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A BACKGROUND REPORT ON TOTAL ELECTRON CONTENT MEASUREMENTS

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A simple presentation of ionospheric characteristics, including the D-, E-, and F-regions, is followed by a general description of electromagnetic waves. One of the more important effects of ionospheric interactions with the Very High Frequency (VHF) and Ultra High Frequency (UHF) radio waves, which are used in modern electronic detection and tracking systems, is refraction. Total electron content (TEC) measurements over specific locations are used as data inputs to numerical models of the ionosphere. Some of the basic considerations for measuring TEC of the ionosphere using the Faraday technique and the over

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group-path-delay technique, and a discussion of variation of TEC are included.

PREFACE

Electromagnetic waves traversing the ionosphere experience a multitude of complex and varied interactions with the medium. A basic appreciation of these interactions is necessary for both the environmentalist and the electronics system manager. This report was prepared with both disciplines in mind.

The author acknowledges the kind assistance and constructive comments of Dr. Dimitris A. Matsoukas, Electronics Department, University of Athens, Greece. Appreciation is also extended to Captain James A. Manley and MSgt Robert H. Potts, Jr., for their editorial reviews and comments.

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A BACKGROUND REPORT ON TOTAL ELECTRON CONTENT MEASUREMENTS

SECTION A — INTRODUCTION

Pinpoint accuracy in the positioning and tracking of space-borne objects, specifically missiles and satellites, is, for obvious reasons, a vital concern to the defense interests of the United States. Operational long-range radar systems, using Very High Frequency (VHF) and Ultra High Frequency (UHF) radio waves, provide the primary means for the detection and tracking of objects in the earth's upper atmosphere. Serious errors in object positioning result from the influence of the ionized portion of the earth's atmosphere, the ionosphere, on traversing electromagnetic waves [2],[5],[6],[11]. Interactions between the medium and the waves come about because of the presence of a large number of free electrons in the ionosphere. Electron concentrations in the ionosphere vary according to the amount of solar radiation received, the state of the geomagnetic field, complex and random electron transport processes, and a host of other less easily understood aberrations. The general purpose of this report is to provide a basic description of the ionosphere, the electromagnetic wave, and the interactions between the ionosphere, geomagnetic field, and electromagnetic wave. The specific intent is to provide relatively simple physical interpretations to the interactions and to lay the groundwork for the analysis of Total Electron Content (TEC) measurements.

SECTION B — THE IONOSPHERE

General Description

The ionosphere is the highly conductive medium in the earth's atmosphere, extending from near 50 kilometers (km) above the surface to an approximate upper limit near 1500-2000 km. As one ascends through the ionosphere, a gradual increase in free electrons is observed until a peak is reached near 300-350 km (Figure 1). Above this point, there is a gradual decrease in the number of free electrons with increasing altitude. By convention, the ionosphere is divided into three regions each of which exhibits somewhat different characteristics. These regions are known, in ascending order, as the "D-," "E-," amd "F-regions." The most prominent properties of each region are briefly described.

D-Region

The D-region, the lowest of the ionospheric regions, extends from 50 to approximately 90 km above the earth's surface. Free electrons in the D-region are created by various means, depending on the level within the region. Below ~ 70 km, free electrons are thought to be produced through the absorption of energetic particles originating in the sun and the rest of the galaxy (cosmic rays). In the 70- to 90-km region, electrons are produced mainly by the ionization of nitric oxide traces by solar radiations in the wavelength of 1216 Angstroms (Å). The very short wavelength radiations (1 to 10 Å) emanating from the sun are an additional significant ionizing source during the years of increased solar activity. These short wavelength radiations ("hard" X-rays), whose intensity varies directly with the level of solar activity, are quite effective in ionizing both nitrogen and molecular oxygen which are relatively abundant in the D-region. Over middle- and low-latitude locations the D-region is generally detectable only during the daylight hours. At higher latitudes (from the auroral zones into the polar caps), a sensible D-region is present all the time and is attributed mainly to the constant "precipitation" of particles from the magnetosphere into the ionosphere. Even over the polar caps, however, there is a distinct variation in the D-region's electron content from night to day. This variation confirms a significant solar radiation dependence. As the earth's magnetic-field lines are very nearly perpendicular to the earth's surface over high latitudes, energetic particles from the magnetosphere have ready access to the ionosphere. Over lower latitudes, the mean daytime electron density of the D-region is about 10^3 electrons/cm^3. The elimination of ionizing solar radiations and the high relative density of the neutral atmosphere (which permits the electrons to freely and rapidly recombine with it's constituents), results in a nighttime electron population near zero. Energetic solar flares can produce some startling, short-lived increases in the D-region's electron density. During strong solar flares, large amounts of "hard" X-rays are released from the sun and are absorbed in the D-region. This absorption results in the rapid ionization of the D-region's constituents, releasing a great number of electrons. Although the lifetime of an individual electron is only a fraction of a second, there are enough produced to effectively remove energy from traversing High Frequency (HF) radio waves to produce the phenomenon known as the Short Wave Fade (SWF) [2]. Even during highly active solar conditions, VHF and UHF radio waves will penetrate the D-region. However, due to the significant number of free electrons present in the daytime D-region, some influence is exerted on these radio waves as they pass through. This influence will be discussed further in Section D.

