulletin,' October, 1911) of some new measurements of the intensity of signals has come to hand, which appears to strengthen the author's position greatly, so far as the measurements go. The inverse square law for the divergence of energy shows that $I \propto x^{-1}$, where I is the intensity of the current received on an antenna, and x is the distance of the sending station. If the waves were travelling in free space of electrical constitution like that of our lower atmosphere, the absorption would demand a formula of the type

$$I \propto x^{-1}\epsilon^{-\alpha x},$$

where α is independent of the wave-length. Also it has been shown above that if the waves were travelling in free space filled with air highly ionised, the absorption would require a formula of the type

$$I \propto x^{-1}\epsilon^{-\alpha x\lambda^2},$$

where α is again independent of the wave-length. Now, the observations quoted support an empirical formula very different from either of these, namely,

$$I \propto x^{-1}\epsilon^{-\alpha x/\sqrt{\lambda}}.$$

A formula involving the wave-length in this manner is not suggested, and cannot even be accounted for, by absorption in an ionised atmosphere or in a badly conducting surface such as that of land or sea; but it is clearly in rough general accord with the law, developed in this paper, that the desired bending of the rays is better with long waves than with short waves; or, to put it in another way, the loss of radiation by failure to turn the curve of the earth is greater with short waves than with long. The measurements made up to the present by Austin and his collaborators have extended to distances of only 900 miles, involving only very slight bending, and, besides, have not been very numerous.

ions moving up and negative ions moving down, with the result that some parts of the middle atmosphere may remain ionised after the sun has set. If we suppose, however, that the ions do for the most part recombine, then the effect of the change from day to night is to remove a veil, as it were, of ionised air from between the upper conducting layer and the earth.

Since the velocity of the waves in the sunlit middle atmosphere is greater the higher the level at which they are travelling, a ray of electric radiation starting from a point of the earth's surface in a direction inclined slightly upward will pursue a straight path in the lower atmosphere and a slightly bent path, with its concavity downwards, in the middle atmosphere, thus following to a greater or less extent the curvature of the earth. If its curvature in the middle atmosphere is on the average greater than that of the earth—and not otherwise—the ray will be turned down to the lower atmosphere and will again traverse a straight line. In other words, the wave-fronts will be tilted forward as they travel, in a manner quite analogous to the refraction of sound in air when the temperature varies upward. This bending of the rays may be given for shortness the name ionic refraction; it would be very rapid in layers where γ approached unity. Thus the radiations diverging in all directions from a lightning stroke or from a wireless telegraph antenna become confined in the day between the conducting surface of the earth and a certain level in the middle atmosphere. Even the rays that start horizontally from a place on the earth's surface must, owing to the earth's curvature, reach, within 300 miles of the source, to heights where the air may be expected to be strongly ionised, and must then suffer refraction downwards. Since the quantity γ is inversely proportional to the frequency of the transmitted waves, the limiting height of penetration of the waves is smaller the lower the frequency, and therefore low-frequency waves become concentrated nearer to the earth's surface than do higher frequency waves.

The curvature of the trajectory of waves travelling at a height z is $dv/(vdz)$, v being the velocity at the place. But when γ is small $v = (1+\frac{1}{2}\gamma)/\sqrt{(\mu\kappa)}$, and therefore the curvature is $\frac{1}{2}d\gamma/dz$ approximately. If we assume a condition of things in which the radius of curvature of rays at all heights is $r+z$, where r is the radius of the earth, and that $\gamma = 0$ at $z = 0$, we find

$$\gamma = 2\log\frac{r+z}{r} = 2\frac{z}{r}, \text{ approximately.}$$

Though, in fact, the bending of rays in the lower atmosphere is probably not so great as this, the equation indicates that the order of magnitude of γ required in the middle atmosphere at, say, a height of 20 miles is about

machinery need be used for operating the station, with the single exception of the small motor revolving the disk.

The potential to which the condenser is charged reaches 18,000 volts when that of the battery or generators is 12,000. This potential is obtained in consequence of the rise of potential at the condenser plates, brought about by the rush of current through the choking or inductance coils at each charge. These coils are placed between the battery or generator and the condenser *c*, figure 6.

No practical difficulty has been encountered either at Clifden or Glace Bay in regard to the insulation and maintenance of these high-tension storage batteries. Satisfactory insulation has been obtained by dividing the battery into small sets of cells placed on separate stands. These stands are suspended on insulators attached to girders fixed in the ceiling of the battery room. A system of switches, which can all be operated electrically and simultaneously, divides the battery into sections, the potential of each section being low enough to enable the cells to be handled without inconvenience or risk.

The arrangement of aerial adopted at Clifden and Glace Bay is shown in figure 7. This system, which is based on the result of tests which I first described before the Royal Society in June, 1906,[1] not only makes it possible to efficiently radiate and receive

FIG. 7.

waves of any desired length, but it also tends to confine the main portion of the radiation to any desired direction. The limitation of transmission to one direction is not very sharply defined, but nevertheless the results obtained are exceedingly useful for practical working.

In a similar manner, by means of these horizontal wires, it is possible to define the bearing or direction of a sending station, and also limit the receptivity of the receiver to waves arriving from a given direction.

The commercial working of radiotelegraphy and the widespread application of the system on shore and afloat in nearly all parts of the world has greatly facilitated the marshaling of facts and the observation of effects. Many of these, as I have already stated, still await a satisfactory explanation.

A curious result which I first noticed over nine years ago in long-distance tests carried out on the steamship *Philadelphia*, and which still remains an important feature in long-distance space telegraphy,

[1] "On methods whereby the radiation of electric waves may be mainly confined, etc." Proc. Roy. Soc., A, vol. 77, p. 413.

is the detrimental effect produced by daylight on the propagation of electric waves over great distances.

The generally accepted hypothesis of the cause of this absorption of electric waves in sunlight is founded on the belief that the absorption is due to the ionization of the gaseous molecules of the air affected by the ultra violet light, and as the ultra violet rays which emanate from the sun are largely absorbed in the upper atmosphere of the earth, it is probable that that portion of the earth's atmosphere which is facing the sun will contain more ions or electrons than that which is in darkness, and therefore, as Sir J. J. Thomson has shown,[1] this illuminated or ionized air will absorb some of the energy of the electric waves.

The wave length of the oscillations employed has much to do with this interesting phenomenon, long waves being subject to the effect of daylight to a very much lesser degree than are short waves.

Although certain physicists thought some years ago that the daylight effect should be more marked on long waves than on short, the reverse has been my experience; indeed, in some transatlantic experiments, in which waves about 8,000 meters long were used, the energy received by day at the distant receiving station was usually greater than that obtained at night.

Recent observation, however, reveals the interesting fact that the effects vary greatly with the direction in which transmission is taking place, the results obtained when transmitting in a northerly and southerly direction being often altogether different from those observed in the easterly and westerly one.

Research in regard to the changes in the strength of the received radiations which are employed for telegraphy across the Atlantic has been recently greatly facilitated by the use of sensitive galvanometers, by means of which the strength of the received signals can be measured with a fair degree of accuracy.

In regard to moderate power stations such as are employed on ships, and which, in compliance with the international convention, use wave lengths of 300 and 600 meters, the distance over which communication can be effected during daytime is generally about the same, whatever the bearing of the ships to each other or to the land stations —whilst at night interesting and apparently curious results are obtained. Ships over 1,000 miles away, off the south of Spain or round the coast of Italy, can almost always communicate during the hours of darkness with the post-office stations situated on the coasts of England and Ireland, whilst the same ships, when at a similar distance on the Atlantic to the westward of these islands and on the usual track between England and America, can hardly ever communi-

[1] Philosophical Magazine, ser. 6, vol. 4, p. 253.

molecular size, and the other is that these same agencies also produce, by direct action on the gases of the atmosphere, condensation nuclei consisting of solid or liquid compounds which are not electrically charged when first formed. Evidently, the condensation nuclei can have only slight influence on the value of the quantity γ as compared with the electrical carriers of molecular size. These heavy ions, or condensation nuclei, doubtless frequently become charged by attaching one or more of the light ions, which has the effect of putting such ions out of action for our purposes. The lighter ions are probably in a majority in the higher parts of the middle atmosphere, and the heavy ions in a majority in the lower parts, and also in the lower atmosphere. It may be mentioned that the heavier ions found in the lower atmosphere, whether consequences of solar radiation or not, escape being counted by the kind of apparatus usually used in measurements of atmospheric electricity, on account of their immobility.

So far as the quantity γ is concerned the principal difference between day and night conditions, and between the conditions at different times of the day, is due to the variations of the number of ions per cubic centimetre provided by solar radiation. It is not possible to be precise on this matter, even in the lower atmosphere. But, broadly, it is clear that the value of n in the lower and middle atmospheres must vary considerably with the obliquity of the sun's rays at the place, that is to say, with the season and the time of day, and also must vary profoundly from daylight to darkness. About the time of sunrise at any particular place the process of ionisation by the solar radiation will be occurring at all heights of the atmosphere over an area extending many miles to east and west of the place; at sunset recombination of the ions will occur through a similar space. Of course the layers nearest the earth will be least disturbed in electrical constitution, mainly for the reason that the sun's rays must have been robbed of much of their ionising powers by the time they reach low levels; but it is known from direct observations at various levels up to heights of several miles that the influence of the sun is quite perceptible. But, in fact, it is easily seen from the formula deduced above for the absorption per wave-length, that the normal ionisation observed in the lower atmosphere produces inappreciable absorption of the waves at any time of day over terrestrial distances.

Our knowledge of the conditions ruling in the hours of darkness is even less precise than that of the day conditions. The very rapid rate of recombination of ions when the ionising agent is removed points to the possibility of the middle atmosphere being perfectly free from ions during darkness. But it is probable that there occurs during the day a great sifting of oppositely charged ions under the operation of the earth's vertical electric field, positive

In air under standard conditions $d\xi/dt = 1{\cdot}5$ cm./sec. in a field having a gradient of 1 volt per centimetre. Take $e = 1{\cdot}0 \times 10^{-20}$ in electromagnetic units, then $f = 7 \times 10^{-13}$, roughly. Again taking $p = 10^7$ and $m = 2 \times 10^{-21}$ in grammes, then $mp = 2 \times 10^{-14}$. Thus for waves of the order of frequency 1,000,000 per second, the two terms in the denominator of the quantity γ are of about the same order of importance at low levels in the atmosphere. For waves of lower frequency the term f^2 is much more important than the term m^2p^2, which may then be neglected in the denominator of γ. At higher levels, on the contrary, the term f^2 probably becomes negligible in comparison with m^2p^2 since the value of f is known to fall off much faster than that of m as the rarefaction increases. Thus, at high levels, we have

$$\gamma = 4\pi ne^2/\kappa mp^2, \text{ approximately.}$$

At low levels the value of γ works out as $0{\cdot}55 \times 10^{-14} \times n$ with the numbers already assumed. The number of ions per cubic centimetre at sea level is often given as between 1000 and 10,000. Thus γ is quite negligible compared with unity if this estimate of n and that of f are valid. At high levels, using the last equation, we find $\gamma = 0{\cdot}6 \times 10^{-11} \times n$ for $p = 10^7$ (corresponding to a wave-length of nearly 200 metres) and $\gamma = 0{\cdot}6 \times 10^{-9} \times n$ for $p = 10^6$ (corresponding to a wave-length of nearly 2000 metres in ordinary air). It is more than probable, however, that at moderately high levels, where the air is rather rarefied—for example, at a height of 20 miles the pressure is, on the theory of convective equilibrium, about $1/100$ of the pressure at sea level—the ion is of much smaller mass, say 100 times smaller, than is assumed above, and this would make the last figure become $\gamma = 0{\cdot}6 \times 10^{-7} \times n$ for $p = 10^6$.

For convenience in discussion, the portion of the atmosphere below the permanently conducting layer and throughout which the equation

$$\gamma = 4\pi ne^2/\kappa mp^2$$

holds good, that is the portion of the atmosphere which is ionised strongly and directly by the sun, will be called the middle atmosphere. The part below this will be called the lower atmosphere, and here the equation

$$\gamma = 4\pi ne^2 m/\kappa f^2$$

is probably appropriate while n has low values. Of the middle atmosphere and of the upper atmosphere we know nothing directly. Perhaps the best information available is that contained in the memoirs of P. Lenard and C. Ramsauer,* who showed that the ultra-violet light of the sun will produce in air two effects of interest in the present connection. One effect is that the ultra-violet light, and possibly the cathode rays, of the sun produce electrical carriers of

* 'Heidelberger Akademie Sitzungsber.,' 1910—11.

cate with these shore stations unless by means of specially powerful instruments.

It is also to be noticed that in order to reach ships in the Mediterranean the electric waves have to pass over a large portion of Europe and, in many cases, over the Alps. Such long stretches of land, especially when including very high mountains, constitute, as is well known, an insurmountable barrier to the propagation of short waves during the daytime. Although no such obstacles lie between the English and Irish stations and ships in the North Atlantic en route for North America, a night transmission of 1,000 miles is there of exceptionally rare occurrence. The same effects generally are noticeable when ships are communicating with stations situated on the Atlantic coast of America.

Although high power stations are now used for communicating across the Atlantic Ocean, and messages can be sent by day as well as by night, there still exist periods of fairly regular daily occurrence during which the strength of the received signals is at a minimum.

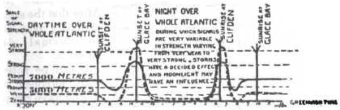


Fig. 8.

Thus in the morning and the evening, when, in consequence of the difference in longitude, daylight or darkness extends only part of the way across the ocean, the received signals are at their weakest. It would almost appear as if electric waves, in passing from dark space to illuminated space and vice versa, were reflected and refracted in such a manner as to be diverted from the normal path.

