GEOPHYSICAL INSTITUTE

UNIVERSITY OF ALASKA

COLLEGE ALASKA

TECHNICAL REPORT NUMBER 1

THE MEASUREMENT OF IONOSPHERIC ABSORPTION USING EXTRATERRESTRIAL RADIO WAVES

Signal Corps Contract	No. DA-36-039-SC-71137
Department of the Army Project	No. 3-99-03-022
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THE MEASUREMENT OF IONOSPHERIC ABSORPTION

USING EXTRATERRESTRIAL RADIO WAVES

C. G. Little

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Introduction

The discovery by Jansky in 1932 of the presence of radio waves incident upon the earth from outer space has led to several new methods of studying the earth's upper atmosphere. This report describes the manner in which these extraterrestrial radio waves may be used to measure the radio absorption characteristics of the ionosphere. It opens with a brief discussion of the theory of ionospheric absorption; this is followed by a description of the basic principles involved in this new technique. Two different types of equipment which may be used for this type of absorption measurement are then discussed. The report concludes with a brief summary of three types of ionospheric absorption phenomena which have been studied at various latitudes with such equipments.

Section I Summary of Theory of Ionospheric Absorption

The Appleton-Hartree magneto-ionic theory shows that a radio frequency wave will be attenuated while traversing an ionized medium in which the free electrons undergo collisions with other particles. This absorption process is analogous to a frictional loss, since the free electrons are caused to oscillate at the frequency of the incident radio wave and will give up some of their oscillatory energy, derived from the radio field, when they collide with other particles.

Quantitatively, the absorption of energy is given by

$$\text{Absorption } \mathbf{A} = -20 \log_{10} \frac{E}{E_o} \text{ decibels,}$$

where **A** is the absorption in db, E_o is the field strength of the incident plane wave, and **E** is the field strength after traversing a distance s through the ionized medium. E and E_o are related by the equation

$$E = E_o e^{-ks},$$

where

$$k = \frac{2\pi e^2}{mc} \cdot \frac{1}{\mu} \cdot \frac{N\nu}{\nu^2 + (w \pm w_L)^2}$$

In this equation, e and m are the electronic charge and mass; μ is the refractive index of the ionized medium, in which the electronic density is N and the electron collision frequency is ν ; w is the angular frequency of the incident radio wave and w_L is the angular gyromagnetic frequency corresponding to the longitudinal component of the magnetic field. The positive sign denotes the ordinary wave, the negative sign the extraordinary wave.

In studies of ionospheric absorption using extraterrestrial radio waves, the observing frequency is usually several times the critical frequency and the refractive index in the absorbing region may therefore be taken as unity. Also, the electron collision frequency in the absorbing region is usually very small compared with the radio frequency, and therefore can usually be neglected compared with $(w \pm w_L)$. Under these circumstances, the preceding equation reduces to

$$k = \frac{2\pi e^2}{mc} \cdot \frac{N\nu}{(w \pm w_L)^2}.$$

Since both N and ν will vary with height, the total absorption along the line of sight will be given by

$$A = -20 \log_{10} \frac{E}{E_o} \text{ decibels} = 8.69 \int k \; ds \; db,$$

or

$$A = \frac{8.69}{(w \pm w_L)^2} \cdot \frac{2 \pi e^2}{mc} \int N \nu \; ds \; dn.$$

A determination of A (the attenuation in db) at a single frequency can therefore be used to determine the value of $\int N\nu$ ds, since the other quantities in the above equation are all known. The measurement does not, however, give any indication of the variation of $N\nu$ with height.

Section II. Extraterrestrial Radio Waves and Ionospheric Absorption

The principle behind the use of extraterrestrial radio waves for the study of ionospheric absorption is essentially very simple. The radio noise power incident at a point outside the earth's atmosphere from a given direction in space is believed to be constant with respect to time. (See Section III for certain exceptions to this statement.) The radio noise power received on a fixed receiving system at the earth's surface should therefore be a function only of sidereal time, since each day the antenna beam will explore the same strip of sky as the earth rotates. The transparency of the earth's atmosphere at a particular instant of time is therefore given by the ratio of the signal strength actually received to that received at the same sidereal time under conditions of negligible ionospheric absorption.