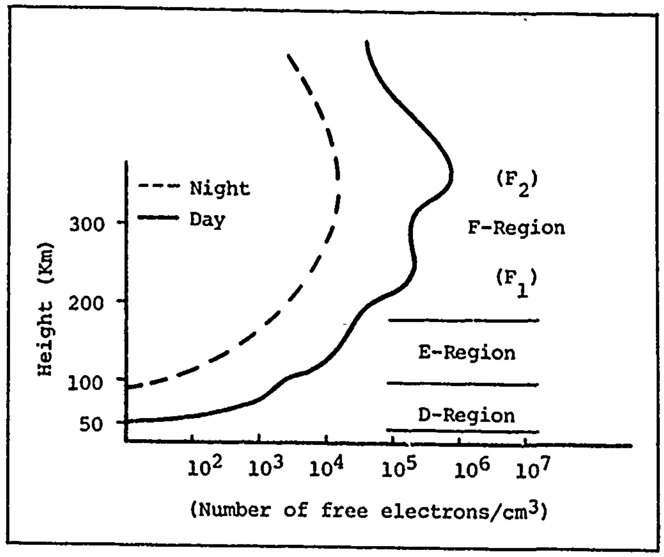

Figure 1. The Vertical Distribution of Free Electrons in the Ionosphere. These are typical distributions over a middle-latitude location during quiet geomagnetic conditions.

E-Region

The E-region, the middle region of the ionosphere, lies between the altitudes of 90 to ~ 150 km with a peak concentration of electrons near 100-110 km. Like the underlying D-region the E-region exhibits a strong solar dependence in terms of diurnal variations in electron population. That is, the E-region over middle- and low-latitude locations is most heavily populated with electrons during the sunlit hours. Ionization of the E-region's constituents in the altitude range from 90 to 100 km is due primarily to the absorption of "soft" X-rays in the wavelengths of 10 to ~ 100Å. Above 100 km, additional ionization is caused by the absorption of radiation in the wavelengths of 800 to 1026Å. Normally, a rather tenuous E-region persists during the nighttime hours as a result of micrometeorite bombardment [2]. Complex wind-shear areas in the E-region tend to produce anomalous concentrations of electrons which appear at random hours and for widely varying durations. At times these concentrations of electrons become so intense that the nighttime E-region density can easily exceed the normal daytime density for short periods. These concentrations of electrons in the E-region are known collectively as "sporadic E" [2]. Near the auroral zones sporadic E tends to be most prevalent during the nighttime hours especially during the winter months. Over lower latitudes sporadic E favors the daytime hours and is most prevalent during the summer months. The normal electron density of the E-region during the daytime hours is near 10^4 electrons/cm^3. During enhanced sporadic E conditions the peak density can easily exceed 10^6 electrons/cm^3. Sporadic E tends to appear in patches and is generally only a kilometer or less thick. Ground-based ionospheric monitoring systems normally use the HF (3 to 30 MHz) range for sounding purposes. These systems are quite sensitive to both the normal diurnal changes in the E-region as well as to the appearance of sporadic E [2]. In addition to its high correlation with E-region wind shears, sporadic E is often observed in the vicinity of thunderstorms [1] and at higher latitudes is commonly observed during disturbed geomagnetic conditions. Great amounts of radiation in the wavelengths from 10 to 100Å are released during some solar flares. These bursts of "soft" X-rays produce a rapid but temporary enhancement in the E-region's electron density. This sudden increase in electron population serves to enhance the electrical currents present in the sunlit E-region. A ground-based magnetometer can detect these current changes by indirect means and record them as a peculiar signature called the magnetic "crochet" [12].

F-Region

The F-region is the highest and the most complex region in the ionosphere. This region extends from an altitude of approximately 150 km to above 1500 km. There is a distinct electron density peak near 300 to 350 km where the number of free electrons may reach $10^7/cm^3$. Since the neutral atmosphere is quite tenuous in the F-region, free electrons may persist for several hours after sunset before recombining with the neutral constituents. Thus, during the nighttime hours the electron density remains more or less stable near $10^4/cm^3$. This diurnal variation in electron density is suggestive of at least some solar radiation dependence. However, the spatial and temporal variations are so complex and varied that solar influence can only be assumed to play a limited role in free electron production and maintenance. Complex transport mechanisms and the appearance of several peculiar phenomena in the F-region suggest that other processes are involved not directly attributable to solar influence [10]. There is a tendency for the region to split into two distinct "layers" during the sunlit hours. This splitting which is most pronounced during the summer months, results in an electron density peak near 150-180 km, and a generally greater peak near 300 to 350 km. These layers are called the F_1 and F_2 layers, respectively. After sunset these two layers merge ... 300 km to form the nighttime F-region. Complex transport processes whereby la.ge volume of electrons are conveyed over long distances, coupled with strong variations as. ciated with disturbances in the geomagnetic field result in an extrem..ly dynamic F-region. Major ionospheric disturbances are highly correlated with maj.. geomag.etic storms. Conversely, anomalous variations in the F-region often occur when ge magnetic conditions are quiet. Various other curious phenomena are observed ir the F-region which warrant further discu sion. One of these is the phenomenon known as "spread F".

Spread F is characterized on ground-based sounding systems as a diffuse signature with a "blob-like" appearance. These blobs may appear over any geographic location and may persist for a few minutes to several hours. The onset and disappearance of spread F is rather abrupt and is so poorly correlated with any other solar-geophysical activity it can only be treated statistically. Over low-latitude locations spread F favors a late summer evening appearance when geomagnetic conditions are very quiet. Over middle-latitude locations, it appears most frequently in the early morning hours immediately following local midnight during the summer months, and when the geomagnetic field is very stable. At higher latitudes, spread F may appear any time, but it does favor the more disturbed geomagnetic periods [2].