Later results, however, seem to indicate that it is unlikely that this difficulty would be experienced in telegraphing over equal distances north and south on about the same meridian, as, in this case, the passage from daylight to darkness would occur more rapidly over the whole distance between the two stations.

I have here some diagrams which have been carefully prepared by Mr. H. J. Round. These show the average daily variation of the signals received at Clifden from Glace Bay.

The curves traced on the diagram (fig. 8) show the usual variation in the strength of these transatlantic signals on two wave lengths —one of 7,000 meters and the other of 5,000 meters.

The strength of the received waves remains as a rule steady during daytime.

Shortly after sunset at Clifden they become gradually weaker, and about two hours later they are at their weakest. They then begin to strengthen again, and reach a very high maximum at about the time of sunset at Glace Bay.

They then gradually return to about normal strength, but through the night they are very variable. Shortly before sunrise at Clifden the signals commence to strengthen steadily, and reach another high maximum shortly after sunrise at Clifden. The received energy then steadily decreases again until it reaches a very marked minimum, a short time before sunrise at Glace Bay. After that the signals gradually come back to normal day strength.

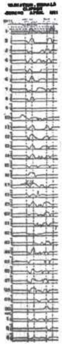


FIG. 9.

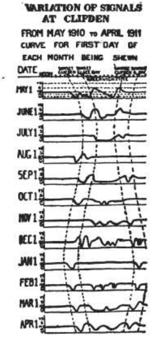


FIG. 10.

It can be noticed that, although the shorter wave gives on the average weaker signals, its maximum and minimum variations of strength very sensibly exceed that of the longer waves.

Figure 9 shows the variations at Clifden during periods of 24 hours, commencing at 12 noon throughout the month of April, 1911, the vertical dotted lines representing sunset and sunrise at Glace Bay and Clifden.

Figure 10 shows the curve for the first day of each month for one year, from May, 1910, to April, 1911.

I carried out a series of tests over longer distances than had ever been previously attempted, in September and October of last year, between the stations of Clifden and Glace Bay, and a receiving station placed on the Italian Steamship *Principessa Mafalda*, in the course of a voyage from Italy to Argentina (pl. 1, fig. 1).

Eliminating β and ζ among these three equations, we have

$$\frac{\partial^2 Z}{\partial x^2} = \mu\kappa \frac{\partial^2 Z}{dt^2} + \frac{4\pi\mu ne^2}{mip+f}\frac{\partial Z}{\partial t}.$$

There is a solution of the form

$$Z = \epsilon^{-lx+ip(t-x/v)}$$

for waves of frequency $p/2\pi$, if the velocity

$$v = \frac{mp}{\gamma f}\sqrt{\left(\frac{2(1-\gamma)}{\mu\kappa}\right)}\left\{\sqrt{\left[1+\left(\frac{\gamma f}{mp(1-\gamma)}\right)^2\right]}-1\right\}^{\frac{1}{2}}$$

and the absorption factor $\qquad l = \frac{\mu\kappa\gamma f}{2m}v.$

Here γ has been put for the quantity

$$\frac{4\pi ne^2 m}{\kappa(m^2p^2+f^2)},$$

which, it will be shown, is usually smaller than unity. In addition, the quantity $\gamma f/mp(1-\gamma)$ is usually very small compared with unity, hence, approximately,

$$v = \frac{1}{\sqrt{(\mu\kappa)}}(1+\tfrac{1}{2}\gamma), \qquad l = \frac{\sqrt{(\mu\kappa)}f}{2m}\gamma(1+\tfrac{1}{2}\gamma);$$

or the absorption coefficient per wave-length is

$$l' = \frac{\pi}{1-\gamma}\frac{\gamma f}{mp}.$$

It should be mentioned that, in forming the equations, it has been implicitly assumed that the ions are so heavy that they acquire only small velocities and make very small excursions under the action of the waves. That is to say, the ions are supposed to be collections of molecules, or, at the smallest, single molecules. The absorption in the case of very small ions, that is, electrons, has been worked out by J. J. Thomson,* and involves different considerations from those appropriate here.

Rough estimates of the various magnitudes involved in the last equations may be obtained by using the results of laboratory experiments on ionised gases, though, unfortunately, there are as yet but very few data available on the ionisation of air by solar radiation. First notice that the friction coefficient f can be estimated from experiments on the terminal velocities of ions in various gases. From the equation of motion of an ion we see that its terminal velocity under a steadily applied electric field Z is

$$\frac{d\zeta}{dt} = \frac{e}{f}Z.$$

* 'Phil. Mag.,' August, 1902, p. 253.

other recorded facts of long-distance transmission be explained. The writer has therefore investigated another, and closely related, possibility, which, it turns out, throws light on the causes of the stray minimum, as well as on many of the observed facts of long-distance transmission. To these new considerations we now turn.

The hypothesis to be introduced is based on the influence of the ionisation of the air on the propagation of electric waves through it. It is well known that, under normal conditions, the air at the sea-level is only slightly ionised even in strong sunshine, and that at a height of a few miles above the earth's surface the ionisation is, according to observations from balloons, sometimes 20 times as great as at the surface. Higher still the ionisation doubtless increases further, on account of the more and more intense ionising action of the solar radiation, which, it is plain, must be greater in these higher and rarer regions than in the dense regions below. No law can be legitimately assigned for the computation of this gradual transition from low conductivity to high conductivity, yet, for the purpose in hand, it is necessary to form some idea of the effect of this heterogeneity on the propagation of electric waves.

It is first necessary to examine the effect of charged ions of molecular mass on the velocity of the waves, and here we may follow, with suitable modifications, the standard methods applied to the study of optical dispersion in media containing electrons. Let e be the charge, m the mass, of each ion, and let n be the number of ions per cubic centimetre at a point whose co-ordinates are x, y, z, referred to a right-handed rectangular frame of axes with the axis of z vertical. Suppose that electric waves are advancing through the medium in the positive direction of the x axis, and with electric force Z, magnetic force β, at the point x, y, z. Then if μ be the permeability of the medium and κ the dielectric constant of the unionised air,

$$\frac{\partial Z}{\partial x} = \mu \frac{d\beta}{dt} \quad \text{and} \quad \frac{\partial \beta}{\partial x} = \kappa \frac{dZ}{dt} + 4\pi ne \frac{d\zeta}{dt},$$

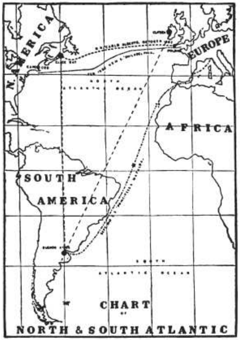
where ζ indicates the displacement of each ion from its original position produced by the waves. The equation of motion of an ion is

$$m \frac{d^2\zeta}{dt^2} + f \frac{d\zeta}{dt} = eZ,$$

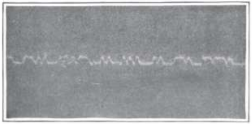
where f is a frictional constant of viscous type.

If the time factor in Z be ϵ^{ipt}, this equation becomes

$$\frac{d\zeta}{dt} = \frac{eZ}{mip+f}.$$



1. Long Distance Wireless Tests in 1910.



2. Record of Wireless Signals.

During these tests the receiving wire was supported by means of a kite, as was done in my early transatlantic tests of 1901, the height of the kite varying from about 1,000 to 3,000 feet. Signals and messages were obtained without difficulty, by day as well as by night, up to a distance of 4,000 statute miles from Clifden.

Beyond that distance reception could only be carried out during nighttime. At Buenos Aires, over 6,000 miles from Clifden, the night signals from both Clifden and Glace Bay were generally good, but their strength suffered some variations.

It is rather remarkable that the radiations from Clifden should have been detected at Buenos Aires so clearly at nighttime and not at all during the day, whilst in Canada the signals coming from Clifden (2,400 miles distant) are no stronger during the night than they are by day.

Further tests have been carried out recently for the Italian Government between a station situated at Massaua in East Africa and Coltano in Italy. Considerable interest attached to these experiments, in view of the fact that the line connecting the two stations passes over exceedingly dry country and across vast stretches of desert, including parts of Abyssinia, the Soudan, and the Libyan Desert. The distance between the two stations is about 2,600 miles.

The wave length of the sending station in Africa was too small to allow of transmission being effected during daytime, but the results obtained during the hours of darkness were exceedingly good, the received signals being quite steady and readable.

The improvements introduced at Clifden and Glace Bay have had the result of greatly minimizing the interference to which wireless transmission over long distances was particularly exposed in the early days.

The signals arriving at Clifden from Canada are as a rule easily read through any ordinary electrical atmospheric disturbance. This strengthening of the received signals has moreover made possible the use of recording instruments, which will not only give a fixed record of the received messages, but are also capable of being operated at a much higher rate of speed than could ever be obtained by means of an operator reading by sound or sight. The record of the signals is obtained by means of photography in the following manner: A sensitive Einthoven string galvanometer is connected to the magnetic detector or valve receiver, and the deflections of its filament caused by the incoming signals are projected and photographically fixed on a sensitive strip, which is moved along at a suitable speed (pl. 1, fig. 2). On some of these records, which I am able to show, it is interesting to note the characteristic marks and signs produced amongst the signals by natural electric waves or other electrical disturbances of

diffraction has been thoroughly settled by the investigations of Rayleigh, Poincaré, Macdonald, Nicholson, and others, whose work has shown irrefutably that the energy propagated round a quarter of the globe by the process of diffraction would be utterly inappreciable. Heaviside has suggested that, in the type of waves used in wireless telegraphy, the Faraday lines of electric force are attached, as it were, to the earth, and slide along its surface, and that therefore they cannot leave it; but this view, in fact, throws us back on the diffraction result. Again, in 1906, Zenneck added to this suggestion a consideration based on a well-known illustration of Poynting's theorem. In his original memoir* on the propagation of energy in the electromagnetic field, Poynting gives as an illustration of the theorem the case of a wire possessing resistance and carrying an electric current. Heaviside,† referring to this illustration, showed that the moving electric field cannot be purely radial; in other words, the Faraday lines belonging to the flowing electricity must lean forward as they move along the wire—so that the energy vector shall have a component perpendicular to the surface of the wire. This particular case has been worked out in great detail since the date of the memoir, but Zenneck's application was to the simple case of the propagation of a plane wave over a badly conducting solid, such as the earth, with a plane boundary. His suggestion is, briefly, that the tilting forward of the wave fronts near the conductor will lead to a general slow turning downward of the waves towards the earth, so that a large proportion of the energy of the waves will be deflected round the bend of the earth instead of being propagated linearly into space. This suggestion does not in reality assist the pure diffraction theory at all.

Another hypothesis was put forward by Heaviside in 1900, when he suggested that the attenuated gases of the upper atmosphere might provide a conducting surface concentric with the earth, between which and the surface of the earth itself the waves might spread with two-dimensional divergence. This hypothesis has not yet been supported or denied by any trustworthy experiments or observations. Such experiments or observations will necessarily have to be made on waves that have travelled long distances, for the upper layers of the atmosphere cannot be greatly concerned in short-distance transmission. But it will be perceived, from the remarks already made on the minima of natural electric waves, that this upper conducting layer might supply the explanation of the phenomenon, and thereby gain some support. On examination, however, it appears that the phenomenon cannot be explained by means of the bare hypothesis, and still less can the

* 'Phil. Trans.,' Jan. 10, 1884.
† 'Electrical Papers,' vol. 2, p. 94.

practically as perfect in strong sunlight as in the dark. On all these counts, therefore, the supposition that the minima phenomena under discussion can be explained by ionisation of the lower layers of the atmosphere must be discarded as untenable.

We must therefore turn to the possibility of alterations in the resistance of the ground round the antenna, alterations of such a nature that the waves are absorbed much more freely during a certain few minutes of twilight than before or after. Here we may at the same time consider a subordinate possibility, namely, that the resistance of the ground within a few yards of the earth plates of the antenna might vary through a minimum value during twilight. If this really happened there would be extra dissipation near the earth plate of the energy of the oscillations excited on the antenna by the incoming waves. Both of these views have been negatived by the author's observations on signals coming from short distances, which show that signals originating at distances of less than 50 miles do not undergo appreciable diminution in strength, even on days when the stray minimum is well marked. But, to make certain of the non-existence of the subordinate possibility just referred to, a long series of determinations was made, during the past autumn, of the high-frequency resistance of the antenna and its earth connection at various frequencies and at various times of the day; and especially at the twilight periods. These measurements were carried out by two distinct and trustworthy methods. The details of the determinations need not be given here; it is sufficient to state that the results leave no doubt that the local earth resistance does not vary in the rapid manner, nor to the wide extent, that is required to explain the twilight minima of the strays.

Another point that supports the view that the stray minimum is not produced by strictly local causes may be stated here. It is very noticeable that the twilight minima are easier to observe when the receiving apparatus is adjusted for long waves (say 6000 metres) than when it is adjusted for short waves (say 1000 metres). This is of obvious significance when taken with the fact that signal waves of great length are most suitable for communication over great distances. Now the most striking difference between signals received from long and from short distances is that in the former case the curvature of the earth may exert appreciable, perhaps very great, influence on the signal intensity.

This immediately raises the question of the manner of propagation of long electric waves round the earth. The fact is now thoroughly established that signal-bearing waves can travel a quarter of the way round the globe and still be easily perceptible. That this is not a manifestation of ordinary

the atmosphere, which, on account of their doubtful origin, have been called "X's."

Although the mathematical theory of electric wave propagation through space was worked out by Clerk Maxwell more than 50 years ago, and notwithstanding all the experimental evidence obtained in laboratories concerning the nature of these waves, yet so far we understand but incompletely the true fundamental principles concerning the manner of propagation of the waves on which wireless telegraph transmission is based. For example, in the early days of wireless telegraphy it was generally believed that the curvature of the earth would constitute an insurmountable obstacle to the transmission of electric waves between widely separated points. For a considerable time not sufficient account was taken of the probable effect of the earth connection, especially in regard to the transmission of oscillations over long distances.

