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INTERPLANETARY RADIO TRANSMISSION THROUGH SERIAL IONOSPHERIC AND MATERIAL BARRIERS

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ABSTRACT

A usual first principle in planning radioastronomy observations is that monitoring must be carried out well above the ionospheric plasma cutoff frequency (~5 MHz). Before space probes existed, radioastronomy was almost entirely done above 6 MHz, and this value is considered a practical lower limit by most radioastronomers. Furthermore, daytime ionization (especially D-layer formation) places additional constraints on wave propagation, and waves of frequency below 10-20 MHz suffer additional significant attenuation. More careful calculations of wave propagation through the earth's ionosphere suggest that for certain conditions (primarily the presence of a magnetic field) there may be a transmission window well below this assumed limit. Indeed, for receiving extraterrestrial radiation below the ionospheric plasma cutoff frequency, a choice of VLF frequency appears optimal to minimize loss. The calculation, experimental validation, and conclusions are presented here. This work demonstrates the possibility of VLF transmission through the ionosphere and various subsequent material barriers. Implications include development of a new robust communications channel, communications with submerged or subterranean receivers / instruments on or offworld, and a new approach to CETI.

Keywords: CETI, ionospheric transmission, Jovian radiation, radioastronomy, Tesla, very low frequency

NOMENCLATURE

jansky, non-SI unit of spectral flux density, 1 Jy = [10^{-26} W Hz^{-1} m^{-2}]

Ordinary wave: The applied frequency is the same as the ionospheric plasma frequency. Magnetic field considerations are unimportant.

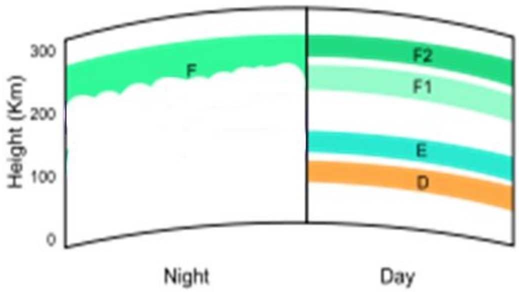
Extraordinary wave: Well below the plasma frequency, the electromagnetic wave interacts strongly with the electrons that are gyrating in the ambient magnetic field.

INTRODUCTION

The shell of plasma called the ionosphere, which surrounds the Earth at 50-1000 km altitude, strongly absorbs or reflects some frequencies of electromagnetic (EM) waves that impinge upon and couple to it. Ionization is naturally maintained primarily by solar UV and X-ray photons, and by certain effects associated with human activity. Figure 1 on the following page depicts how the daytime ionospheric structure with ions and free electrons is created by solar photons, while ions recombine at night. By late evening, the F layer thins to a narrow F2 layer, with some ions remaining at higher altitudes.

In this paper, transmission of an EM wave through the ionosphere is discussed, and the effect of Earth's magnetic field on EM wave propagation is explicitly considered. Calculations are presented which suggest that certain polarizations and frequencies may pass through the ionosphere, or other barriers, with minimal transit loss under quiet sun, nighttime conditions. It is shown that radioastronomy (RA) observations, study of extraterrestrial sources, and communications through various media may be possible in experiments where polarization, frequency and direction are carefully chosen. Data are presented documenting penetration of the ionosphere by very low frequency (VLF, or 3-30 KHz) signals at minimal loss, as measured by careful observers using modern equipment. This has implications for observers of VLF and sudden ionospheric disturbance (SID) phenomena, for research on communications with extraterrestrial intelligence (CETI), and general radio communication.

1. THEORETICAL DEVELOPMENT: MAGNETIC FIELD-FREE IONOSPHERIC ABSORPTION



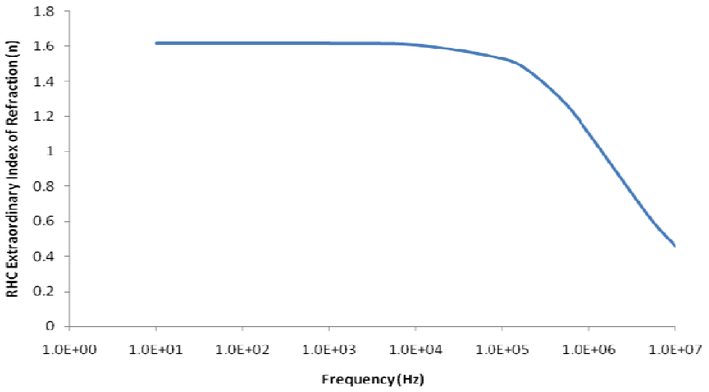


Fig. 1. Layers of the ionosphere at night and day (*left*) **Fig. 2. RHC extraordinary wave refractive index** (*right*)