In radio astronomical work it is convenient to make use of the concept of equivalent antenna temperature when one is dealing with the reception of random noise signals from diffuse sources. If a matched antenna were installed in an enclosure at temperature T degrees Kelvin, it can be shown that a power $P_n = k\ TB$ could be extracted from it, where k is Boltzman's constant and B is the observing bandwidth. Using this fact, it is possible to relate any noise power P_n, received over a given bandwidth B, to its equivalent temperature T_e given by

$$P_n = k\ T_e\ B.$$

Consider therefore the case of a receiving system whose antenna beam is fully occupied by a medium whose effective radio temperature is T_1. Under these circumstances, the antenna signal power would be given by $P_1 = K\ T_1\ B$. If now, some absorbing medium (such as the ionosphere) with a power transmission coefficient α and temperature T_2 is inserted over the full width of the antenna beam, the received signal power from the original medium would be reduced to $\alpha\ k\ T_1\ B$. However, the absorbing medium would itself radiate radio noise, in proportion to its temperature and effectiveness as an absorber. The antenna would therefore receive an additional signal,

$$P_2 = k\ (1 - \alpha)\ T_2 B,$$

from the absorbing medium.

In the case where the antenna signal is transferred to the receiver via a transmission line whose power transmission coefficient is E, the transmission line will itself act both as an attenuator and a generator of radio noise. The noise power reaching the receiver will be given by

$$E \alpha T_1\ k\ B + E(1 - \alpha)\ T_2\ k\ B + (1 - E)\ k\ T_3 B,$$

where T_3 is the temperature of the transmission line. It is assumed that the antenna and the receiver are both matched to the transmission line, and that the power transfer from the antenna to the receiver is complete apart from the effect of absorption within the transmission line.

This received noise power will add to the noise power generated within the receiver itself, which is given by the expression

$$P_r = (F-1)\ k\ TB,$$

where T is room temperature and F is the noise figure of the receiver.

If the above system is now used to observe extraterrestrial radio noise, the power output of the receiver may be written as

$$P_o = G\ (P_s + P_i + P_c + P_r + I) \qquad (1)$$

where P_o = output noise power from the receiver;

P_s = noise power from sky = $E \alpha T_s$ kB;

P_i = noise power from ionosphere= $E (1 - \alpha) T_i$ kB;

P_c = noise power from cable = $(1 - E) T_3$ kB;

P_r = noise power from receiver = $(F - 1)$ T kB;

I = power from interfering signals;

G = receiver power gain;

T_s is the effective noise temperature of the sky in the absence of any ionospheric absorption; and

T_i is the temperature of the absorbing region.

Section III. The Measurement of Ionospheric Absorption Using Extraterrestrial Radio Waves

A. With a Simple Receiver

The simplest equipment capable of ionospheric absorption measurements by the "cosmic-noise" method consists of a receiver connected to an antenna by means of a transmission line, and a monitoring system (usually a pen recorder) to measure the receiver output noise power.

The absorption measurements made with a simple receiving system such as that described above are based on the comparison of the observed values of P_o with those obtained at times of negligible absorption. After correcting, wherever possible, for variations in the other parameters in equation (1), any residual discrepancy is attributed to variations in P_s, and in particular to variations in α, the transparency of the ionosphere at the frequency concerned. It is clear that the simple equipment described above is very susceptible to variations in receiver gain G, and also to a lesser degree, to changes in P_i, P_c, P_r, and I.

These factors are discussed in the succeeding paragraphs.

1. Variations of receiver gain

It is clear from equation (1) that the accuracy of the measurements of absorption, which rely upon the comparison of P_o on different days, will be critically affected by the stability of the receiver gain, G.

For this reason, it is important to try to stabilize the gain in receivers of the type indicated above. It is therefore customary to use electronically stabilized a-c and d-c power supplies to the receiver. Further improvements in receiver gain stability can usually be obtained by using crystal-controlled local oscillators, temperature stabilization of the equipmental environments and by stabilizing the current through each radio tube.