Physicists seemed to consider for a long time that wireless telegraphy was solely dependent on the effects of free Hertzian radiation through space, and it was years before the probable effect of the conductivity of the earth was considered and discussed.

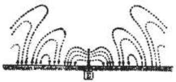


FIG. 11.

Lord Rayleigh, in referring to transatlantic radiotelegraphy, stated in a paper read before the Royal Society in May, 1903, that the results which I had obtained in signaling across the Atlantic suggested "a more decided bending or diffraction of the waves round the protuberant earth than had been expected," and further said that it imparted a great interest to the theoretical problem.[1] Prof. Fleming, in his book on electric wave telegraphy, gives diagrams showing what may be taken *to* be a diagrammatic representation of the detachment of semiloops of electric strain from a simple vertical wire (fig. 11).

As will be seen, these waves do not propagate in the same manner as does free radiation from a classical Hertzian oscillator, but instead glide along the surface of the earth.

Prof. Zenneck[2] has carefully examined the effect of earthed receiving and transmitting aerials, and has endeavored to show mathematically that when the lines of electrical force, constituting a wave front, pass along a surface of low specific inductive capacity—such as the earth—they become inclined forward, their lower ends being retarded by the resistance of the conductor, to which they are

[1] Proc. Roy. Soc., vol. 72, p. 40.
[2] "Annalen der Physik," vol. 23, p. 846, "Physikalische Zeitschrift," 1906, pp. 50, 553.

attached. It therefore would seem that wireless telegraphy as at present practiced is, to some extent at least, dependent on the conductivity of the earth, and that the difference in operation across long distances of sea compared to over land is sufficiently explained by the fact that sea water is a much better conductor than is land.

The importance or utility of the earth connection has been sometimes questioned, but in my opinion no practical system of wireless telegraphy exists where the instruments are not in some manner connected to earth. By connection to earth I do not necessarily mean an ordinary metallic connection as used for wire telegraphs. The earth wire may have a condenser in series with it, or it may be connected to what is really equivalent, a capacity area placed close to the surface of the ground. It is now perfectly well known that a condenser, if large enough, does not prevent the passage of high-frequency oscillations, and therefore in this case, when a so-called balancing capacity is used, the antenna is for all practical purposes connected to earth.

I am also of opinion that there is absolutely no foundation in the statement which has recently been repeated to the effect that an earth connection is detrimental to good tuning, provided of course that the earth is good.

Certainly, in consequence of its resistance, what electricians call a bad earth will damp out the oscillations, and in that way make tuning difficult; but no such effect is noticed when employing an efficient earth connection.

In conclusion, I believe that I am not any too bold when I say that wireless telegraphy is tending to revolutionize our means of communication from place to place on the earth's surface. For example, commercial messages containing a total of 812,200 words were sent and received between Clifden and Glace Bay from May 1, 1910, to the end of April, 1911; wireless telegraphy has already furnished means of communication between ships and the shore where communication was before practically impossible. The fact that a system of imperial wireless telegraphy is to be discussed by the imperial conference, now holding its meetings in London, shows the supremely important position which radiotelegraphy over long distances has assumed in the short space of one decade. Its importance from a commercial, naval, and military point of view has increased very greatly during the last few years as a consequence of the innumerable stations which have been erected, or are now in course of construction, on various coasts, in inland regions, and on board ships in all parts of the world. Notwithstanding this multiplicity of stations and their almost constant operation, I can say from practical experience that mutual interference between properly equipped and efficiently tuned instru-

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may be regarded as very small in itself. But, in the present case, the result is so completely inexplicable by the ordinary conceptions of the propagation of electric waves through the atmosphere, that we are compelled by its refusal to fit into the accepted scheme of things to attempt an extension of that scheme. Now, in searching for an explanation of these twilight minima, we have to notice that there are two main alternative possibilities. In the first place, the atmospheric discharges that produce the strays may themselves, for some reason, become temporarily infrequent at twilight; and, in the second place, the space through which the waves travel may become temporarily less easily traversed in twilight. The former alternative, when taken in conjunction with the author's experience over nearly 20° of longitude that it is the receiving station's local time which is concerned, implies that the bulk of the strays received at a given station are produced by atmospheric discharges occurring in regions of the atmosphere that have the same sunset and sunrise as that station; or, in other words, implies that the strays observed have their origin at places on (roughly) the meridian of the receiving station. Evidence has been already quoted, however, to show that the larger proportion of the strays observed at any station usually originate at a great distance from the station; hence the alternative under discussion leads to the unlikely conclusion that every station receives its strays from atmospheric discharges occurring at a great distance along its own meridian, and from that place solely.

We turn, therefore, to the other alternative, that the propagation of electric waves towards any place is hindered by some unknown effect of twilight. That this latter alternative is really the correct one is strongly indicated by observations (to be described later) on artificial electric waves coming from considerable distances.

Electric waves travelling near the earth's surface might conceivably be affected by the presence or absence of the sun at a point of observation in two obvious ways: First, light may ionise the air locally in sufficient degree to cause considerable absorption of the energy of the waves; and, secondly, sunlight might affect the electrical resistance of the ground within, say, 50 miles round the antenna, and thus have an effect on the absorption of the waves when they run over this region. Considering the former hypothesis first, the atmospheric absorption by ionisation due to solar radiation must, if it exists, be greater in strong sunshine than during twilight, which is contrary to observation. In point of fact, the absorption arrived at in this manner is, as will be shown incidentally later, much too small at any time of day to produce the effects actually observed. Moreover, it has long been known that the propagation of electric waves over short distances is aggregate area of the representative marks in any convenient intervals of time. The value of this time integral taken over, say, two minutes, is treated as the ordinate corresponding to the middle moment of the interval, which is taken as abscissa and a smooth curve drawn. But an even rougher method, consisting of counting the number of marks in each two minutes' interval, and using these numbers as ordinates corresponding

FIG. 2.—Strays, November 14, 1909. Sun rises at 7.17 A.M.

FIG. 3.—Strays, November 13, 1911. Sun sets at 4.13 P.M.

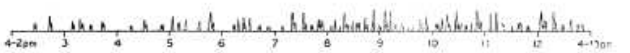

FIG. 4.—Strays, November 23, 1911. Sun sets at 4.0 P.M.

FIG. 5.—Strays. December 9, 1911. Sun sets at 3.50 P.M.

to the mid-times, may suffice in many cases. Of course, a theoretically more perfect procedure would be to pass the detector currents through a sensitive galvanometer possessing a heavy moving system. A time record of the deflections indicated by the instrument would, at first sight, give a better quantitative result than the hand-made record just described; but actual trials show that there is an increase of accuracy only when the strays are very numerous, more numerous, in fact, than on the average occasion. Adopting, then, the method already described, we obtain curves such as that of fig. 6. These observations were made at the author's laboratory in London.

The scientific value or importance of an isolated result like the present one

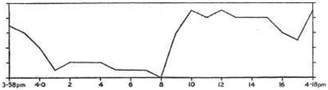

FIG. 6.—Integral Intensity Curve, Sunset, December 9, 1911.

ments has so far been almost entirely absent. Some interference does without doubt take place between ships, in consequence of the fact that the two wave lengths adopted in accordance with the rules laid down by the international convention, are not sufficient for the proper handling of the very large amount of messages transmitted from the ever increasing number of ships fitted with wireless telegraphy. A considerable advantage would be obtained by the utilization of a third and longer wave to be employed exclusively for communication over long distances.

In regard to the high-power transatlantic stations, the facility with which interference has been prevented has to some extent exceeded my expectations. At the receiving station situated at a distance of only 8 miles from the powerful sender at Clifden, during a recent demonstration arranged for the Admiralty, messages could be received from Glace Bay without any interference from Clifden when this latter station was transmitting at full power on a wave length differing only 25 per cent from the wave radiated from Glace Bay, the ratio between the maximum recorded range of Clifden and 8 miles being in the proportion of 750 to 1.

Arrangements are being made to permanently send and receive simultaneously at these stations, which, when completed, will constitute in effect the duplexing of radiotelegraphic communication between Ireland and Canada.

The result which I have last referred to also goes to show that it would be practicable to operate at one time, on slightly different wave lengths, a great number of long-distance stations situated in England and Ireland without danger of mutual interference.

The extended use of wireless telegraphy is principally dependent on the ease with which a number of stations can be efficiently worked in the vicinity of each other.

Considering that the wave lengths at present in use range from 200 to 23,000 feet, and moreover that wave group tuning and directive systems are now available, it is not difficult to foresee that this comparatively new method of communication is destined to fill a position of the greatest importance in facilitating communication throughout the world.

Apart from long-distance work, the practical value of wireless telegraphy may perhaps be divided into two parts, (1) when used for transmission over sea and (2) when used over land.

Many countries, including Italy, Canada, and Spain, have already supplemented their ordinary telegraph systems by wireless-telegraphy installations, but some time must pass before this method of communication will be very largely used for inland purposes in Europe generally, owing to the efficient network of land lines already existing which render further means of communication unnecessary; and therefore it is probable that, at any rate for the present, the main use of radiotelegraphy will be confined to extra-European countries, in some of which climatic conditions and other causes absolutely prohibit the efficient maintenance of land-line telegraphy. A proof of this has been afforded by the success which has attended the working of the stations recently erected in Brazil on the upper Amazon.

By the majority of people the most marvelous side of wireless telegraphy is perhaps considered to be its use at sea. Up to the time of its introduction, ships at any appreciable distance from land had no means of getting in touch with the shore throughout the whole duration of their voyage. But those who now make long sea journeys are no longer cut off from the rest of the world; business men can continue to correspond at reasonable rates with their offices in America or Europe; ordinary social messages can be exchanged between passengers and their friends on shore; a daily newspaper is published on board most of the principal liners, giving the chief news of the day. Wireless telegraphy has on more than one occasion proved an invaluable aid to the course of justice—a well-known instance of which is the arrest, which took place recently through its agency, of a notorious criminal when about to land in Canada.

The chief benefit, however, of radiotelegraphy lies in the facility which it affords to ships in distress of communicating their plight to neighboring vessels or coast stations; that it is now considered indispensable for this reason is shown by the fact that several governments have passed a law making a wireless-telegraph installation a compulsory part of the equipment of all passenger boats entering their ports.

connected to an earth plate. The inductance was usually about 6×10^6 cm., and the natural period of the antenna was about 50,000 per second—which corresponds to a wave-length of about 6000 metres. This frequency was selected merely because it was of the same order of magnitude as that of the Marconi Transatlantic stations, signals from which were also being measured from time to time. The antenna inductance engaged inductively with another coil forming part of a secondary circuit that could be tuned to the antenna by aid of a variable condenser in it. A detector and telephone were connected with the circuit in the ordinary way. The Pickard zincite-chalcopyrite detector was used.

With such apparatus several ways of making and recording observations present themselves. The easiest and most obvious method consists in listening at sunrise and sunset to the noises made in the telephone by the natural electric wave trains; other methods involve the use of a galvanometer in place of a telephone receiver. The observations in this paper were practically all made with the telephone. A careful listener will find that on a typical morning the following phenomena appear:—First, starting to listen about half an hour before sunrise, the strays heard in the telephone are loud and numerous and much as they have been all night; then about 15 minutes before sunrise a change sets in, the strays get weaker and fewer rather quickly, till at about 10 minutes before sunrise a distinct lull occurs, of perhaps a minute's duration. At this period there is sometimes complete silence. Then the strays begin to appear again, and within 10 minutes of the lull they have settled down to the steady stream proper to the daytime. These day strays are weaker and fewer than the night strays, except on rare occasions. The lull is sometimes very pronounced, and at other times there is no lull at all. It is usually more marked at sunset than at sunrise.

The simplest way of representing these events, just as they are heard in the telephone, is by a hand-written record of the sounds. With practice, it becomes easy to make pencil marks on paper ruled in convenient units of time in such a way that the height of the mark represents the intensity of the sound, and the general shape of the mark the duration and character of the sound. Some of the records that have been obtained in this way are reproduced in figs. 2 to 5. These are selected out of a large number of records as examples of the different kinds of minima obtained at both sunrise and sunset. It will be noticed that at sunset the minimum is about 10 minutes after the calendar time of setting. Records such as these can be made to yield quantitative results of sufficient accuracy for the discussion of so irregular a phenomenon, by plotting rough estimates of the time integral of the intensity of the strays, that is, by estimating the

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radius of two or three hundred miles of the receiving station.) During the winter months, on the contrary, the number and intensity of the strays are relatively regular. The study of the phenomena belonging to the strays of distant origin may clearly be more favourably pursued in the winter than in summer, since the confusing feature of local lightning discharge is absent in winter. Besides the seasonal variations in the number and the intensity of the strays there is at every station a well-marked diurnal variation. Leaving out the irregularities due to local storms, we may say that the strays are in general more frequent and numerous during the night hours than during the day hours. The variations may be represented graphically as a curve in any of the methods indicated below and then they appear as shown in fig. 1, which may be regarded as a typical 24 hours' continuous record of the integral of number and intensity. These diurnal

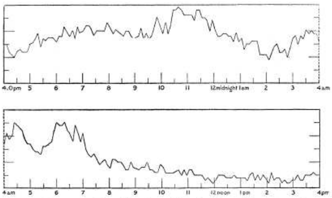
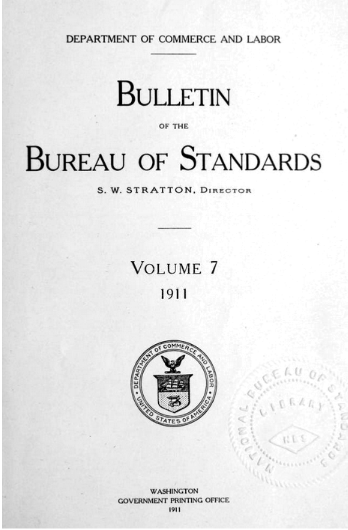


Fig. 1.—Twenty-four hours' Continuous Record of Integral Intensity of Strays, November 14 and 15, 1910.

variations have not yet been investigated thoroughly. The author has not been able to find any account of observations in which the effects of local storms have been eliminated.