Even though the high-altitude plasma shell is called the "ionosphere", referring to ions, it is primarily the free electrons with which EM waves interact. But not all frequencies of EM waves couple to the ions and free electrons resident in the ionosphere. Practical long-distance point-to-point communication by reflecting signals off the ionosphere is not usually attempted above a "maximum useable frequency" of ~5-20 MHz, depending on conditions. Above this frequency, the "first bounce" waves begin to penetrate through the ionosphere – and so the signal leaks away. EM waves do not interact much with the ionosphere above this frequency, and thus it is at higher frequencies that radio astronomers make their observations.

Such considerations lead to a conclusion: radioastronomy research is not practical below roughly 5 MHz during daytime, because of losses to ionospheric plasma. The mechanism of energy absorption can be significant below this "plasma frequency", because electronic response is actually considered an energy-dissipative plasma instability called "Langmuir wave generation" . If a quantum mechanical viewpoint is taken instead, this response is called "plasmon generation". Numerically, the plasma frequency may be computed by:

$$\omega_0 = 2\pi f_0 = \sqrt{\frac{Ne^2}{\varepsilon_0 m}} \tag{1}$$

where $\boldsymbol{N}$ is the free electron density, $\boldsymbol{e}$ and $\boldsymbol{m}$ are electron charge and mass, and $\boldsymbol{\varepsilon}_0$ the permeability of free space. This is the standard equation for the definition of plasma frequency, but if an accurate calculation is desired, $\boldsymbol{\varepsilon}_0$ should be slightly modified. Langmuir waves are formed in the ionosphere below ~5 MHz in daytime conditions, and ~2-3 MHz under nighttime (low electron density) conditions. If the frequency of the EM wave is lower than the plasma frequency, then the wave can be expected to couple to the electrons and lose energy. It is clear that the ionosphere can be a strong absorber/reflector of EM below the plasma frequency.

2. MAGNETIC FIELD CONSIDERATIONS

The Earth's ionosphere is actually a "magnetically-biased magneto-ionic medium".[1,2] Analysis of EM wave propagation in the ionosphere must consider the effect of the Earth's magnetic field on the free electrons. In the presence of a magnetic field, electrons above absolute zero (certainly the case for Earth's ionosphere) have a "cyclotron" orbital component to their motion, which has a radial frequency of:

$$\omega_{\mathrm{H}} = 2\pi f_H = \frac{B_0 |e|}{m} \tag{1}$$

where $\boldsymbol{B}_0$ is the field strength of Earth's field, about 0.5 gauss or 0.00005 [T] (Tesla), and f_{H} is the EM wave's frequency [Hz]. This equation follows from equating the inertial force of an electron to the magnetic deflection force. The cyclotron frequency for Earth's field is shown by this equation to be about 1.4 MHz.

The interaction of an impinging EM wave of frequency ***f*** with the ionosphere in the presence of a magnetic field can be expressed as n(f), the index of refraction. This index is the ratio of the velocity in the ionosphere to the velocity in free space. n(f) varies with frequency, usually expressed as the Appelton-Hartree[3] equation:

$$n^2 = 1 - \frac{2X(1-X)}{2(1-X) - Y^2 \pm [Y^4 + 4(1-X)^2 Y^2]^{1/2}}$$

$X = 1$ the ordinary wave

$X = 1 - Y$ the extra ordinary wave

Where:

$$X = \left(\frac{f_n}{f} \right) \qquad Y = \frac{f_H}{f} \qquad f_n = \sqrt{\frac{N e^2}{m\varepsilon_0}} \qquad f_H = \frac{e\beta_0}{2\pi m} \tag{3}$$

Equation 3 may be used to predict ionospheric interaction with an "extraordinary mode" EM wave that travels along the magnetic field. The extraordinary mode occurs when the electromagnetic wave interacts strongly with the electrons that are gyrating in the ambient magnetic field. If $n^2 > 0$ in a magneto-optic medium, then propagation can occur with minimal absorption.