Even when all the above steps have been taken, it is important to check the stability of the receiver. This is usually done by periodically disconnecting the antenna from the receiver and feeding a standard, fixed quantity of noise power from a noise diode source into the receiver. When possible, it is desirable that these calibrations should be done at several levels of noise diode power, since this enables the complete input-output calibration of the receiver to be checked, rather than just one point on the curve. As an example, one of the equipments at the University of Alaska makes use of a one revolution per hour electric motor and a series of micro-switches to calibrate the receiver automatically at three different levels of noise diode input power. As an additional check, the noise diode current is itself recorded continuously.

2. Variations of extraterrestrial radio noise power

In the above discussion, it has been assumed that the strength of the extraterrestrial signal reaching the earth's upper atmosphere from a particular direction in space is constant, and therefore that any variation observed at ground level can be attributed to ionospheric effects.

The sun, however, provides an important exception to this statement. At wavelengths of the order of 10 meters, the signal power from the sun when undisturbed is less than 1 per cent of the signal power from the diffuse background of radio noise observed on a wide beam antenna, and can therefore normally be neglected. When active sunspot groups are present, and also occasionally at other times, the sun's radio output at these frequencies may increase enormously and render this absorption measuring technique useless during the daytime for the duration of the activity. This must be regarded as a serious fault of the technique, since it is often at these times that one desires information on the ionospheric absorption. The effect can, however, often be limited to the major phases of the activity by utilizing a polar diagram that discriminates against the sun, e.g. an antenna beamed toward the Pole Star.

Four other minor sources of variation in P_s may be mentioned. Three of these are due to true variations in the signal power from discrete sources, namely the planets Jupiter and Venus and a source recently discovered by the Australian workers. In these cases the ratio of source signal power to diffuse background signal power is so low as to render their effects negligible on a wide beam antenna. The fourth source of variations in P_s is the scintillation of the discrete sources due to diffraction effects in the ionosphere. These scintillations take the form of variations (of period about 30 seconds) in the intensity of the localized sources, but average out for the diffuse background radiation. When one of the more intense sources, such as the Cygnus or Cassiopeia source, is in the antenna beam, these scintillations may result in fluctuations of the order of 2 or 3 per cent of the input power on a wide beam antenna; however, their effect is rarely serious, since the power received from a source, averaged over several fluctuations, is unaffected by the presence of scintillations.

The above relates to the variations in the extraterrestrial signal strength reaching the antenna. The proportion actually received by the receiver is determined by the power transfer efficiency factor, E, of the transmission line, and by the accuracy of the impedance matching at each end of the line. In order to minimize the effect of the receiver noise, it is important that the efficiency of power transfer should be as high as possible; for accurate absorption measurements, it is also important that this efficiency should remain constant with time. It is therefore usually desirable to bury any appreciable length of RF cable in the ground and to shield the remainder from direct sunlight. This serves to minimize temperature variations and any resultant variations in attenuation or impedance matching. Air or gas filled transmission lines are preferable to solid dielectric cables, since they are considerably less temperature sensitive; the gas filled lines also have the advantage of significantly lower attenuation. For accurate work, it is important to use a metal reflecting screen (usually made of parallel wires) below the antenna. This serves to eliminate the effect of changes in the electrical properties of the ground due to changing meteorological conditions. Such changes could cause significant variations in the reflection coefficient of the ground, and therefore of the antenna impedance and of the amount of power picked up by the antenna after reflection from the ground.

The above indicates design features which should be incorporated to ensure that the proportion of the antenna power that actually reaches the receiver is constant with time. Checks of the antenna and receiver input impedances and of the transmission line attenuation should be made periodically, to confirm that everything is operating as expected.

3. Radio noise from the ionosphere

The intensity of the radio noise originating in the ionosphere will normally be very small compared with that of extraterrestrial radio origin, except perhaps at low frequencies. For example, at 30 mc the equivalent antenna temperatures are about 20,000 degrees while electron temperatures in the absorbing region are not likely to be in excess of a few hundreds of degrees Kelvin. Moreover, to determine the magnitude of the ionospheric contribution to the antenna noise power, it is necessary to multiply this latter figure by the absorption coefficient, which is usually less than 10 per cent at 30 mc. Under extreme conditions, and at low frequencies, where the absorption of the extraterrestrial signal is much greater, uncertainty in the value of T_i can limit the accuracy of the measurement of the absorption.