The next F-region peculiarity is the Travelling Ionospheric Disturbance (TID). This phenomenon can be likened to a broad wave front, which may extend over horizontal distances of several hundred kilometers. On ionospheric records it will appear as a sharp enhancement of electrons followed shortly by a rapid depletion. This sequence will continue and is analogous to a long series of "breakers" or "rollers" in the ocean as they approach the shore. In the late evening hours during disturbed geomagnetic conditions, TIDs often originate near the auroral zones. They generally migrate in a southerly direction with little change in character and are detectable over distances of several thousand kilometers [3],[13],[14]. The TID appears over a fixed geographic point as a near sinusoidal variation in electron density. This variation may range from 2% to 5% of the total electron content over a given site [4],[13]. Oscillations in the electron density may continue for several hours, but several minutes is probably closer to the mean duration. TIDs have also been observed following large earthquakes and have appeared concurrent with major solar eclipses [8]. The east-west dimensions of a TID may exceed 3000 km [14]. Enhancements in the electron content of the F-region can also result from solar-flare-generated X-rays. The greatest enhancements take place in the lower F-region where there is an appreciable amount of ionizable material available [9]. The strong absorption of radio waves used for ionospheric sounding purposes in the underlying D-region prevents an accurate assessment of solar flare effects in the F-region.

Summary

This brief review of the ionosphere is very elementary. The ionosphere is an extremely complex and dynamic medium, and a full treatment of the many variations and complicated aspects of the medium is well beyond the scope of this report. A more comprehensive treatment of the ionosphere can be found in works by Davies [2], Gaut and German [5], and Ratcliffe [12].

SECTION C — ELECTROMAGNETIC WAVES

General Description

Any interaction between an electric field and a magnetic field will result in the outward propagation of an electromagnetic wave. In simpler terms, the electric and magnetic fields become coupled and are detectable at some distance from the origin. This theory provides the basis for this discussion on the fundamental properties of an electromagnetic wave.

The Fundamental Properties of the Wave

The fundamental properties of an electromagnetic wave can best be visualized by assuming that the electric field component of the wave will approximate a vector we shall call $\vec{E}$ (Figure 2). At the time (t) of the generation of the wave (t=0), $\vec{E}$ has a strength or amplitude of zero. At a later time ($t=t_1$), the strength of $\vec{E}$ increases to a maximum positive value. At this time the strength of the vector begins to decrease, and at $t=t_2$ it again reaches the zero point. The strength of the vector again increases, but in the opposite direction, until a maximum is reached at $t=t_3$. The vector magnitude reverses at this point and reaches the zero level again at $t=t_4$. Thus, the wave form describes a sine curve. As the magnetic field is coupled to the electric field at the point of origin, the tip of the magnetic vector $\vec{H}$ will also vary in a sine function. In a simple electromagnetic wave, $\vec{H}$ will have the same shape as $\vec{E}$ but will be offset in angular rotation by 90 degrees along the line of propagation (Figure 3). Next to be considered are some of the other properties of the wave (Figure 4). The maximum strength attained by the electric (or magnetic) vector of the wave is called the amplitude (A). The completion of one 360-degree rotation of the wave along the line of propagation is called one cycle, i.e., the electric vector begins at zero, passes through the maximum positive amplitude point, recrosses the zero level, passes through the maximum negative amplitude point, then returns to

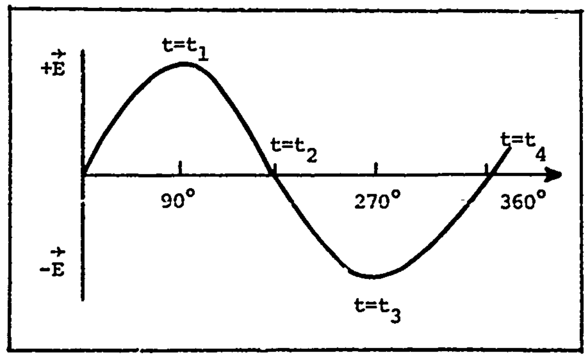

Figure 2. Example of a Sinusoidally-Varying Electric Field. The direction of propagation is to the right.

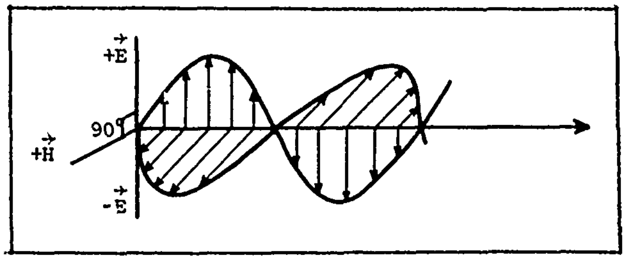

Figure 3. A Propagating Electromagnetic Wave. The direction of propagation is to the right.