From what has been said it is plain that the most interesting parts of the diurnal curve are those at which day and night conditions meet and change one into the other. To investigate these important parts of the curve the ordinary apparatus of a wireless telegraph station may be utilised. The apparatus employed by the author consisted of an antenna of 12 wires sloping from south to north at an angle of about 45° from a height of 170 feet, connected at the bottom to a coil of variable inductance, which was in turn

Some Quantitative Experiments in Long-Distance Radiotelegraphy
By: L.W. Austin, 1911



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1911

SOME QUANTITATIVE EXPERIMENTS IN LONG-DISTANCE RADIOTELEGRAPHY

By L. W. Austin

During December, 1909, and the spring and summer of 1910 the Navy Department carried on long-distance wireless tests between the scout cruisers *Birmingham* and *Salem* and the large Fessenden station at Brant Rock, which was leased by the Government for this purpose. These tests were primarily for the determination of the range of communication between the two cruisers and between the cruisers and the Brant Rock station. The United States Naval Wireless Laboratory had charge of the taking of certain quantitative measurements in connection with these tests, and this enabled us to obtain scientific data in regard to the laws which govern the radiation and reception of electrical waves, and, what was of especial interest, to study the course of the so-called atmospheric absorption up to a distance of about one thousand miles. The following paper contains the results of this work.

It was shown by Duddell and Taylor[1] in experiments carried on between a land station and the steamer *Monarch* in the Irish Sea that the received current over water fell off very nearly in proportion to the distance. This law has since been verified by Tissot.[2]

As the data obtained during the July experiments were by far the most full and accurate, all the theoretical deductions have been based on these results and the others have been employed only for comparison and verification. The Brant Rock station, situated directly on the shore 20 miles south of Boston, employs for its antenna a steel tower 420 feet high and 3 feet in diameter thoroughly insulated at its base. From the top of the tower extend four arms 50 feet in length and from each of these two 300-foot cylindrical cages are drawn out by means of guys at an angle of

[1] W. Duddell and J. E. Taylor, Electrician, **55**, p. 260; 1905.
[2] C. Tissot, Electrician, **56**, p. 848; 1906.

On the Diurnal Variations of the Electric Waves Occurring in Nature, and on the Propagation of Electric Waves Round the Bend of the Earth.

By W. H. Eccles, D.Sc., A.R.C.Sc.

(Communicated by Sir Arthur W. Rücker, F.R.S. Received March 5,—Received in revised form June 5,—Read June 27, 1912.)

Since the earliest days of electric wave telegraphy it has been known that there exist natural electric waves which frequently affect the receiving apparatus at a wireless telegraph station more powerfully than do the message-bearing waves. In the telephonic method of receiving signals, where the apparatus is so arranged that the effect of a train of waves is to cause a pulse of electric current to pass from the "detector" through the telephones, the natural electric waves make themselves evident as clicks, or as rattling noises, in the telephones. They are easily distinguished from signals, for the sounds produced by the latter are more regular, and, in fact, are often musical in character. The natural electric waves are doubtless due to electric discharges taking place between masses of electrified air, or between such masses and the earth. Till recently it was not known whether the discharges affecting any particular station were taking place at distances of hundreds of miles or at distances of thousands of miles from the station; but it is now certain that for stations in England the distances concerned must usually be reckoned in thousands of miles. This point was settled by tracing and identifying individual natural wave trains at two receiving stations, one in London and the other in Newcastle.* It was found that about 70 per cent. of the natural wave trains perceived at one station could be identified with those perceived at the other, and, further, that more than half of these were of much the same intensity at both stations—from which it may fairly be inferred that the distance of the discharge is great compared with the distance between the stations.†

The number of natural wave trains, or "strays" as they are commonly called for brevity, received at any station varies in general from hour to hour. In England these variations are most pronounced during the summer months, principally on account of the frequency of local lightning storms during these months. (The word local is here intended to mean within a

* Eccles and Airy, 'Roy. Soc. Proc.,' 1911, A, vol. 85.
† In all that follows it is assumed that the sources of the wave trains are not extra-terrestrial.

7 to 30 amperes antenna heights 37 to 130 feet, wave lengths from 300 to 3750 meters, and distances up to 1000 nautical miles.

In regard to the value of the day absorption it is only possible to say that the above expression is satisfied within the limits of error of the observations. It is quite possible that when observations are made at distances of 2000 to 3000 miles, the value of the absorption coefficient will have to be corrected by 10 or even 20 per cent, as this amount of error could exist without discovery at the distances covered in these experiments. It is also possible that the square root law relating the absorption with the wave length is only an approximation.

U. S. Naval Wireless Telegraphic Laboratory,
Washington, February 1, 1911.

about 45°. This forms a system of eight conductors spaced symmetrically about the tower. These cages are approximately 4 feet in diameter and consist of four wires each, separated by a system of hoops. The cages are insulated at the bottom and electrically connected to the steel tower at its top, thus forming a type of umbrella antenna. The inductance of the complete antenna system amounts to 0.055 millihenry, and the capacity is 0.0073 microfarad. The closed circuit was inductively coupled to the antenna just loosely enough so that but one wave length[3] was radiated. The closed circuit condensers were of the well-known Fessenden compressed-air type, and for a wave length of 3750 meters the capacity was 0.18 microfarad. The spark gap was of the Fessenden synchronous rotary type with two fixed electrodes and a system of rotary electrodes mounted on the shaft of the generator. The generator was rated at 100 kilowatts at 500 cycles, thus producing 1000 sparks per second. It was not possible to run the generator at full power with the steam engine available at the time of the experiments, the actual power expended being 50 to 60 kilowatts.

The scout cruisers were provided with flat top antennas supported by steel masts surmounted by wooden topmasts. The antenna dimensions were: Length 116 feet, breadth 40 feet, number of longitudinal wires 14, cross wires 15. During the December test, the height above the water was approximately 112 feet, but this height was increased in the three later tests to 130 feet. The capacity was about 0.0018 microfarad and the inductance 0.038 millihenry. During the May experiments the capacity of the *Birmingham* was increased by two 70-foot cages forward and two 80-foot cages aft set at an angle of approximately 30° with the vertical. These cages were similar to those forming the umbrella of the Brant Rock tower. This increased the capacity to about 0.0025. In the midst of the July tests, cages were added to the *Salem* also, but the change resulted in no observable variation in the intensity of the signals, the increase in capacity being apparently counterbalanced by the decrease in effective height. The closed circuit was coupled to the antenna, so that but one wave length was radiated, and the closed circuit capacity was 0.036 microfarad at 3750

[3] Experience has shown that when the closed circuit is properly designed—that is, without undue waste of energy from brushing, etc.—the greatest range is obtained by a coupling loose enough to give but one wave length in the antenna.

meters, and 0.018 microfarad at 1000 meters wave length. The motor generators were 500-cycle machines rated at 10 kilowatts, and the spark gap was of the same type as that used at Brant Rock but of smaller dimensions.

JULY EXPERIMENTS

I_S. Sending antenna current in amperes.
I_R. Received antenna current through 25 ohms.
N. Night observations.
K. Received antenna current at 1 kilometer distance.
d. Distance in kilometers.
h. Height of flat top antenna.
α. Day absorption coefficient = 0.0015.
λ. Wave length.
H. Stat. Heavy static = atmospheric discharges preventing reception of signals.
Miles. Nautical mile = 1.85 kilometers.
For good communication. $I_R = 40 \times 10^{-6}$ amperes through 25 ohms $= 4 \times 10^{-8}$ watts.
For audible signals. $I_R = 10 \times 10^{-6}$ amperes through 25 ohms $= 2.5 \times 10^{-9}$ watts.

Preliminary experiments were begun early in July, the scout cruisers lying at anchor in the harbor at Provincetown, 22 miles from Brant Rock. The path of the waves between the ships and the shore station, except for a narrow strip of sand hills bounding Provincetown Harbor, lay entirely over water. Later, when the ships put to sea, it was found that this strip of land made no appreciable difference in the received signals. Careful measurements were made on the intensity of the received antenna current at Brant Rock for the two wave lengths 1 000 meters and 3 750 meters. This current was measured either by means of a hot-wire ammeter of 15 ohms resistance, provided with a mirror for mirror and scale readings,[4] or by a tellurium constantan thermo-element,[5] also of 15 ohms resistance. The hot wire ammeter gave a scale deflection of about 0.2 millimeter for 1 milliampere oscillatory current in the antenna and 9.4 millimeters for 10 milliamperes. One millimeter galvanometer deflection with the thermo-element was equivalent to 263 microamperes, and the deflections

[4] L. W. Austin, Electrical World, **49**, p. 308; 1907.
[5] This Bulletin, **7**, p. 304.

heights of from 30 to 80 feet and wave lengths from approximately 1500 to 4000 meters.

(c) Taking account of the influence of antenna height and wave length equation (2) may be extended and a general day transmission formula written as follows

$$(3) \quad I_R = 4.25 \frac{I_s h_1 h_2}{\lambda d} e^{-\frac{0.0015 d}{\sqrt{\lambda}}}$$

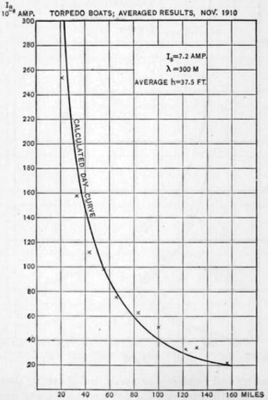

Fig. 28

where the currents are given in amperes and all lengths in kilometers.[19] This formula has been tested for sending currents from

[19] From this it would appear that it is advisable to rate stations according to the magnitude of the antenna current, or perhaps better, according to the product of the current into the height.

Variations also appear to occur during the daytime, but these are probably in general small.

(*b*) The received antenna currents between two stations with salt water between are proportional to the product of the heights [18]

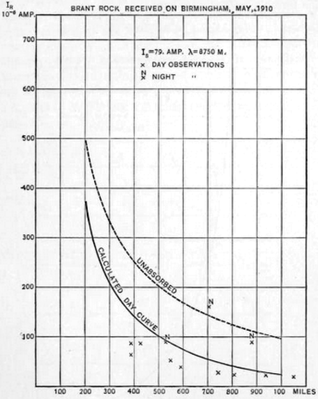

Fig. 27

of the sending and receiving antennas and inversely proportional to the wave length, provided the antenna resistances remain constant. These experiments were carried on with flat-top antenna

[18] The experiments indicate that for the greatest efficiency of a flat-top antenna the vertical lead wires should be bunched so as to reduce their capacity as much as possible and concentrate the capacity at the greatest height.

were, as nearly as could be determined, directly proportional to the square of the oscillatory current. For the 1000-meter wave length a variable air condenser was placed in series with the Brant Rock antenna, and in this way it was possible to adjust the antenna resistance for both wave lengths to about 25 ohms. From a number of observations it was determined that the received current at Brant Rock for a wave length of 1000 meters was 10 500 microamperes for the *Birmingham*, with a sending antenna current of 33 amperes,[6] and 11 000 microamperes for the *Salem*, corresponding to a sending antenna current of 27 amperes. For a wave length of 3750 meters the received currents were 3200 microamperes for the *Birmingham* and 4100 microamperes for the *Salem*, corresponding to sending antenna currents of 27 and 24 amperes.

After the ships had attained distances too great to permit the reading of the received signals at Brant Rock by means of thermoelements, a chalcopyrite zinkite rectifier with galvanometer was employed whenever the atmospheric disturbances permitted. This was connected in a secondary circuit coupled to the antenna and calibrated by means of a thermoelement in the antenna and an exciting buzzer circuit which could be tuned to the wave length used.[7]

Throughout the experiments, both at Brant Rock and on shipboard, shunted telephone readings were taken on the incoming signals. The detectors used for the shunt readings were of the free wire electrolytic type and the head telephones connected in series were each of 600 ohms resistance,[8] the shunt being placed across one of these according to the Fessenden method. The circuits for the galvanometer and for the shunt readings at Brant Rock are shown in Fig. 1.

An extended comparison of antenna currents through circuit A and the shunt readings as taken in circuit B was made, and the

[6] It will be noticed that while the radiation current of the *Birmingham* is considerably greater than that of the *Salem*, the strength of received signal is slightly less. It is possible that the apparently greater radiation of the *Birmingham* was due to a deck insulator which gave trouble throughout the July test. It is not improbable, therefore, that the actual antenna current was not greater than that of the *Salem*. The mean of the readings of the two ships, 30 amperes at a wave length of 1000 meters, has been taken as a basis for calculation.

[7] See this Bulletin, 7, p. 295.

[8] The inductive resistance of each telephone used in calculating the shunt ratio was 2000 ohms.

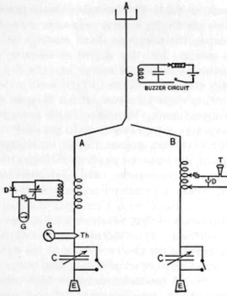

Fig. 1

TABLE I

Shunts on 600-Ohm Telephone with Electrolytic Detector, and Antenna Current Through 25 Ohms

Shunt Ohms	Antenna Current 10^{-6} Amp.	Shunt Ohms	Antenna Current 10^{-6} Amp.
0.5	672	25	95
.6	614	30	87
.7	568	40	76
.8	530	50	68
1.0	474	70	58
2	336	100	49
3	274	150	40
4	237	200	35
5	212	300	29
6	194	400	26
8	168	600	22
10	150	1000	18
12	137	2000	15
15	122	3000	13
20	106	∞	10

wave length and which may be expressed mathematically by the term e^{-Ad}.