4. Radio noise from the transmission line

In the case of radio noise from the transmission line, it is possible to correct for this source of noise since the temperature of the cable and the attenuation within it can be determined with fair accuracy. In general, however, and particularly in the case of low-loss cables, no correction is required.

5. Radio Noise generated within the receiver

All electronic devices have a certain minimum noise power generated within them due to the statistical fluctuations in the flow of the electrons. By careful design, it is possible to reduce the equivalent input noise power from a matched radio frequency amplifier to, say, three times that generated in the matched input resistor, assuming this to be at room temperature. In this case, the noise power generated within the receiver itself is 2kTB, since kTB is the noise power available from the input resistor at temperature T. The equivalent noise temperature of the receiver input due to receiver noise would therefore be about 600° Kelvin, i.e. considerably less than the equivalent antenna temperature.

For accurate work, it is clearly important to know what proportion of the output noise power is generated within the receiver, since this determines the base level from which all other signals must be measured.

Its value can be obtained by means of a noise diode calibration of the receiver input/output characteristic and of the noise factor. Periodic checks of the receiver noise figure are necessary, since it is likely to change as the input tubes age.

6. Interference

The signal powers used in these absorption measurements are weak, and the equipments are very susceptible to interfering signals, whether man-made or of natural origin. It is therefore important to use a site where man-made interference due to power lines, electrical machinery, automobiles, etc. is at a minimum, and to try to use frequencies that are not affected by transmitted signals. The latter problem is particularly severe, since there is no assurance that an interference-free channel will remain clear indefinitely. For this reason, it is becoming customary to use a sweep frequency receiver and filtering circuits that record the minimum signal intensity received during the frequency sweep. The width of the frequency sweep is usually many bandwidths, to insure high probability of at least one clear channel per sweep. This technique, which has been used with considerable success by Dr. W. O. Roberts of the High Altitude Observatory of Colorado University, is likely to become increasingly desirable as radio propagation conditions in the HF band improve with the sunspot cycle. The problem may, however, be solved if certain bands are cleared of man-made transmissions to enable them to be used for research purposes.

In addition to the above experimental uncertainties, there remains a fundamental practical limitation to the accuracy with which the noise power can be measured. As has been shown by Ryle, there is a statistical fluctuation in the output level, whose r.m.s. value is given by

$$\Delta P_o \simeq P_o \frac{1}{\sqrt{BT}},$$

where B is the input bandwidth as far as the second detector and T is the output time constant.

Typical values of B and T for absorption measuring equipments are 10^4 cycles per second and one second respectively; hence ΔP_o is of the order of 1 per cent of the output power (0.05 db). Greater accuracy can be obtained only by using wider input bandwidths and longer output time constants, or by integrating over several output fluctuations. In practice, the input bandwidth can be increased only at the risk of increasing the amount of interference from man-made transmitters. The time constant is usually kept fairly short in order to be able to follow rapid changes in signal, and to have a fast recovery time after a burst of interference.

An idealized simple equipment would therefore incorporate an antenna with a metal ground screen. The antenna could with advantage be directed toward the Pole Star, in order to eliminate the sidereal variation of signal power, and to minimize the effects of the sun and the strong radio sources in the constellations of Cygnus and Cassiopeia. The antenna should be carefully matched to a short, low-loss transmission line, buried in the ground or otherwise protected from temperature variations, and should be located at an interference-free site. The receiver should be carefully matched to the transmission line, and should have a low noise factor. All power supplies should be carefully regulated, and every effort should be made to obtain maximum stability of receiver gain. The receiver input/output characteristic should be monitored periodically (say once per hour) and such parameters as the observing frequency, receiver and antenna input impedances, and transmission line loss should also be checked periodically.

Under such carefully controlled conditions, it should be possible to maintain a long term accuracy (over several months) of the order of 0.2 db. Over shorter periods (say several days) an accuracy of the order of 0.1 db should be obtainable. In general, the most important limitations likely to be met in such an equipment are the variations in receiver gain and in receiver noise factor.