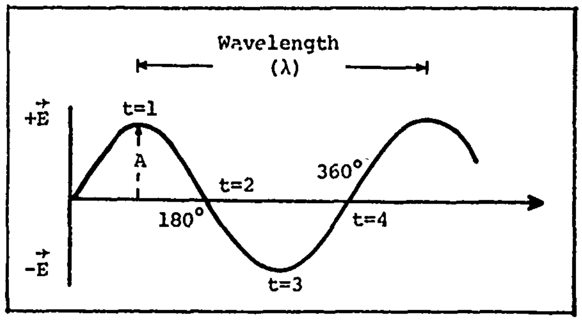

Figure 4. Schematic of Various Properties of a Simple Electromagnetic Wave.

zero. The time required for the wave to complete one cycle is the period of the wave. The number of cycles completed by the wave in one second is the frequency of the wave. The unit of frequency equal to one cycle is the hertz (Hz). The argument of the sine function originating the wave is the phase. The distance between successive wave crests (amplitude) is called the wavelength (λ). The relationship between the wavelength (λ) and the frequency (f) of the wave is expressed as follows:

$$f = \frac{V}{\lambda} \quad (1)$$

where V is the speed of the wave through a medium (in a vacuum, V would equal c, 3×10^8 meters/sec, the speed of light).

Electromagnetic Coupling

The coupling process in the electromagnetic wave, that is, the interconnection of the electric and magnetic fields, occurs simultaneously with the generation of the wave. The discussion up to here has described, in schematic form, certain properties of a simple electromagnetic wave in a "snapshot" situation. The various properties of a wave in motion are discussed next.

Polarization

The polarization of an electromagnetic wave can best be defined as the angular variation of either the electric or magnetic vector with time. For the intent of this report, we need only consider the angular variation of the electric vector. Polarization of electromagnetic waves can assume any of several configurations. First, we will consider linear or plane polarization. A wave is linearly polarized when the tip of the electric vector shows no angular variation as the wave travels over a distance (Figure 5). If the top of the vector describes an angular rotation at a constant rate with time and there is no change in maximum amplitude (either positive or negative), the wave is said to be circularly polarized (Figure 6). Figure 6a depicts a schematic of a circularly polarized wave propagating from left to right. Figure 6b depicts the same wave with a line of propagation toward the observer. In this illustration, the tip of the electric vector has rotated throughout an angular distance of 180 degrees from the time of the first positive maximum amplitude

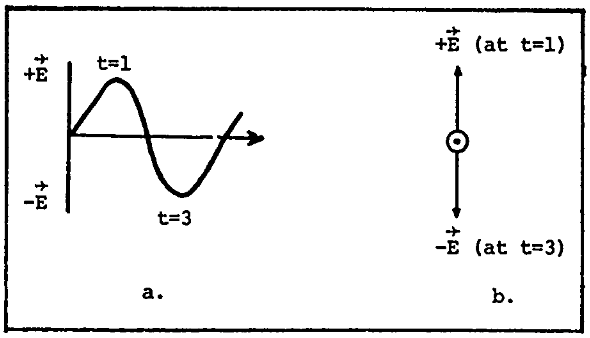

Figure 5. A Plane Polarized Wave. The direction of propagation is to the right in a., and toward the observer in b.

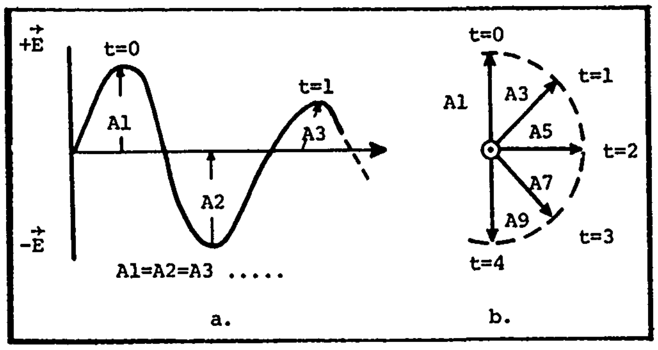

Figure 6. A Circularly Polarized Wave and the Rotation of the Electric Vector with Time. Direction of propagation is to the right in a., and out of the plane of the paper in b.

point (t=0) to the time of the fifth excursion to the maximum positive amplitude point (t=4). Other types of polarization do occur, but it is sufficient for the purpose of this report to understand the concepts of plane and circular polarization.

Phase and Phase Differences

As pointed out earlier in this section, the argument of the sine function describing the phase of the electromagnetic wave. If two electric fields of similar frequencies and amplitudes are permitted to begin oscillating at slightly different times, their individual wave forms would appear as illustrated in Figure 7. Each wave would travel at the same speed through a homogeneous medium, but each would be "out of phase" with respect to the other. Should both waves impinge on the same receiving antenna tuned to the appropriate frequency, they would be combined and the resultant wave would have somewhat different characteristics than either of the original waves. Assuming the two waves generated were of equal frequency and amplitude, but were out of phase by 90 degrees, the resultant wave would have the same frequency. However, the amplitude would be some 40% greater than that of either of the original waves. Figure 8 illustrates some other combinations of two individual waves. Phase

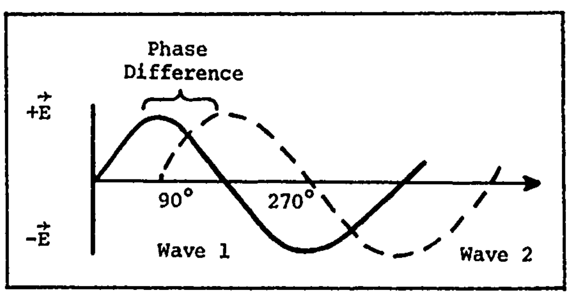

Figure 7. Phase Differences for Similar Waves. The phase difference in this example is 90 degrees. The same phase relationship would exist for the magnetic vector.