The complete expression for the received current is then

$$(2)\quad I_R = \frac{K}{d} e^{-Ad}$$

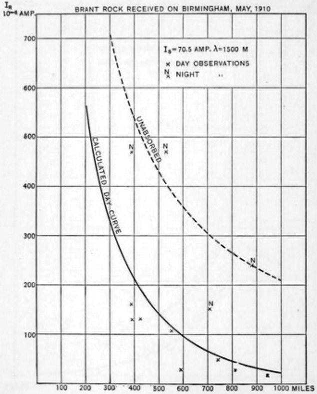

Fig. 26

This is true in general for day transmission. The absorption at night is entirely irregular varying from zero to the day value,[17] but is on an average much less during the winter than in summer.

[17] The great variations in night absorption make useless all attempts to judge the quality of wireless apparatus from night distances. For this purpose only observations on the average day range have any value.

SUMMARY AND CONCLUSIONS

Quantitative measurements have been carried out in long distance wireless telegraphy up to 1000 miles for the purpose of determining the law of the variation of strength of signal with distance.

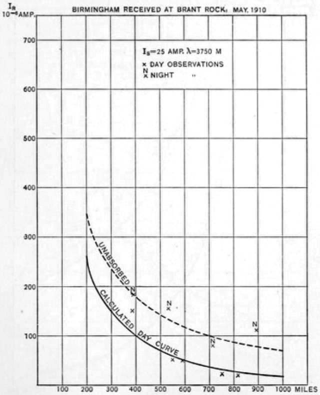

Fig. 25

Supplementary work was also done on the effect of height of antenna and wave length on sending and receiving.

The results are given briefly as follows:

(*a*) Over salt water the electrical waves decrease in intensity in proportion to the distance as found by Duddell and Taylor. In addition they are subject to an absorption which varies with the

results are shown in Table I. The table shows the amount of current in an antenna having a total resistance of 25 ohms which would correspond to the telephone shunt readings on a detector coupled to the antenna with the degree of coupling capable of drawing the maximum amount of energy into the detector.[9]

Shunt readings are very difficult to take even under the best circumstances. In a quiet laboratory it has been found possible to make them agree among themselves with average errors in the single observations not greater than 10 per cent. In a wireless station, with its varying degree of noise, especially if the station is on shipboard, the errors are much greater than this, amounting under ordinary circumstances with good operators to from 20 to 40 per cent; while in a stormy time, or when the atmospheric discharges are heavy, the observed strength of signal will often be only a small fraction of that which would have been observed under normal conditions. It is evident that most of these sources of error tend to decrease the observed value of the signal. Occasionally, however, a loose contact or a loose plug where plug resistance boxes are used, will produce abnormally high values. Then, too, the difference in ear sensitiveness of different operators produces variations in the record. For this reason it is necessary that a very large number of observations be taken to make the results of much value.

As the received currents given in the curves and tables are proportional to the square root of the loudness of signal, the percentage errors are of course smaller than the errors in taking the shunt readings.

The standard of audibility taken in this work is that strength of signal which permits a clear differentiation of the dots and dashes.

The *Birmingham* sailed from Provincetown early on the morning of July 14, taking a course nearly south until she had attained a distance of about 1200 miles from Brant Rock. The *Salem*

[9] The actual amount of current in the antenna for the same intensity of signal in the detector varies with the effective resistance, which in turn depends on the wave length and amount of tuning inductance. The energy in the detector, required to produce given signals is constant, however. This energy is what is actually measured in taking shunt readings, and for convenience of comparison its square root is put in terms of micro amperes through 25 ohms which was the resistance actually employed in the thermoelement readings at Brant Rock, and which is approximately the effective resistance of a properly coupled ship's antenna of moderate size at a wave length of 1000 meters.

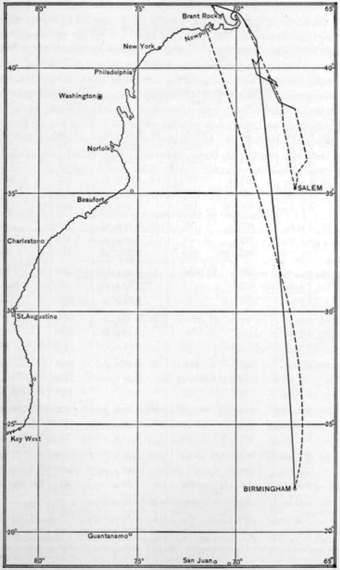

Fig. 2

curve as calculated from Table XVI for antenna heights of 37.5 feet, a sending current of 7.2 amperes, and a wave length of 300 meters. The agreement is remarkable, considering the fact that the table from which the theoretical curve was calculated was based on data derived from ships with 130-foot masts working at

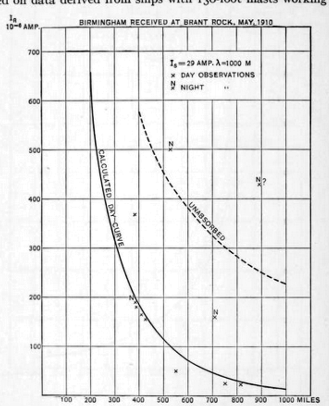

Fig. 24

a wave length of 1000 meters and employing a spark frequency of 1000 per second. These results show, as has often been observed in our laboratory, how little the ratio of sending currents and received signals depends on the spark frequency, the telephones apparently never showing the added sensitiveness for high frequencies exhibited in the case of sinusoidal alternating currents.

mately 1.12. The telephones on both boats were of approximately the same sensitiveness and were of 2000 ohms resistance with an inductive resistance under working conditions of about 4000 ohms.

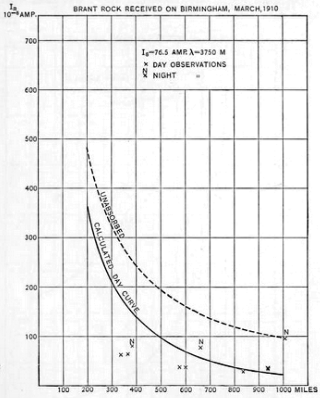

Fig. 23

The observations of these tests, shown in Table XVII, were taken with great care, the engines being stopped during the time of observation. Each one is the mean of a number of readings.

In the last column are given the received currents averaged for both boats corrected to a sending current of 7.2 amperes and to the readings of the electrolytic detector. In Fig. 28 is shown the

TABLE II

Birmingham Received at Brant Rock

July		λ=1000 M. I_s=33 amp. Distance, Nautical Miles	λ=1000 M. I_s=33 amp. Received Current 10^{-6} amp.		July		λ=3750 M. I_s=27 amp. Distance, Nautical Miles	λ=3750 M. I_s=27 amp. Received Current 10^{-6} amp.	
14	8 a. m.	22	10500	Galvanometer	14	8.30 a. m.	22	3000	Galvanometer
	2 p. m.	50	4600			3.30 p. m.	60	1370	
	8 p. m.	110	N 2100			9.30 p. m.	120	N 520	
15	8 a. m.	256	520		15	9.30 a. m.	266	180	
	2 p. m.	335	157			3.30 p. m.	345	67	
	8 p. m.	415	N 336			9.30 p. m.	425	N 77	
16	8 a. m.	550	77		16	9.30 a. m.	560	49	
	2 p. m.	626	54			3.30 p. m.	636	H. Stat.	
	8 p. m.	702	N 210			9.30 p. m.	712	N 106	
17	8 a. m.	854	H. Stat.		17	9.30 a. m.	864	26	
	2 p. m.	927				3.30 p. m.	937	Stat.	
	8 p. m.	1000	N 19			9.30 p. m.	1010	N 10	
18	8 a. m.	1170	H. Stat.		18	9.30 a. m.	1170		
	2 p. m.	1185	H. Stat.			3.30 p. m.	1185		
	8 p. m.	1200	N 51			9.30 p. m.	1200	N 44	
19	8 a. m.	1152	H. Stat.		19	9.30 a. m.	1152	26	
	2 p. m.	1103	H. Stat.			3.30 p. m.	1103		
	8 p. m.	1035	N 210			9.30	1025	N Not send	
20	8 a. m.	890	35		20	9.30 a. m.	880	26	
	2 p. m.	841	29			3.30 p. m.	831		
	8 p. m.	772	N 240			9.30 p. m.	762	N Not send	
21	8 a. m.	648	26		21	9.30 a. m.	638	26	
	2 p. m.	559				3.30 p. m.	549		
	8 p. m.	470	N 150			9.30	460	N Not send	
22	8 a. m.	320	210		22	9.30 a. m.			
	2 p. m.	240				3.30 p. m.			
	8 p. m.	190				9.30 p. m.			

followed on the morning of July 15 and proceeded slowly to a point about 450 miles from Brant Rock. The courses of the two ships are shown in figure 2. Regular sending and receiving periods were observed at the three stations. At Brant Rock the signals were received as far as possible on the thermoelement and a few readings were taken with the rectifier, but while the preceding week had been almost completely free from atmospheric disturbances, unfortunately, soon after the ships sailed, strong disturbances set in which precluded the possibility of galvanometer measurements, so that for the rest of the experiments all the readings had to be taken by the shunted telephone method. On the ships no attempt was made to use deflection methods, although

TABLE III

Brant Rock Received on Birmingham

July		$\lambda=1500$ m, $I_s=56$ amp. Distance, Nautical Miles		$\lambda=1500$ m, $I_s=56$ amp. Received Current 10^{-6} amp.	July		$\lambda=3750$ m, $I_s=69$ amp. Distance, Nautical Miles		$\lambda=3750$ m, $I_s=69$ amp. Received Current 10^{-6} amp.
15	10.15 a. m.	290		336	15	10.45 a. m.	295		120
	10.15 p. m.	445	N	274		10.45 p. m.	450	N	63
16	10.15 a. m.	580		58	16	10.45 a. m.	585		
	10.15 p. m.	727	N	160		10.45 p. m.	732	N	77
17	10.15 a. m.	885		28	17	10.45 a. m.	890		
	10.15 p. m.	1040	N	106		10.45 p. m.	1045	N	37
18	10.15 a. m.	1180		Stat.	18	10.45 a. m.	1185		
	10.15 p. m.	1215	N	130		10.45 p. m.	1215	N	110
19	10.15 a. m.	1115		Stat.	19	10.45 a. m.	1110		30
	10.15 p. m.	1005	N	106		10.45 p. m.	1000	N	212
20	10.15 a. m.	850		37	20	10.45 a. m.	845		28
	10.15 p. m.	730	N	336		10.45 p. m.	725		Not send
21	10.15 a. m.	600		150	21	10.45 a. m.	595		51
	10.15 p. m.	435	N	194		10.45 p. m.	430	N	54
22	10.15 a. m.	275		390	22	10.45 a. m.	270		Not send
	10.15 p. m.	115	N	336		10.45 p. m.	110		Not send

TABLE XVII

	Distance, Nautical Miles	Stringham Received on Bailey $\lambda=340$ m: I_S amp.	Received Current 10^{-6} amp.: Observed	Received Current 10^{-6} amp.: Corrected to $I_S=7.2$ amp.	Bailey Received on Stringham $\lambda=280$ m: I_S amp.	Received Current 10^{-6} amp.: Observed	Received Current 10^{-6} amp.: Corrected to $I_S=7.2$ amp.	I_R Average of Received Currents Corrected to Electrolytic and to $I_S=7.2$ amp. 10^{-6} amp.
Nov. 3, 1910	21.5	5.45	170	225	5.4	....	....	253
	33	6.00	132	159	5.1	87	123	158
	43	6.14	68	80	5.1	86	121	112
	55	6.00	58	70	5.1	76	107	99.0
Nov. 7,	65	6.27	55	63	7.5	75	72	75.5
	83	6.54	51	56	7.5	57	55	62.2
	100	6.00	39	47	7.2	45	45	51.6
Nov. 8,	122	6.55	23.9	26	7.0	32	33	33.0
	131	6.27	24.5	28	7.0	33	34	34.8
	156	6.82	Interference		7.0	18	18.6	20.9

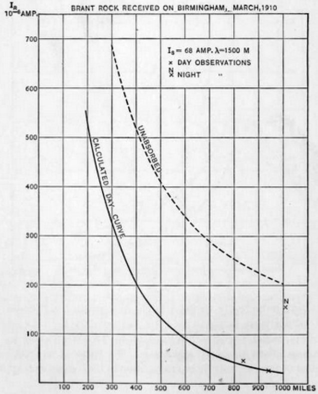

Fig. 22

The antenna of the *Stringham* consisted of four wires 2 feet apart, 135 feet long, and 48.5 feet above the water. Its capacity was 0.00134 microfarad. The closed circuit condenser was the same as that of the *Bailey*. The length of the *Stringham's* radiated wave was 340 meters. The receiving apparatus of both boats was of

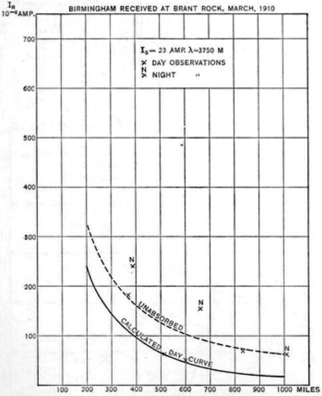

Fig. 21

the latest inductively coupled type, and perikon detectors were used which were standardized by comparison with electrolytic detectors, which experiments have shown to have a constant sensitiveness when properly adjusted. The ratio of current sensitiveness of the electrolytic to the perikon in both cases was approxi-

it is possible that satisfactory measurements could have been taken by means of marine galvanometers. Tables II to VI contain the data of the experiments, the received signals being reduced to terms of current through 25 ohms antenna resistance.