B. The Continually Self-Calibrating System

The above discussion has been limited to the simplest form of absorption measuring equipment, in which the gain of the receiver is implicitly assumed to remain constant for the period (usually many minutes) between automatic gain calibrations. However, a very elegant radiometer developed by Ryle and his colleagues for use in radio astronomical work may be used with advantage in the study of ionospheric absorption.

The basic principles of the equipment are as follows: The receiver input-connection is switched at a rapid rate (many cycles per second) between the antenna and a noise diode. If any inequality exists between the noise power fed into the receiver from these two sources, the output of the receiver will include a component at the switch frequency. Here it is amplified in an amplifier tuned to the switch frequency and fed into a phase-sensitive detector. This stage produces a d-c signal whose amplitude is proportional to the inequality of the two noise signals, and whose polarity is dependent upon which of the two signals is the greater.

This d-c signal is then used to adjust the filament temperature, and hence the noise power, from the noise diode in such a way as to make the two input signals equal in strength. As the antenna signal varies in strength, the power from the noise diode is thereby automatically adjusted to bring it into equality. To measure the antenna noise power, it is therefore necessary only to record the current through the noise diode, since this current is accurately proportional to the noise power generated by the diode.

In such an equipment, the receiver is used as a null-detector, and the accuracy of the reading is therefore not affected by relatively large variations of receiver gain. Since the equipment operates under balanced conditions, equation (1) is replaced by

$$P_{nd} = P_s + P_i + P_c + \Delta P_r + I, \qquad (2)$$

where P_{nd} is the noise power from the noise diode (proportional to the current following through it), P_s, P_i, P_c, and I have the same meaning as in equation (1), and ΔP_r is the difference between the equivalent noise input power of the receiver when connected to impedances equal to the antenna impedances and noise diode impedances respectively. It will be seen that the accuracy of the readings is no longer dependent upon variations in receiver gain; also, ΔP_r, the change in receiver noise factor as the receiver switches from antenna to noise diode, is normally very much smaller than P_r and the equipment is therefore relatively insensitive to changes in receiver noise figure. A third important advantage is that the recording system is now linear with input power. To measure relative signal power it is necessary only to divide the two meter readings. This is far simpler than the procedure for the simple equipment, for which it is necessary first to correct the observed chart readings for possible gain variations and then to use a receiver input/output calibration to determine the actual received powers.

This servo system, which can result in increased accuracy and in simplification of the data scaling, requires careful design if these advantages are to be fully realized. The problem of receiver stability is now replaced by that of accurate, stable switching between the two noise sources. In practice, this may be done either by a capacity switch or by diode switches; in both cases, good long-term stability may be expected. It is important, however, to check the switch periodically, by replacing the antenna by a second noise diode. Considerable attention should also be paid to impedance matching, since the ΔP_r of equation (2) will be zero only if the noise diode and the antenna present equal impedances to the receiver input when connected via the switch. It is also important to insure that the noise diode is operated with a sufficiently high plate voltage, since it is only under temperature limited conditions that the noise power will be accurately proportional to the current flowing through the diode. The equipment also requires that the precautions already outlined in the discussion of the simple equipment be taken to insure that the antenna and the transmission line are functioning satisfactorily.

Using a self-balancing radiometer of this type, with a carefully designed antenna and transmission line system, it is believed that relative signal powers can be measured with a long-term accuracy of better than 0.1 db, with a short-term accuracy probably limited by temperature effects in the system.

C. Some additional points

Three additional points should be remembered in interpreting the absorption measurements made by use of extraterrestrial radio waves.

(1) Ionospheric absorption is only one of the mechanisms by which the extraterrestrial signal may be reduced in strength. Measurements made at vertical incidence with sweep frequency ionospheric sounders have shown that at vertical incidence effects such as reflection and scatter are not sufficiently strong to reduce the extraterrestrial signal at frequencies well above the critical frequency. At low angles of elevation, however, significant reflection and refraction effects may be expected to occur at frequencies up to at least five times the critical frequency.

(2) These equipments measure the average value of the absorption over the polar diagram. Particularly at high latitudes, the absorption may be nonuniformly distributed across the sky.