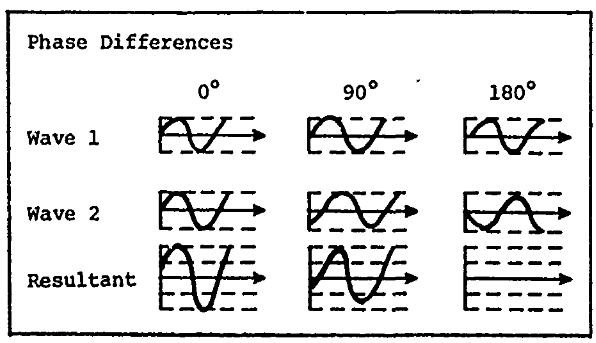

Figure 8. Some Combinations of Two Similar Waves. Note that the amplitude of the resultant wave may vary from twice as much (0° phase difference) to zero (180° difference).

differences between two or more waves result from either, or a combination of the following processes: (a) two or more sources of similar electromagnetic waves are transmitting signals along the same path of propagation, but the signals are offset in phase; (b) the original wave from a single transmitter separates into two or more components or "packets" with each packet travelling along an independent path at it's own speed. On arrival at the receiving antenna the waves are combined and the resultant wave has properties that are equal to the vector sums of the properties of the individual waves or packets. These properties include the frequencies, amplitudes, and polarizations of the individual waves.

Phase and Group Speeds

The speed of a pure sinusoidal wave, either through a vacuum or some other medium (such as the ionosphere), is called its phase speed. However, if two waves of slightly different frequencies are combined, their individual wave forms are changed and their individual phase speeds become ill-defined because of the structure of the new signal (Figure 9). The individual waves (waves 1 & 2) are observed to be in phase at some points and as much as 180 degrees "out of phase" at others. It will also be noted that the combined wave (wave 3) is composed of "envelopes" of identical but randomly formed amplitude oscillations. These envelopes or "groups" now become periodic functions with their own characteristic speed, the "group speed." If the phase speeds of the individual original waves (waves 1 & 2) are equal (as they would be in a vacuum), their phase speeds and the group speed of the combined wave (wave 3) would be the same. However, in a medium such as the ionosphere, the phase speed of a wave is dependent on its frequency. Therefore, the group speed of the wave will be different than the speeds of the individual phases of the combining waves (Figure 9c). Since the wave-phase speed varies according to the frequency of the wave as it passes through the

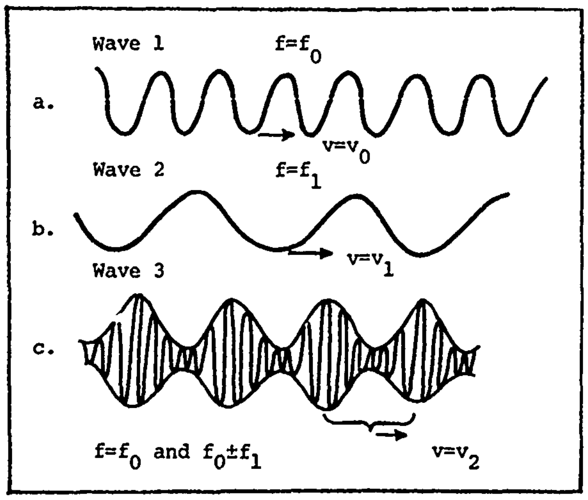

Figure 9. The Amplitude Modulation of an Electromagnetic Wave. Figure 9a shows the carrier wave unmodulated. Figure 9b depicts the modulating frequency, and Figure 9c is the combined (modulated) wave. The speeds v_0 and v_1 indicate the phase speeds of the carrier and modulating waves, respectively. The new speed, v_2, is the speed of the "groups" of the combined waves.

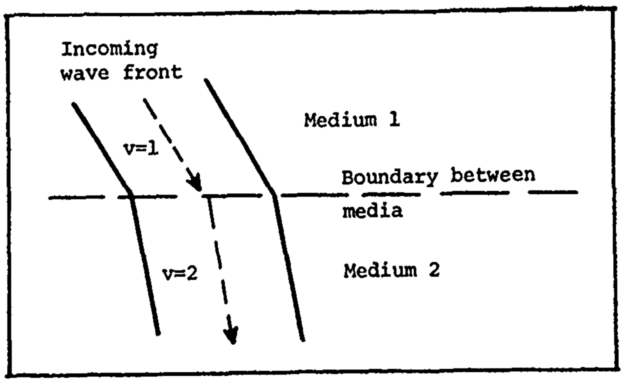

Figure 10. Refraction of an Electromagnetic Wave. As the wave enters medium 2, its speed decreased from v_1 to v_2 resulting in a change in direction of propagation (refraction).

ionosphere, the ionosphere is said to be a "dispersive" medium. Dispersive effects become important when discussing the phenomenon of refraction and the resultant changes imparted on the group speed.

Refraction

Refraction of an electromagnetic wave occurs as the wave crosses the boundary between two media, each with different speeds of propagation through the media. Figure 10 illustrates the refractive process for a wave passing through two media with different propagation characteristics. Refractive effects through two media may be likened to a line of marching men executing a turn. The speed of the men on the inside part of the line is reduced while that of the men on the outer part of the line remains constant. After the turn is completed, the direction of travel has changed. This analogy departs from reality at this point, for in the case of the marching men, the final speed is equal to the original speed. In the case of an electromagnetic wave, a new speed is attained and is maintained as long as the medium remains homogeneous. Phase changes and refraction exert a tremendous influence on electromagnetic waves passing through the ionosphere.