3. POLARIZATION AND FREQUENCY DEPENDENCE OF THE "EXTRAORDINARY" WAVE

A most interesting part of the above expression of the Appelton-Hartree equation for the extraordinary wave is that the "+" (plus-sign) corresponds to the *left-hand* circularly (LHC) polarized "ordinary wave", whereas the "–" (minus-sign) corresponds to the *right-hand* circularly (RHC) polarized "extraordinary wave". LHC and RHC waves interact in different ways with the free electrons gyrating in the ionosphere.

Choosing the positive sign in the denominator for LHC, we see that at frequencies below the plasma frequency, the LHC has a negative value of n^2, and the wave will be damped (absorbed).

Choosing the negative sign in the denominator for RHC, we see that for certain frequencies below the plasma frequency the mathematical sign of n^2 is positive, and the wave will not lose significant energy to the free electron field. This condition is sometimes called the "free-space" mode.

For typical values of the nighttime plasma and cyclotron frequencies appropriate to Earth's ionosphere, and for RHC radiation along the magnetic field and well below the collision frequency, the Appelton-Hartree equation reduces to the expression:

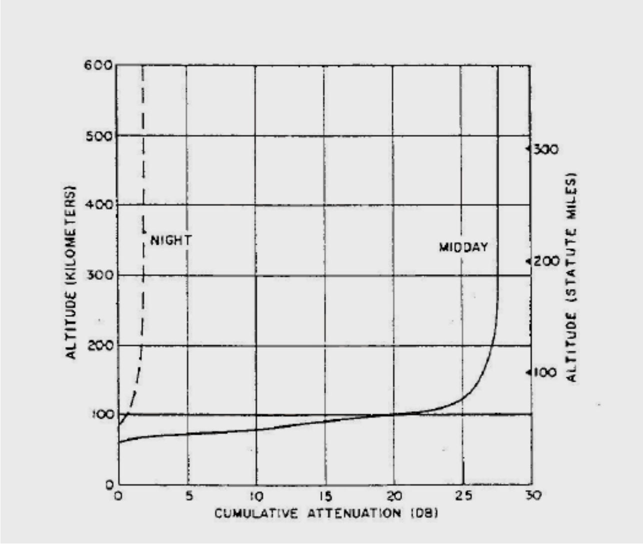
$$n^2 = 1 - \frac{2(1-Y)}{(2-Y) + Y\sqrt{5}} \tag{4}$$

The value of the index of refraction is calculated and plotted as a function of frequency, (see Figure 2 above on page 2), for which the cyclotron frequency was assumed to be 1.4 MHz. The RHC refractive index shows low-loss propagation (for this special case) extending into the VLF (3-30 KHz) region. Extraterrestrial signals which meet the criteria described herein may thus penetrate the ionosphere. This calculation is an approximation that is valid only for frequencies well below the plasma frequency. *Therefore a theoretical basis exists, in certain situations, to expect transmission of VLF signals through the ionosphere*.

4. EXPERIMENTAL VALIDATION OF PROPAGATION BELOW PLASMA FREQUENCY

Existence of the "VLF window" was confirmed by satellite monitoring experiments in 1961 that demonstrated an ionospheric attenuation ranging from 4dB to 29dB at a frequency of 18 KHz.[4] These experiments were conducted between a U.S. Naval Research Station transmitter in the Panama Canal Zone and a receiver on the U.S. satellite LOFTI-1. The researchers applied the Appleton-Hartree equation and concluded that an optimal theoretical attenuation of ~2dB is possible for extraterrestrial signals penetrating the ionosphere. In this case, less than half of the initial signal would be lost! The results were interpreted as verifying that more than 50 percent of the time, attenuation was better (i.e., less) than 13 dB at night, and better than 38 dB during the day.

These transionospheric experiments were studied by other researchers[5], who interpreted the results graphically. Figure 3 below shows the minimum cumulative transmission loss of an 18KHz signal passing vertically upward, based on measurements by the US LOFTI-1 satellite orbiting above the ionosphere.