TABLE IV

Salem Received at Brant Rock

July		λ=1000 m I_s=27 amp. Distance, Nautical Miles		Received Current 10^{-6} amp.	July		λ=3750 m I_s=23 amp. Distance, Nautical Miles		Received Current 10^{-6} amp.
					15	6 a. m.	22		4400
15	5 a. m.	22		11000		9 a. m.	52		1420
	8 a. m.	45		5000		3 p. m.	70		1250
	2 p. m.	60		3600		9 p. m.	117	N	* 613
	8 p. m.	117	N	2170					
16	8 a. m.	125		2250	16	9 a. m.	130		693
	2 p. m.	105		2275		3 p. m.	110		* 567
	8 p. m.	137	N	1328		9 p. m.	140	N	* 474
17	8 a. m.	207		* 1062	17	9 a. m.	210		* 274
	2 p. m.	190		646		3 p. m.	190		* 500
	8 p. m.	196	N	400		9 p. m.	196	N	* 179
18	8 a. m.	249		580	18	9 a. m.	250		* 237
	2 p. m.	270		520		3 p. m.	275		* 274
	8 p. m.	290	N	410		9 p. m.	295	N	* 194
19	8 a. m.	366		200	19	9 a. m.	370		* 106
	2 p. m.	394		182		3 p. m.	400		* 115
	8 p. m.	425	N	* 672		9 p. m.	430		Not send
20	8 a. m.	322		325	20	9 a. m.	315		Not send
	2 p. m.	254		582		3 p. m.	245		Not send
	8 p. m	181	N	Stat.		9 p. m.	175		Not send

* Telephone readings

Wherever possible the readings taken by the deflection method are used. During the experiments the atmospheric disturbances were heavy most of the time, especially at night and at the longer wave length. These frequently entirely prevented the reception of the signals as indicated by the blanks in the received current column. No table is given for Brant Rock received on the *Salem*, because during a great part of the time the signals were too strong for accurate shunt readings. No tables are given for the work between the two cruisers at a wave length of 3 750 meters, as their antennas seemed too small to work successfully at this

TABLE V

"Salem" Received on "Birmingham"

July		λ=1000 m I_s=27 Amp.		
		Distance, Nautical Miles		Received Current 10^{-6} Amp.
15	8 a. m.	253		170
	2 p. m.	274		196
	8 p. m.	312	N	120
16	8 a. m.	420		87
	2 p. m.	521		54
	8 p. m.	574	N	87
17	8 a. m.	661		21
	2 p. m.	750		20
	8 p. m.	840	N	30
18	8 a. m.	960		Stat.
	2 p. m.	972		Stat.
	8 p. m.	960	N	46
19	8 a. m.	828		10
	2 p. m.	720		26
	8 p. m.	618	N	46
20	8 a. m.	589		43
	2 p. m.	566		54
	8 p. m.	555	N	69
21	8 a. m.	666		46
	2 p. m.			
	8 a. m.			

TABLE VI

"Birmingham" Received on "Salem"

July		λ=1000 m I_s=33		
		Distance, Nautical Mile		Received Current 10^{-6} Amp.
15	8.30 a. m.	256		160
	2.30 p. m.	278		150
	8.30 p. m.	315	N	105
16	8.30 a. m.	425		60
	2.30 p. m.	526		43
	8.30 p. m.	579	N	63
17	8.30 a. m.	666		H. Stat.
	2.30 p. m.	755		H. Stat.
	8.30 p. m.	845	N	38
18	8.30 a. m.	960		10
	2.30 p. m.	972		10
	8.30 p. m.	960	N	10
19	8.30 a. m.	823		10
	2.30 p. m.	715		Stat.
	8.30 p. m.	613	N	77
20	8.30 a. m.	584		38
	2.30 p. m.	561		38
	8.30 p. m.	555		Messages
21	8 30 a. m.	661		38

wave length and only a few unsatisfactory shunt readings were obtained.

For determining the law of the decrease of the intensity of the signal with the distance a smooth curve was drawn through the observed day readings and points on this were taken as the

with small 120-cycle directly connected sending sets which, however, could be coupled loosely enough so that but one wave length was radiated. The flat-top antenna of the *Bailey* consisted of four wires 2 feet apart, 80 feet long, 32 feet above the water. The

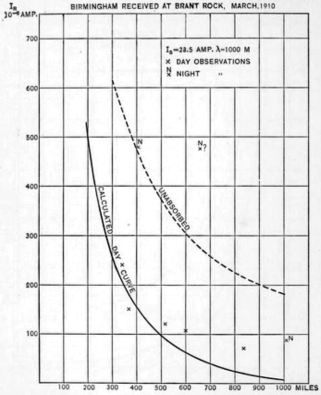

Fig. 20

antenna capacity was 0.000875 microfarad; the closed circuit condenser consisted of Leyden jars in air having a capacity of 0.015 microfarad. The length of the wave radiated by the *Bailey* was 280 meters.

of long range night communication must be considered exceptional so late in the year, though perhaps it would not be so considered in midwinter.

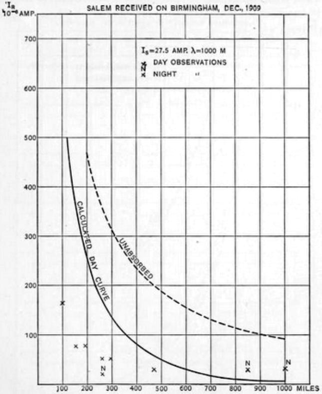

Fig. 19

TORPEDO-BOAT TESTS

In order to test the validity of equation (3) for very short wave lengths and small antennas, the torpedo boats *Stringham* and *Bailey* were detailed to carry out a series of tests in Chesapeake Bay during the month of November, 1910. The two boats were fitted

TABLE VII

Birmingham Received at Brant Rock, July

Nautical Miles	d Km	I_S=33 amp. λ=1000 m. K=475000 10^{-6} amp.			I_S=27 amp. λ=3750 m. K=138000 10^{-6} amp.		
		$\frac{K}{d}$ 10^{-6} amp.	I_R 10^{-6} amp. Obs.	I_R 10^{-6} amp. Cal.	$\frac{K}{d}$ 10^{-6} amp.	I_R 10^{-6} amp. Obs.	I_R 10^{-6} amp. Cal.
20	37	12830	11500	12200	3730	3500	3620
50	92.5	5135	4600	4460	1492	1400	1385
100	185	2565	2100	1940	746	700	645
200	370	1283	800	737	373	260	280
300	555	856	260	370	249	120	161
400	740	642	130	212	187	60	105
500	925	514	80	128	149	40	73
600	1110	428	50	81.5	124	30	52
800	1480	321	35	35	93	24	29
1000	1850	257	20	15.4	75	22	18

TABLE VIII

Brant Rock Received on Birmingham, July

Nautical Miles	d Km	I_S=56 amp. λ=1500 m K=310000.10^{-6} amp.			I_S=69 amp. λ=3750 m K=160000.10^{-6} amp.		
		$\frac{K}{d}$ 10^{-6} amp.	I_R 10^{-6} amp. Obs.	I_R 10^{-6} amp. Cal.	$\frac{K}{d}$ 10^{-6} amp.	I_R 10^{-6} amp. Obs.	I_R 10^{-6} amp. Cal.
20	37	8380		8000	4325		4200
50	92.5	3350		2980	1730		1610
100	185	1675		1340	865		750
200	370	838		533	432		324
300	555	558	320	283	288	120	187
400	740	419	160	170	216	85	121
500	925	335	80	108	173	65	84.5
600	1110	279	52	72.5	144	52	60.8
800	1480	209	38	34.7	108	40	34.1
1000	1850	167	25	17.1	87	30	20.6

observed values for purposes of calculation. It was assumed from the results of Duddell and Taylor and Tissot that the received currents would be inversely proportional to the distance provided no absorption existed. The observed curve indicated that this was approximately true up to a point between 100 and 200 miles, but beyond this point the currents evidently dropped much more rapidly. The simplest assumption in regard to absorption is that it is proportional to the distance. Joining this to the Duddell and Taylor law we have as an expression for the received current

$$I_R = \frac{K}{d} e^{-Ad} \qquad (1)$$

where *d* is the distance, *K* the received current at unit distance, e the base of the natural logarithms, and *A* a constant. Dr. Louis Cohen of the National Electric Signaling Co., while testing the validity of this formula made the discovery that *A* was inversely proportional to the square root of the wave length within the limits of accuracy of the observations. Then, writing $A = \frac{\alpha}{\sqrt{\lambda}}$ the expression becomes

$$I_R = \frac{K}{d} e^{-\frac{\alpha d}{\sqrt{\lambda}}} \qquad (2)$$

α is the absorption coefficient and in these experiments equals 0.0015, the distance and wave length being expressed in kilometers.

Tables VII to XI contain a comparison of the calculated values with those taken from the smoothed observation curves. It is seen that the agreement is exceedingly good in the case of the signals between the *Birmingham* and the *Salem* and those of the *Salem* received at Brant Rock. In the case of the signals between Brant Rock and the *Birmingham*, however, the observed values fall somewhat below the calculated, from 300 to 600 miles. As the observed curve has the same form both for the signals received on the *Birmingham* and those received at Brant Rock the divergence is probably not accidental, and is probably due to a temporary increase of absorption accompanying a marked change in the weather at about this time. The effect is not observed in the *Salem* signals received at Brant Rock because the *Salem* at this time had not attained a great enough distance to make the absorption play an important part.

and the short wave at 1305 miles. Night signals from Brant Rock were first received at 2776 miles and were heard without interruption from that point on. Both waves from the *Birmingham* were received faintly in the daytime at Brant Rock at 2090

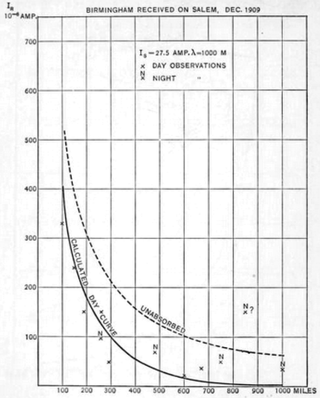

Fig. 18

miles, and the long wave again at 1315 miles, no other day signals being received until the distance was reduced to 815 miles. Night signals were received by Brant Rock from the *Birmingham* first at 2418 miles and continued nightly for the rest of the voyage, though very irregular in intensity. This remarkable continuation errors of observation, or possibly to some kind of reflection from the upper atmosphere.[16] Beyond the range of the curves abnormal signals were again observed, faint day signals of the Brant

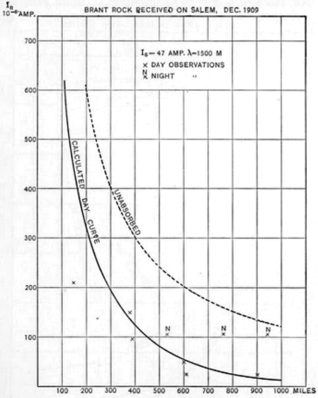

Fig. 17

Rock long wave being received on the *Birmingham* at 2330 miles,

[16] There can be no doubt that at times something of the nature of a reflection of signals from the upper atmosphere takes place. During the past winter the Norfolk station sending at a wave length of 1000 meters and with an antenna current of 10 or 12 amperes and antenna height below 200 feet was distinctly heard at night at the Mare Island Navy Yard in San Francisco, a distance of approximately 2000 nautical miles across the continent. Although it is possible that over sea water a clearing up of the atmospheric absorption would have explained this phenomenon, when we take into account the ground absorption which is probably independent of day and night and generally much greater than the atmospheric absorption, this explanation becomes untenable.

TABLE IX

"Salem" Received at Brant Rock, July

Nautical Miles	d Km	I_S = 27 Amp. λ = 1000 m K = 490000 10^{-6} Amp.			I_S = 23 Amp. λ = 3750 m K = 170000 . 10^{-6} Amp.		
		$\frac{K}{d}$ 10^{-6} Amp.	I_R 10^{-6} Amp.		$\frac{K}{d}$ 10^{-6} Amp.	I_R 10^{-6} Amp.	
			Obs.	Cal.		Obs.	Cal.
20	37	13250	12000	12500	4595	4500	4460
50	92.5	5300	4700	4610	1838	1800	1710
100	185	2650	2200	2000	919	850	800
150	278	1760	1200	1170	612	500	495
200	370	1325	750	760	459	330	344
300	555	883	370	382	306	190	198
400	740	662	200	218	230	115	129
500	925	530	130	132	184	88	90

TABLE X

Salem Received on Birmingham, July

Nautical Miles	d Km	I_s = 27 amp. λ = 1000 m. K = 230000 10^{-6} amp.		
		$\frac{K}{d}$ 10^{-6} amp.	I_R 10^{-6} amp.	
			Obs.	Cal.
20	37	6220		5880
50	92.5	2486		2160
100	185	1243		941
200	370	622	325	357
300	555	414	165	179
400	740	311	95	102
500	925	249	65	62
600	1110	207	45	39.4
800	1480	155	19	17.1
1000	1850	124	10	7.5

TABLE XI

Birmingham Received on Salem, July

Nautical Miles	d Km	I_s = 33 amp. λ = 1000 m. K = 185000 10^{-6} amp.		
		$\frac{K}{d}$ 10^{-6} amp.	I_R 10^{-6} amp.	
			Obs.	Cal.
20	37	5000		4730
50	92.5	2000		1740
100	185	1000		757
200	370	500	260	287
300	555	333	130	144
400	740	250	75	82.4
500	925	200	50	49.9
600	1110	167	35	31.7
800	1480	125	16	13.8
1000	1850	100	10	6.2

The curves of figures 3 to 10 give the results in graphic form. The dotted line gives the strength of signal which would have been received if the K/d law had obtained; that is, if there had been no absorption. The continuous curve gives the theoretical day values as calculated from equation 2, while the individual observations

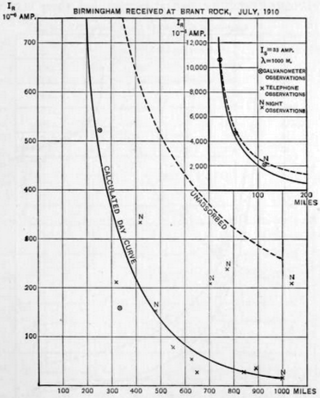

Fig. 3

are represented by crosses. Observations taken by the deflection method are indicated by circles around the crosses, while night observations are accompanied by the letter N. It is seen that the day observations correspond approximately to the values of the calculated curve, but that the night signals are entirely irregular,

Birmingham at 2550 miles, while on the same night both waves from the *Birmingham* were received at Brant Rock.