Wave Modulation

Certain properties of an electromagnetic wave can be modified, or modulated, in a transmitting system. This is accomplished by combining waves with different frequencies, amplitudes, or polarization within the transmitting system itself. For example, Frequency Modulation (FM) of transmitted radio signals provides exceptional clarity and fidelity at the receiving unit and is used extensively for stereophonic broadcasting. Frequency modulation provides equal amplitudes to the very high (treble) and very low (bass) frequency audio tones. Amplitude Modulation (AM) is used in commercial radio stations where variances in fidelity are less critical. Amplitude modulation of a radio wave provides a means of transmitting intelligence as a part of a strong radio signal (called a "carrier" wave), by creating "sidebands" (Figure 11). Figure 11a depicts the initial unmodulated wave (the carrier). Figure 11b illustrates the final modulated wave. In the modulating process, two sideband

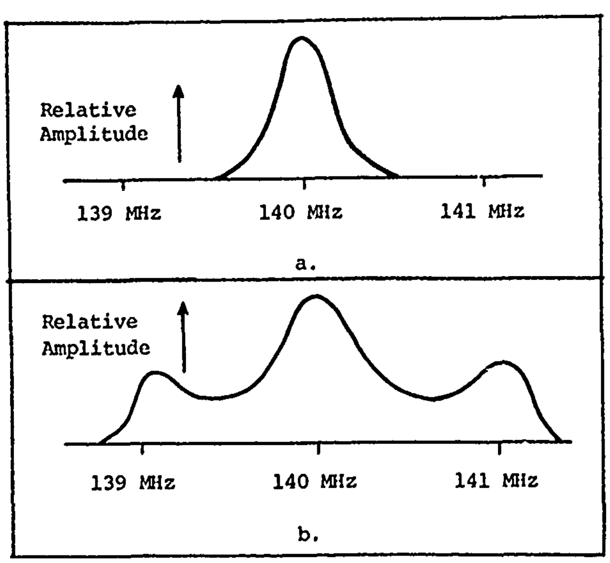

Figure 11. The Creation of "Sidebands" on a given Carrier Wave. This example depicts a carrier wave with a frequency of 140 MHz in Figure 11a, and the sidebands with frequencies of 139 and 141 MHz in Figure 11b. This is done by introducing a modulating wave with a frequency of 1 MHz to the existing carrier.

frequencies are produced for each carrier frequency. For example, a carrier wave ($f=f_o$) that is modulated with an added frequency ($f=f_s$) will contain two frequencies, f_o-f_s and f_o+f_s, in addition to the original carrier frequency (f_o). These additional frequencies are the sidebands which, when combined with the carrier, will travel at the group speed. If, for example, a carrier wave of a frequency of 140 MHz is combined with a modulating frequency of 1 MHz, two sidebands will be created, one with a frequency of 139 MHz and the other with a frequency of 141 MHz. In this case, the total bandwidth will be 2 MHz, twice that of the modulating frequency. AM is necessary for certain TEC measurements and provides the conceptual transition between the phase speeds of individual radio waves, and the group speeds of combined waves as discussed earlier in this section. The application of this technique is discussed in Section E. A complete understanding of the wave properties is mandatory when analyzing the effects of the ionosphere on the wave.

SECTION D — IONOSPHERIC EFFECTS ON AN ELECTROMAGNETIC WAVE

General

Artificially generated radio waves which traverse the ionosphere, particularly at the oblique angle, are drastically affected by the medium. Whether the wave originates from a ground-based or satellite-borne transmitter, the effects are the same.

Refractive Effects

As a radio signal penetrates the ionosphere, refraction begins to affect the signal. As the signal speed decreases, the direction of propagation departs more and more from a straight line (Figure 12). When the signal crosses the narrow "slab" where the electron density is greatest in the ionosphere (the F-region peak), an inflection in the direction of travel occurs. As the signal leaves the ionosphere, the propagation path again becomes straight but appears at the receiver to have originated at some point other than the true origin. Refraction causes errors in measurements of the distance and direction of the source. The distance error is caused by the reduction in signal speed as it passes through the medium. The refraction process, or "bending" of the signal, results in the direction error.

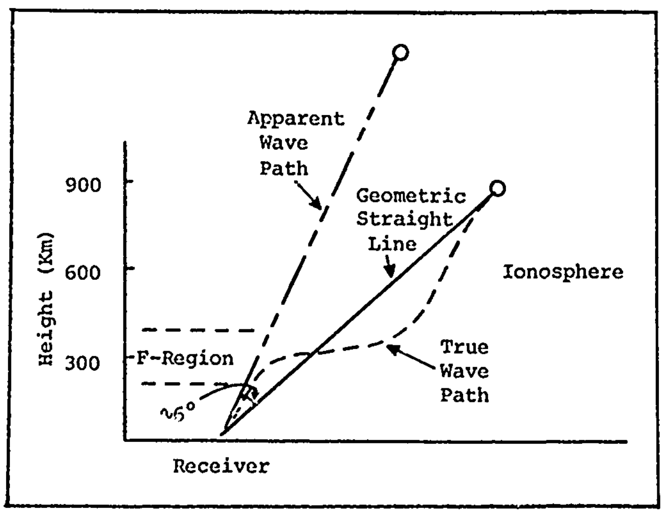

Figure 12. The Deviation of an Electromagnetic Wave as It Passes from a Space-Borne Transmitter, through the Ionosphere, to a Ground-Based Receiver. Radar waves are affected in the same manner.