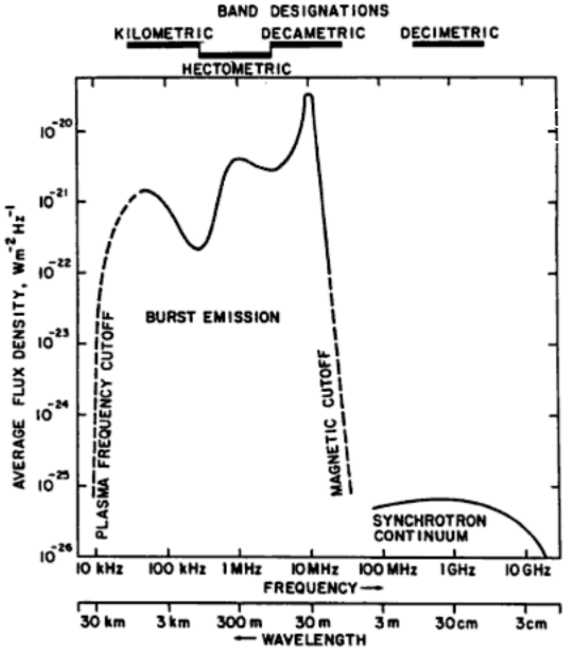


Fig. 3. cumulative transmission loss of 18KHz signal (*left*) **passing vertically upward** [5]

Fig. 4. Jovian nonthermal magnetospheric (*right*) **radio flux at 4.04 AU** [8]

These results experimentally confirm low-loss transmission of VLF waves through the ionosphere at night. Leiphart, *et al* also confirmed the likely transmission of extraordinary VLF signals with as little as 2dB to 4dB loss transiting the ionosphere. The geometric values in Figure 3 were plotted with respect to terrestrial zenith, but the Appelton-Hartree equation and results discussed above are for extraordinary wave VLF signals propagating along the magnetic field vector. Qualitative agreement between the theoretical argument and the figure is valid.

5. POSSIBILITY OF DETECTING OF JOVIAN SIGNALS BELOW PLASMA FREQUENCY

Emissions from Jupiter can be intense, many orders stronger than usual cosmic sources. High-frequency (HF) Jovian radiation consists of "L-bursts" (seconds in duration) and "S-bursts" (5-50 ms in duration). Based on Voyager measurements, the HF radiation peaks at 1 MHz.[6] Hectometric (hundreds of meters wavelength) radiation extends to below 700 KHz.[7] Kilometric radiation has both broadband and narrowband components. The broadband component is reported from Voyager results to be bursty, strongly circularly polarized, and extending to below 10 kHz. This broadband component has been reported to be in antiphase with the hectometric radiation. The flux density of Jovian nonthermal magnetospheric radio emissions, normalized to a distance of 4.04 AU, has been compiled by Schauble and Carr[8] and characterized elsewhere.[9] It is shown in Fig. 4 above.

Thus, based on published data, there is more Jovian flux at 20 KHz than at 20 MHz. Circularly-polarized Jovian VLF radiation may meet the criteria for low-loss transmission through Earth's ionosphere. The conclusion of this paper is that it would be reasonable to search for Jovian VLF signals under certain conditions, including:

- Nighttime conditions (low ionic number density in early morning);
- Solar activity minimum (no recent coronal mass ejection activity);
- Low anthropogenic (termed "QRM" in RA jargon) and natural electrical storm activity ("QRN");
- Angular bearing of the source consistent with ionospheric magnetoplasma assumptions;
- Jovian planetary and emission region positions optimal for signal beaming to Earth;
- Careful choice of frequency to avoid military VLF transmissions;
- Antenna alignment toward Jupiter;
- Antenna gain set high, to minimize unwanted signals; and
- Antenna design optimized for RHC polarization from extraterrestrial targets.

6. PROBABLE EARLIEST DETECTION OF ET SIGNALS BELOW PLASMA FREQUENCY

As discussed above, Jovian VLF radiation source intensity from Io’s plasma torus was measured by Voyager I and found to be significant, on the order of 10^7 janskys [Jy], if measured at Earth using typical close Jupiter-Earth distances. The signal strength of ordinary interstellar radio sources is measured in single janskys. Conditions necessary for detecting any of this radiation at a VLF transmission window are: nighttime observing; choice of suitable frequency; proper orientation of source direction with respect to the magnetic field (Earth’s); accounting for terrestrial atmospheric noise and military transmitters; receiver sensitive enough to reach the quiet atmosphere noise level, and careful choice of antenna (right-hand circular polarization). Radioastronomers do not usually expect ET signals below the plasma frequency, but the question arises whether they have been detected before.