MAY EXPERIMENTS

During the month of May the *Birmingham* returned from Liberia to Hampton Roads, and the results of the telephone observations taken during this voyage are shown in figures 24 to 27.

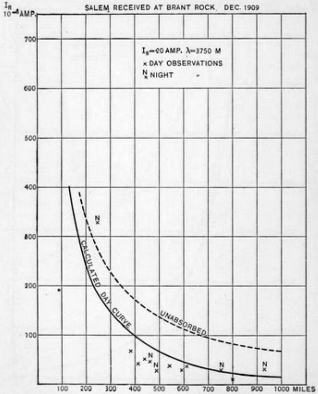

Fig. 16

Within the range covered by the curves the day observations are not as irregular as during the March voyage, although, as was also the case in March, some of the night observations lie above the curve calculated for zero absorption. As has already been said in describing the July experiments, these may be due to

In some of the curves it is seen that the observations are exceedingly irregular, the day signals showing as much variation as the night signals during the July tests. In addition to the observations shown on the curves, faint day signals from the *Birmingham* were received at Brant Rock at a distance of 1325 miles, and again at 1720 miles, while the Brant Rock short wave was received

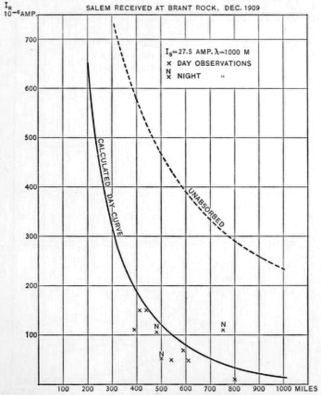

Fig. 15

faintly on the *Birmingham* at 1325 miles. All of these observations are beyond the range of calculated day audibility and show that there was an abnormally low absorption on these days.

Night signals during this voyage were also heard at times at great distances, the Brant Rock short wave being received on the

being in general stronger than the day signals, as was first observed by Marconi. Sometimes they lie close to the K/d curve, indicating that the absorption has disappeared, while at others they are practically of the same strength as the day readings. In a very few cases, night signals were observed considerably stronger than the calculated value for zero absorption, but these may very

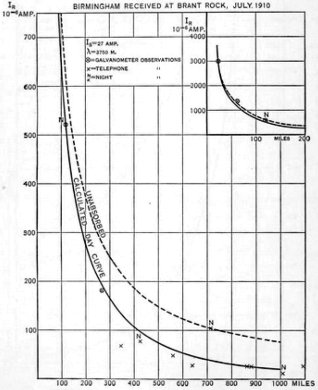

Fig. 4

probably be due to errors of observation, since it is not observed that the remarkable strength of signal is reciprocal between the two stations. If the observations are genuine, however, it would perhaps indicate some kind of reflection from the upper layers of the atmosphere.

THE CAUSE OF THE ABSORPTION

According to the calculations of Zenneck,[10] the conductivity of air at moderate heights can not explain the magnitude of the observed absorption, neither can the sea-water absorption be of

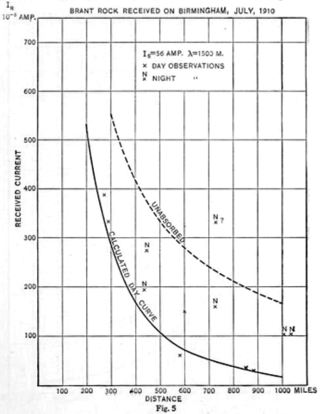

Fig. 5

the proper magnitude, according to the same author. But as the wave front at any considerable distance from the sending station must extend far into the upper layers of the atmosphere, it does not seem improbable that this is the region of absorption. If

[10] Zenneck, Ann. d. Phys., **23**, p. 846; 1907.

The arrangement of the apparatus on the cruisers was highly unsatisfactory, largely on account of lack of space. In addition to this the weather was extremely tempestuous much of the time. In the light of all this, it is not surprising that the observed received currents fell below the calculated values.

The results are shown in the curves of Figs. 12 to 19.[15]

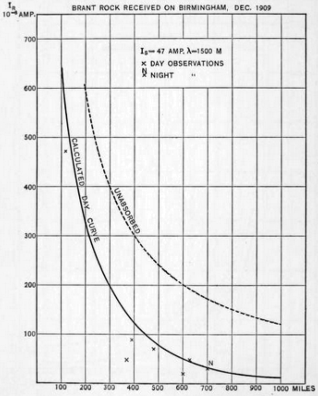

Fig. 14

MARCH EXPERIMENTS

In March the *Birmingham* was sent to Liberia, and during the voyage current measurements were made on the ship and at Brant Rock. The results are shown in Figs. 20 to 23.

[15] Neither of the cruisers was able to take any satisfactory measurements on the 3750-meter wave.

all this into account, the results of these earlier tests can not by any means be considered to have the same weight as those in July. But as it is desirable to obtain all the light possible on the validity of the transmission formula, the following observations are given.

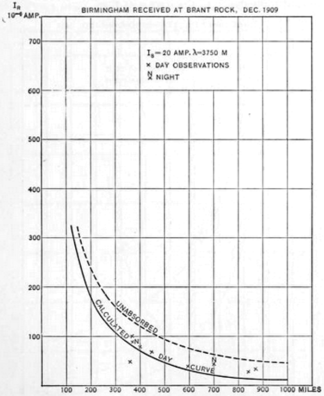

Fig. 13

DECEMBER EXPERIMENTS

The December experiments were made shortly after the installation of the sets on the cruisers, the *Birmingham* taking an easterly course from Provincetown, while the *Salem* sailed to the southward. At the greatest distance attained the two ships were distant from each other and from Brant Rock approximately 1000 miles.

the conductivity is increased by the sun's rays at these heights, this would also explain the differences in the strength of the day and night signals. The observations would indicate, if this explanation is true, that the excessive ionization may, especially in

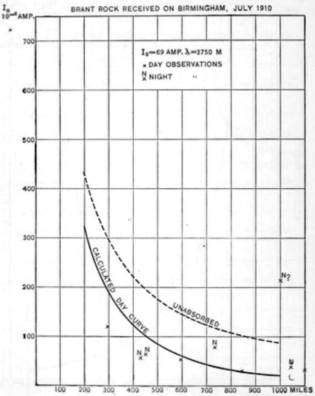

Fig. 6

summer, persist through many nights. The general experience of wireless telegraphy would indicate that during the colder months the absorption dies out more uniformly at night. The day absorption appears from the data obtainable to be fairly uniform throughout the year, at least in the portion of the ocean covered by our observations, although there are undoubtedly variations at times, as has been already mentioned in regard to the *Birmingham*-Brant Rock signals. There are well-authenticated instances

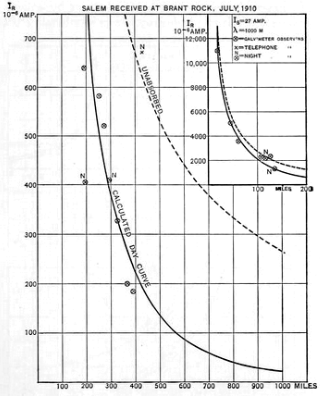

Fig. 7

when, for a day or two, the absorption seems to nearly disappear in the daytime. A case in point is that of the long-distance day signals between the *Birmingham* and Brant Rock on the return voyage from Liberia mentioned on page 351.

OTHER LONG-DISTANCE WORK

In all of the experiments with the cruisers excepting those carried on during the month of July the calculated received currents at unit distance were estimated from the ratio of the sending cur-

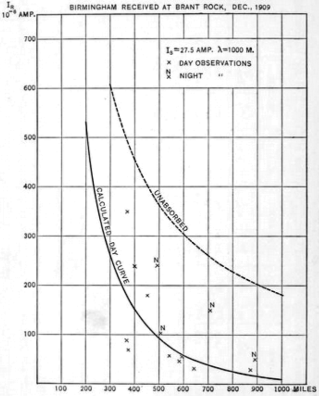

Fig. 12

rents to those observed at the corresponding stations in July, account of course being also taken of the change in antenna heights on the cruisers from 112 feet to 130 feet after the close of the December tests. This calculation is somewhat arbitrary, since there were many changes in the arrangement of the apparatus which very probably had an influence on the efficiency of the sets. Taking

TABLE XVI–A

Sending Currents Required to Produce Received Currents as Given in Table XVI for Various Antenna Heights

$h_1=h_2$	I_S amp.	$h_1=450$ ft. h_2	I_S amp.	$h_1=200$ ft. h_2	I_S amp.	$h_1=130$ ft. h_2	I_S amp.	$h_1=100$ ft. h_2	I_S amp.
32.5 ft.	480	32.5 ft.	34.5	32.5 ft.	78	32.5 ft.	120	32.5 ft.	156
65	120	65	17.3	65	39	65	60	65	78
100	51	100	11.3	100	25.3	100	39	130	39
130	30	130	8.7	130	19.5	160	24.4	160	31.8
160	19.8	160	7.1	160	15.8	200	19.5	200	25.4
200	12.7	200	5.6	300	8.5	300	13	300	16.9
300	5.66	300	3.76	450	5.65	450	8.7	450	11.3
450	2.5								

SUPPLEMENTARY MEASUREMENTS

PROPORTIONALITY OF SENDING AND RECEIVING CURRENTS

It was thought possible that when the antennas were used with the highest power, especially at the longer wave lengths, there might be losses of energy, either by brushing or by leakage over the insulators, which might destroy the proportionality between

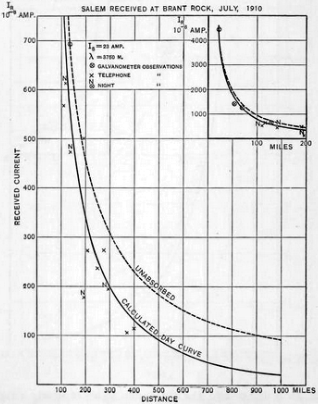

Fig. 8

sending antenna current and received antenna current. To settle this question, the station at Brant Rock sent with varying powers at a wave length of 3750 meters. The signals were received on the antenna at the Bureau of Standards at Washington, D. C., 380 miles away. The receiving antenna was of the harp form, 180 feet high at top, 40 feet high at bottom, and 18 feet wide, with 8 wires. The capacity was approximately 0.0012 microfarad. A chalcopyrite zinkite rectifier, with a sensitive galvanometer, was connected in a tuned secondary circuit coupled to the antenna

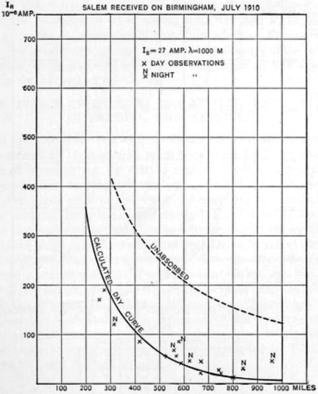

Fig. 9.

inductance so as to give maximum deflection, the circuits being those shown under circuit A in Fig. 1. The results are shown in the curve of Fig. 11. The galvanometer deflections are proportional to the square of the current, hence the square roots of the deflections expressed in microamperes of received antenna current are compared with the sending antenna current at Brant Rock.

TABLE XVI

Currents in Microamperes Received Through 25 Ohms for a Sending Current of 30 Amperes and Sending and Receiving Flat Top Antenna Heights of 130 Feet, over Salt Water

[Calculated from Eq. 3]

Nautical Miles	d Km	λ=300 m		λ=600 m		λ=1000 m		λ=1500 m		λ=2500 m		λ=3750 m		λ=6000 m	
		$K=6.67.10^5$		$K=3.33.10^5$		$K=2.10^5$		$K=1.33.10^5$		$K=8.10^4$		$K=5.33.10^4$		$K=3.33.10^4$	
		$\frac{K}{d}$	I_R	$\frac{K}{d}$	I_R	$\frac{K}{d}$	I_R	$\frac{K}{d}$	I_R	$\frac{K}{d}$	I_R	$\frac{K}{d}$	I_R	$\frac{K}{d}$	I_R
20	37	18000	16300	9000	8350	5400	5100	3590	3430	2160	2080	1440	1400	900	880
50	92.5	7200	5600	3600	3020	2160	1880	1435	1282	864	790	576	536	360	340
100	185	3600	2170	1800	1270	1080	817	720	573	431	361	280	249	180	161
200	370	1800	650	900	433	540	310	359	228	216	152	144	108	90	71.8
300	556	1200	263	600	205	360	156	240	122	144	85	96	62.4	60	42.7
400	740	900	116	450	107	270	89	180	73	108	53.6	72	40.8	45	28.6
500	925	720	55.4	360	60.2	216	53.8	144	46.3	86.4	35.9	57.6	28.2	36	20.5
600	1110	600	27.6	300	34.8	180	34.2	120	31.1	72	25.3	48	20.4	30	15.2
800	1480	450	7.72	225	12.8	135	14.7	90	14.8	54	13.1	36	11.5	22.5	9.06
1000	1850	360	2.27	180	4.97	108	6.7	72	7.5	43.1	7.42	28.8	6.77	18	5.80
1200	2220	300	0.66	150	2.0	90	3.24	60	3.95	36	4.36	24	4.34	15	3.89
1500	2780	240	0.12	120	0.54	72	1.10	48	1.58	28.8	2.04	19.2	2.25	12	2.18
2000	3700	180	0.0081	90	0.069	54	0.205	36	0.385	21.6	0.64	14.4	0.817	9	0.928
2500	4630	144	....	72	0.0086	43.2	0.038	24.8	0.098	17.3	0.213	11.5	0.318	7.2	0.418
3000	5560	120	....	60	0.0010	36	0.0079	24	0.031	14.4	0.073	9.1	0.129	6.0	0.198

currents and four wave lengths. The table shows the great advantage of long wave lengths for very distant stations. It is seen that for good communication at a distance of 2500 miles not less than 240 amperes [13] must be used at a wave length of 6000 meters, though one-fourth of this would be audible.