Refractive effects are directly proportional to the number of electrons encountered by the wave and are inversely proportional to the wave frequency. At a given frequency, refractive effects are most severe at shallow angles of incidence between the path of propagation and the ionosphere. To minimize positional errors in the tracking of orbiting objects, vigorous efforts have been expended to develop realistic models of the ionosphere. Measurements of the TEC over numerous geographic locations are used as inputs to these models by the Air Weather Service. The Air Force Cambridge Research Laboratories (AFCRL) [6],[7] adapted and developed the models and techniques for the Air Weather Service for obtaining reasonably accurate TEC measurements.

SECTION E — TEC MEASUREMENTS

General

TEC measurements infer the number of electrons encountered by radio waves as they pass from a satellite through the ionosphere to ground-based receiving systems [7]. These measurements are possible by monitoring satellite beacon frequencies that are far above the ionospheric penetration frequency to be receivable at all times. On the other hand, the frequency must be low enough to sustain measurable group speed and polarization changes as a result of interactions with the ionosphere and the geomagnetic field. The frequency range from about 40 to 400 MHz is best suited for reliable TEC measurements. One current technique (the Faraday technique), makes use of the 136, 137, or 140 MHz beacons aboard near-geostationary satellites such as the Applications Technology Satellite (ATS), International Telecommunications Satellite (INTELSAT), and Synchronous Communications Satellite (SYNCOM) series [3], [7],[10]. Another more complex technique involves the use of two beacons on the same satellite, widely spaced in frequency, and relates the difference in signal group speeds to the number of electrons encountered by the wave [3],[7]. Both the Faraday and the "group-path delay" techniques are described in this section. Geostationary satellites permit consistent and continuous observations from a fixed geographic location over long periods of time. Such satellites can be monitored from almost any point on the earth's surface, excluding the polar caps, as the satellites are near stationary over the equator. The most obvious and serious limitation to this technique is that only certain portions of the ionosphere can be sampled, the middle- and low-latitude areas; whereas, the most complex and dynamic changes in the ionosphere occur over the high-latitude areas. The Faraday technique is based on the principles of "magneto-ionic splitting" and is explored next.

The Faraday Technique

Measurements of the TEC of the ionosphere using the Faraday technique are based on the amount of polarization change the signal experiences along its path of propagation.

a. Magneto-Ionic Splitting. As a radio signal leaves the satellite and encounters the magneto-ionic medium, the ionosphere, it separates into components

(Figure 13). Each of these components has it's own speed, path of propagation, and index of refraction. To simplify this discussion, assume that the wave has two components; each will be treated as an entity. The splitting of the wave is the result of the presence of the earth's magnetic field. The separate components, or "rays," are given the names "ordinary" and "extraordinary" rays and are denoted by the letters "O" and "X", respectively (Figure 14a). (Note: The term "X" ray as used in this context should not be confused with the extremely short wavelength solar radiations called X-rays.) Each of these rays, the "O" and the "X", travels through the ionosphere at a different rate of speed, with the "O" ray being the slower of the two. Each ray undergoes a rotation of it's plane of polarization that is in an angular direction opposite from the other (Figure 14b). The amount of rotation experienced by the "X" ray (α degrees) is determined by the strength of the local magnetic field and the angle of intercept between the ray and the field line. The amount of rotation experienced by the "O" ray (β degrees) is determined by the number of free electrons encountered by the ray along the path of propagation.

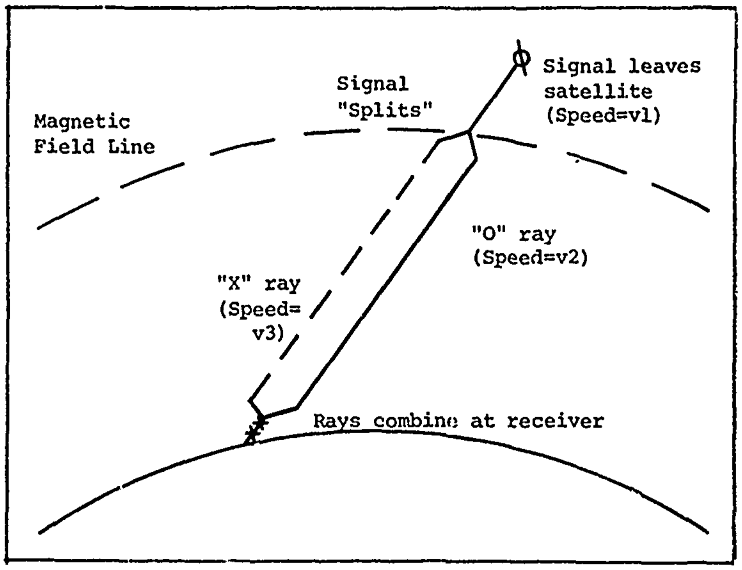

Figure 13. Schematic of Satellite-to-Earth Propagation.