(3) As was seen from the equation in Section I, the ordinary wave is less strongly absorbed than the extraordinary wave, and polarization effects can therefore be introduced by the absorbing region. For values of $w \gg w_L$, these effects will be small, but even at 30 mc the extraordinary wave will suffer 20 per cent more absorption in db than the ordinary wave. Careful measurements of the absorption of the ordinary and extraordinary waves may offer an opportunity to determine the ratio of ν^2 to $(w \pm w_L)^2$, and hence the possibility of determining something about the height of the absorbing region. In this connection, it should

be remembered that, although it is normally taken that the extraterrestrial radio noise is randomly polarized, few accurate polarization studies have been made. It is important that such studies be made, especially on the lower frequencies, where the magneto-ionic effects may be expected to be greater.

Section IV. Some Experimental Observations of Ionospheric Absorption Using Extraterrestrial Radio Waves

Three different types of ionospheric absorption studies have been made using extraterrestrial radio waves. The first studies were those of the Australian workers (at 18.3 mc), who studied the regular ionospheric absorption at about latitude 38°S. This work has been continued and has shown that the E-region of the ionosphere frequently plays an important role in the absorption of the extraterrestrial signal, the effect increasing in severity as the critical frequency of the layer increases. A regular D-region absorption was also observed. Typical values of absorption at noon were of the order 0.5 to 1.0 db at vertical incidence and 18.3 mc; both the above types of absorption tended to show regular daily variations associated with the changes in the sun's zenith angle.

A second type of study conducted using this technique is the study of sudden ionospheric disturbances (SIDs) associated with solar flares. Several examples of the sudden cosmic-noise absorptions (SCAs) associated with SIDs and/or solar flares have been published by Shain and Mitra. During a period of one year commencing July 1950, 176 SCAs were observed; the most intense exceeded 7 db for 18.3 mc radiation from the zenith. A typical

SCA shows an abrupt onset lasting a few minutes, followed immediately by a slow recovery lasting several tens of minutes. Occasionally, the burst of absorption is compound and seems to be built up of two or more simple bursts, superimposed upon each other. The onset of the absorption is sometimes masked by the outburst of solar radio noise often associated with solar flares.

Such SCAs are only seen during daylight hours and may be expected to be most severe near the subsolar point.

A third study is that of high latitude absorption, made at the Geophysical Institute of the University of Alaska. At such latitudes, (near the auroral zone) the absorption phenomena are very different from those observed at lower latitudes, both in intensity and origin. Direct solar effects, such as the D and F-region effects observed by the Australian workers and the SCAs that occur simultaneously over the whole sunlit hemisphere, decrease with increasing latitude owing to the greater solar zenith angle. Near the auroral zone, the absorption effects due to solar electromagnetic radiation are masked by absorption arising from corpuscular bombardment of the earth's upper atmosphere. In an extreme case, this corpuscularly-induced absorption may be so severe as to cause a "polar blackout," during which ionospherically propagated HF signals are rendered so weak as to be unusable. Since the College work is largely unpublished, a brief summary of the major results of these absorption studies is given here:

1. The absorption can occur at any hour of the day, but is most frequently detected during the noon hours.

2. It is frequently intense (> 3 db at 30 mc for vertical incidence; on occasions it has exceeded 15 db).

3. This excess absorption shows pronounced equinoctial maxima.

4. The duration of individual bursts of absorption can range from a few minutes to many hours, and usually shows a more rapid onset than decay.

5. The occurrence of absorption correlates well with periods of magnetic activity, as night absorption is usually, if not always, associated with auroral luminosity.

6. The absorption is usually not equal at the different azimuths from College, the NW and NE quadrants typically showing greater absorption than those in the SW and SE.

Many important problems remain to be solved, particularly the height at which the absorption is taking place. The observations at College indicate that is must be occuring at heights below 95 km, but as yet give no further information.

A second important factor is the average lateral extent of the absorbing region. The observations at College indicate that the absorption often varies largely over a range of 5 degrees in latitude. Whether the absorption is uniform across a 60 degree beamwidth directed toward the zenith is not known. Experiments are now being made to investigate this.

Other important unknowns are the latitude dependence of this corpuscular bombardment type of absorption, its variation with elevation angle, and its correlation with different types of ionospheric irregularities and disturbances.

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