For the purpose of easily calculating the probable day working distance for various sending currents, heights, and wave lengths according to equation (3) Tables XVI and XVI-A are given. Table XVI gives the current which may be expected to be received through 25 ohms for an antenna height at both stations of 130 feet and a sending antenna current of 30 amperes. Table XVI-A gives the sending currents which will be required for various heights of the sending and receiving antennas h_1 and h_2 to give the values of the received currents as shown in Table XVI. To determine the current which will be received for any antenna height, wave length, and distance for a given sending current, multiply the value, given in Table XVI for the given distance and wave length, by the given current, divided by the value of I_s in Table XVI-A for the given antenna heights.[14] In Table XVI it may be assumed that 40×10^{-6} ampere insures good communication and that 10×10^{-6} ampere is just audible.

[13] From the experience of the Marconi transatlantic stations it would appear possible that for the same antenna current the distances given in the table could be obtained with a smaller antenna height provided a bent antenna were used.

[14] Example: If $h_1=200$ feet, $h_2=130$ feet, $\lambda=600$ meters, distance=500 miles, and $I_S=12$ amperes, then $I_R=60.2 \times 12/19.5=37.0 \times 10^{-6}$ ampere. The above tables have been given in this convenient form for calculation largely with the hope that they will be tested by the experience of the various wireless companies. It is very common in wireless stations to have an antenna meter for the measurement of the sending current. When this is used with a shunt, the multiplying value of the shunt for the given frequency may easily be obtained by connecting a like unshunted hot-wire meter in the antenna in series with the regular instrument and sending with reduced power so that the needle of the unshunted meter just remains on the scale. The ratio of the readings of the two meters then gives the multiplying value. When only one meter is available an approximate calibration may be obtained by sending with reduced power and observing the reading of the meter without the shunt and then with the shunt connected. Of course this calibration must be carried out with the same wave length used in regular work. The range of good daylight communication with another flat-top antenna of known height over sea water can be compared with the values in the table for the given wave length, distance, and sending current, provided the sending station radiates but a single wave length. If the equation is correct, the tables should indicate a current of from 20 to 40 microamperes.

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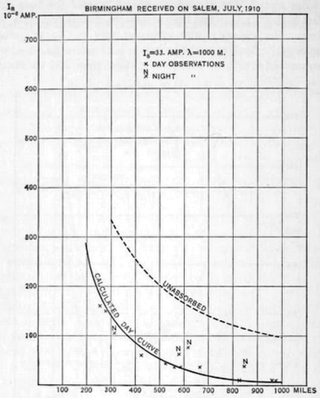

Fig. 10

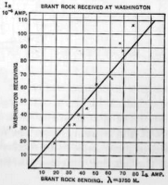

Fig. 11

The proportionality is fairly good. It is possible that in the changes of adjustment of the circuits at Brant Rock the tuning became somewhat deranged, or that the change of the coupling at Brant Rock produced a change in the damping of the waves, which was not compensated for by a change in the coupling at Washington. A few observations were taken at Brant Rock on signals sent from the *Birmingham* when coming into Newport, R. I., both at wave lengths of 1000 meters and 3750 meters. From these it was concluded that there was no marked overloading of the sending antenna, although there were slight indications in this direction at the wave length of 3750 meters.

THE EFFECT OF ANTENNA HEIGHT AND WAVE LENGTH IN SENDING AND RECEIVING

At the close of the test with the scout cruisers, a flat top antenna was erected at Plymouth, 11 miles from Brant Rock, for the purpose of investigating the relationship of height of antenna and wave length to sending and receiving. Except for a narrow sand spit the whole path of the waves between the two stations lay over water. The antenna was swung between two noninsulated steel masts in order to reproduce as fully as possible the conditions on board ship. The Plymouth antenna had a length of 110 feet and consisted of 11 wires 2 feet apart. The capacity was approximately 0.001 microfarad. The Plymouth station was furnished with a 2-kilowatt, 500-cycle Fessenden sending set, and a somewhat larger 500-cycle set used at Brant Rock. The currents were measured at both stations by means of 15-ohm thermoelements with galvanometers as described on page 317. The experiments were begun by my assistants, but were completed by Dr. Cohen of the National Electric Signalling Co.

SENDING

Table XII gives the results of observations taken by Dr. Cohen and his assistants, Plymouth being the sending station and Brant Rock the receiving. This table is for the most part self-explanatory. The deflections of the galvanometer connected to the thermoelement are proportional to the square of the current, so that the square roots of these deflections are taken as proportional to the current itself. The deflections are in arbitrary units. For

much as 30 per cent under ordinary conditions. This difference in the value of the constant does not, however, make a very great difference in the range of communication, although for short distances it would make a considerable difference in the loudness of signal. To show the variation in range of communication with different antenna currents, Table XIV is given, showing the range of communication between two flat top antennas 130 feet high at a wave length of 1000 meters for various values of the sending antenna current, assuming that 40×10^{-6} ampere assures good communication. A quarter of the indicated current would produce audible signals under favorable conditions. The table shows how very slowly the range increases with increasing sending current. Increasing the current from 30 to 60 amperes increases the distance only from 565 miles to about 725 miles, while even with 10 amperes, corresponding to a moderately efficient 2-kilowatt set, 345 miles is easily reached.

In columns 3 and 5 are given the distances attainable for regular communication and audibility on the assumption that there is no atmospheric absorption; that is, the extreme range of night communication.[12]

TABLE XV

Good Working Distance and Sending Current for Two Stations with Flat Top Antennas 450 Feet High

Nautical Miles	$\lambda=1000$ m	$\lambda=2500$ m	$\lambda=3750$ m	$\lambda=6000$ m
1000	15 amp.	13.5 amp.	15 amp.	17 amp.
1250	38	27	27	30
1500	91	49	44	46
1750	200	95	77	74
2000	490	155	122	105
2250		245	200	160
2500		470	314	235
2750			500	335
3000			775	500

In Table XV is given the estimated day range of two large stations with flat-top antennas 450 feet high for various antenna

[12] Excluding the possibility of the effects of reflection from the upper atmosphere.

We may write this equation as follows:

$$I_R = 4.25 \frac{I_s h_1 h_2}{\lambda d} e^{-\frac{\alpha d}{\sqrt{\lambda}}} \qquad (3)$$

where I_R represents the current received through 25 ohms resistance, I_s the sending current, h_1 the height of one antenna, h_2 that of the other, d, the distance between the stations, and λ the wave length, where all the lengths are taken in kilometers and the currents in amperes. α is the absorption coefficient, which in our experiments was found to be equal to 0.0015. This disregarding the absorption term $e^{-\frac{\alpha d}{\sqrt{\lambda}}}$, corresponds in form to the Herzian equation for the electromotive force in a vertical resonator at a distance from the oscillator.

TABLE XIV

Calculated Relation between Antenna Current and Distance for Two Ships with Antenna Heights of 130 Feet

$\lambda = 1000$ m

Antenna Current I_S	Working Distance 40.10^{-6} amp.		Extreme Distance of Audibility 10.10^{-6} amp.	
	Day	Night (Zero Absorption)	Day	Night (Zero Absorption)
1 amp.	75 miles	90 miles	200 miles	360 miles
2	135	180	300	720
3	180	270	375	1080
5	235	450	475	1800
7	280	630	550	2520
10	345	900	630	3600
15	420	1350	725	5400
20	475	1800	790	7200
25	525	2250	840	9000
30	565	2700	900	10800
40	630	3600	970	14400
50	685	4500	1025	18000
60	725	5400	1150	21600

In our formula the constant 4.25 applies strictly only to ship antennas with the same losses due to masts, rigging, etc., both in sending and receiving, as found on the scout cruisers. On other ships the value of the constant might probably differ by as

comparison, the square roots of the deflections were reduced to a uniform sending antenna current. These values are given under I_R in the next to the last column, while the last column gives this quantity divided by the height. Although there is considerable

TABLE XII

Plymouth Received at Brant Rock

$\lambda = 3900$ m

Antenna Plymouth h	I_S	Deflection Receiving D	$I_R = \sqrt{D}$ reduced to $I_S = 4.7$ amp.	$\frac{I_R}{h}$
80 ft.	4.7 amp.	62.3	7.9	0.099
70	4.6	34	5.95	.085
60	4.7	30.3	5.5	.092
50	4.85	24.1	4.76	.095
40	4.9	15.6	3.79	.095
30	5.1	7.4	2.51	.084

$\lambda = 1585$ m[1]

h	I_S	D	I_R ($I_S = 5.5$ amp.)	$\frac{I_R}{h}$
70 ft.	5.5 amp.	292	17.1	0.244
60	5.5	198	14.1	.235
50	5.65	110.7	10.2	.204
40	6.05	84	8.32	.207
30	6.3	62	6.88	.229

h = 80 ft.
35 ohms added in receiving antenna

λ	I_S	D	I_R ($I_S = 4.2$ amp.)	$I_R \times \lambda$
3900 m.	4.2 amp.	4.0	2.0	7800
2980	4.5	8.3	2.69	8030
2400	4.75	13.6	3.26	7830
1985	5.1	26.3	4.22	8400

[1] Shorter wave lengths were not used on account of the long natural wave length of the Brant Rock station.

variation in the values of this column it is evident that there is no systematic variation, and for the individual wave lengths we must consider that the received current is proportional to the height of the sending flat-top antenna. The receiving antenna was tuned by means of a variable inductance in series with the thermo-element.

In the last section of Table XII the results show the variation with wave length, and in this case the equivalent received current is multiplied by the wave length and the product is seen to be approximately constant. Thirty-five ohms was introduced into the receiving antenna to nullify the changes in the resistance of the inductance during the process of tuning. This table shows that the received antenna current is proportional to the height of the sending attenna and inversely proportional to the wave length.

RECEIVING

Table XIII gives similar data in regard to the Plymouth antenna used for receiving, the sending station being Brant Rock. This table shows that the same relationship holds for receiving as for sending; that is, for a constant sending antenna height and current the received current is proportional to the height of the receiving antenna and inversely proportional to the wave length.[11]

While it appears that the sending and receiving relations for a flat-top antenna are reciprocal, this is apparently not the case for an umbrella antenna. It is seen from the observations that the scout cruisers, sending with 10 kilowatts, were received at Brant Rock with almost the same strength as that with which Brant Rock, sending with 60 kilowatts, was received on the cruisers. Comparing the strength of the sending and receiving currents, it appears that the umbrella antenna at Brant Rock for sending is only equivalent to a flat-top antenna 170 feet high, which is not far from the height of the lower ends of the umbrella, while for receiving its equivalent height is much greater. A few experiments have also been made on an umbrella and flat top at Plymouth, which also showed that an umbrella is a better receiver than radiator.

[11] This will not strictly hold in the case where the radiation resistance of the receiving antenna is comparable with the rest of the antenna resistance. See R. Ruedenberg, Ann. d. Phys., 25, p. 446; 1908.

TABLE XIII

Brant Rock Received at Plymouth

$\lambda = 4000$ m

Antenna Plymouth h	I_S	Deflection Receiving D	$I_R = \sqrt{D}$ reduced to $I_S = 7.0$ amp.	$\frac{I_R}{h}$
80 ft.	7.0 amp.	8.4	2.90	0 0362
70	10.0	12.4	2.46	.0352
60	9.4	8.0	2.10	.0350
50	9.75	6.0	1.76	.0352

$\lambda = 1980$

h	I_S	D	I_R ($I_S = 7.4$ amp.)	$\frac{I_R}{h}$
80 ft.	7.4 amp.	26.0	5.1	0.0637
70	7.6	24.0	4.77	.0682
60	11.1	41.1	4.28	.0713
50	10.9	22.6	3.22	.0644
40	10.4	15.5	2.80	.0700

h = 70 ft.
35 ohms added in receiving antenna

λ	I_S	D	I_R ($I_S = 10$ amp.)	$I_R \times \lambda$
4000 m	10.0 amp.	4.3	2.07	8300
3550	9.1	4.8	2.41	8560
2980	8.6	6.0	2.85	8500
2510	9.9	12.9	3.63	9110
1984	7.6	10.0	4.16	8240

Uniting the experimental data contained in the last two tables with the data obtained from the experiments with the cruisers, we may write an equation which will cover the normal day received current over salt water through 25 ohms for two stations with flat-top antennas of any height, with any value of sending current and any wave length, provided the sending station is so coupled as to give but one wave length.