In 1899, Nikola Tesla performed an extensive study of background radio noise.[10] Several papers are found that document Tesla’s use of coherer detectors that were biased by externally-applied RF fields, and several references are made to the high gain in power that this approach allowed. The amplification apparently approached 2000 (+66 dB).[11] Tesla’s receivers used his physically large “Tesla” coils as antennas, which were “high-gain antennas” resonant at 18 KHz, the same frequency used for the LOFTI-1 satellite experiments.

The coherer detectors used by Tesla do not provide envelope detection. Tesla’s coherers were not appropriate for detecting modulated signals, and so entered a technological *cul-de-sac*. Nevertheless his system provided very high sensitivities to step changes in received power levels. The system antenna sensitivity was estimated to in the 30-300 microvolt range. His reception limits were driven not by receiver sensitivity, but by antenna selectivity and by the terrestrial noise field.

Tesla was well-prepared for interpretation of signals, and was working at a period of minimum solar activity. Tesla reported detecting a series of clicks, resembling an intelligently generated series, and not, in his judgment, generated by “normal” terrestrial atmospheric electrical activity. Overhead were Mars (much in the news) and Jupiter (much more distant). In mid-June 1899 when he started these observations, both planets set late in the evening. He continued his observations, which included an Io-A event[12] on July 22, 1899 (July 21 local time).

Observations recorded by Tesla suggest that he may have been the first Radio Scientist to actually detect extraterrestrial signals, in this case interplanetary radio waves originating from the planet Jupiter. If this is true, then we might consider Nikola Tesla to be the First Radio Astronomer.

One might question the applicability of ionospheric transit of VLF extraordinary waves because of the requirement that the wave propagation direction should coincide with the magnetic field vector. Figure 5 below shows the magnetic field direction in the ionosphere above Colorado Springs, Colorado, where Tesla made his 1899 observations. The modern-day magnetic environment near Colorado Springs indicates that the magnetic field has a vertical dip angle of approximately 66 degrees. This value is a “reasonable” angle of incidence of an extraterrestrial radio signal, at an F2 layer altitude of 300 km, for low-loss VLF extraordinary wave transit.

You clicked here:
Latitude: 38° 37' 0.7" N
Longitude: 104° 43' 18.1" W
Magnetic declination: 8° 44' EAST
Declination is POSITIVE
Inclination: 65° 36'
Magnetic field strength: 52275.6 nT

Fig. 5. Modern day magnetic environment near Colorado Springs, CO (*center*)

CONCLUSION -- OPPORTUNITIES FOR VLF AND SID MONITORING

Considerations presented here are important because they suggest that radioastronomy researchers may be missing the use of an important radio band. There are additional implications such as: development of a new robust communications channel; communications with submerged or subterranean extra-Earth colonies and research instruments; and a new approach to communications with extraterrestrial intelligence[13] (CETI). The VLF portion of the spectrum may be available for reception/transmission to terrestrial researchers. Indeed, Jupiter emissions monitoring may be possible from Earth-based receivers and may be useful for solar and Jovian studies. VLF signals are already used for worldwide communication with deeply cruising submarines. Furthermore, the large skin depth of lower frequencies ensures that they will penetrate material barriers better than higher (e.g., microwave) frequencies usually chosen for communications.

Jovian VLF radiation source intensity from the Io plasma torus was measured by Voyager I and found to be of the order of 10^7 [Jy] (normalized to Jupiter-Earth distance at close-approach). Conditions necessary for using this transmission window for radio astronomy are: nighttime observing; choice of suitable frequency; proper orientation of source direction with respect to Earth's magnetic field; accounting from terrestrial atmospheric effects and military transmitters; receivers sensitive enough to reach the quiet atmospheric noise level, and careful choice of antenna (right-hand circular polarization).

It is possible that SID monitoring will occasionally show "s-modulation" (*staccato*) patterns similar to those often seen at 15-m wavelengths (20 MHz) by Jove researchers. Based on the analyses and experimental results discussed here, SID researchers may find that their results support the assertion that transmission of extraterrestrial signals through the Earth's ionosphere is, under the right circumstances, to be expected.

ACKNOWLEDGMENTS

This paper is dedicated *in memoriam* to Nikola Tesla. Tesla carefully applied astute experimental techniques to the earliest radioastronomy investigations. His genius in building and operating the most sensitive receivers of his day, combined with the good fortune to make observations at a time of minimal solar noise and with no competing transmitting stations probably combined to give outstanding results that demonstrate low-loss ionospheric transit by VLF signals. Modern equipment has sensitivity far superior to that at Tesla's time.

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