In a ground-based receiver, the "O" and "X" rays are combined into a single wave form denoted by the letter "R" (Figure 14b). The "O" and "X" rays have crossed the ionosphere at different speeds, and when combined into the "R" ray there is a difference in phase from that of the originally transmitted signal. This phase difference, because of the angular rotation (polarization change) of both the "O" and "X" rays, results in a total polarization difference between the

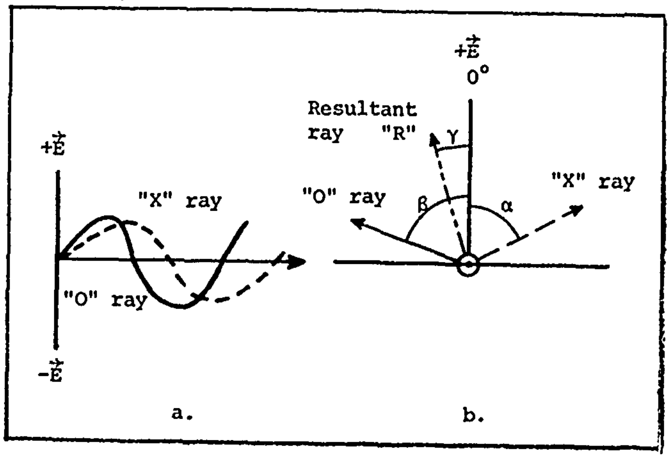

Figure 14. The Difference in Angular Rotation Between the Ordinary ("O") and Extraordinary ("X") Components of an Electromagnetic Wave Crossing a Magnetic Field. The direction of propagation is to the right in Figure 14a, and toward the observer in Figure 14b.

transmitted and received signals (γ degrees). The amount of polarization change experienced by "X" ray can be determined if the local magnetic field strength and the angle of intercept between the ray and the magnetic field lines are known. As the source of the signal (the satellite) and the ground-based receiver remain in fixed positions, this value can be determined and subtracted from the resultant ray. The residual may be converted to yield the total number of electrons encountered by the wave along its passage through the ionosphere. This technique is reasonably accurate in measuring the TEC in the lowest 2000 km of the atmosphere [7]. The actual conversion process will be discussed at the end of the next section. But first, a description of the recordings of the polarization technique is in order.

b. Observing Principles. The system commonly used for measurement of polarization change is known collectively and appropriately as the "polarimeter." The basic components of the system are: a fixed receiving antenna; a radio receiver/amplifier; and a simple recorder. Since the satellite remains near-stationary with respect to the receiving antenna for long periods of time, and the cone of acceptance of the antenna is near 10 degrees, only occasional positional adjustments of the antenna are required. Similarly, as the transmitted frequency remains constant for long periods of time, only normal tuning and calibration adjustments are required at the receiver. A typical recording device consists of a continuous strip chart with signatures imprinted on three channels simultaneously (Figure 15). One of the three channels, the amplitude channel, records the amplitude of the received signal on a relative scale. The other two channels are interconnected and record the polarization change in the satellite signal. These two channels record the same signals, but for convenience are offset internally by 25 chart divisions (millimeters). That is, for a given chart division reading on one channel, the reading of the other channel must be adjusted by 25 millimeters (mm) to compensate. This capability is helpful when one channel becomes inoperative.

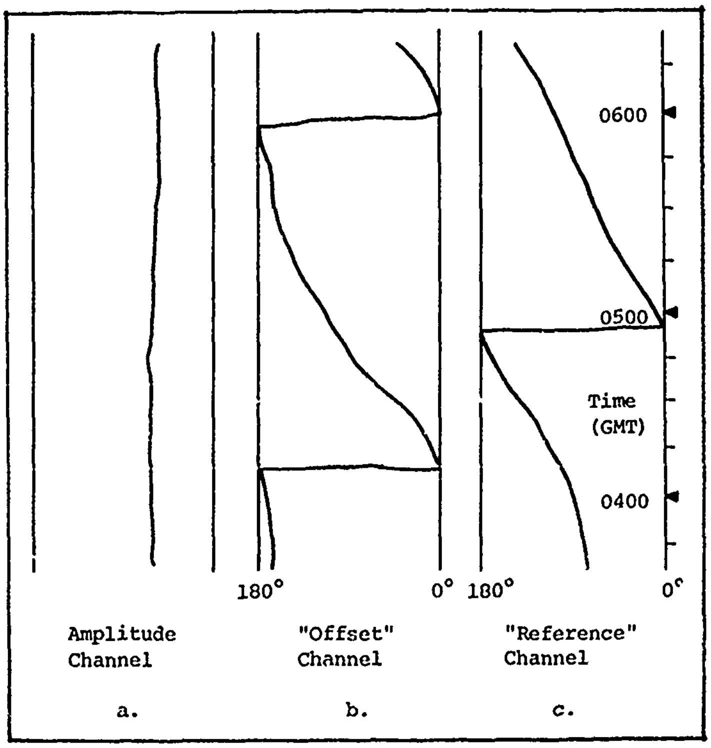

Figure 15. Example of a TEC Recording Using the Faraday Rotation Technique. The amplitude channel (a) records the amplitude of the satellite signal, with increasing values from right to left. The polarization channels (b and c) depict the rotational change in the signal due to passage through the ionosphere. Each excursion across the polarization channels indicates a polarization rotation of 180 degrees.

Only one of the two channels is required (the reference channel), and the remainder of this section is devoted to the analysis of the reference channel.

The recorder chart consists of two axes. The vertical axis is continuous and has a constant rate of speed with time. The horizontal axis extends 50 mm across the chart with increasing values from right to left. Each excursion of the trace across the channel from right to left indicates an increase in polarization of the received signal of 180 degrees. Thus, each millimeter change measures a polarization of 180/50, or 3.6 degrees. This change of 3.6 degrees is equal to a change of 0.1×10^{16} electrons/meter^2 along the path of signal propagation. A full excursion across the reference channel (a change of 180 degrees in polarization) is equal to a change of 5.0×10^{16} electrons/meter^2 along the same path. As mentioned earlier, an excursion across the chart from right to left indicates an increase in TEC, and conversely, a full excursion from left to right indicates a decrease by the same amount. The TEC can be found by the use of the following equation:

$$TEC_m = TEC_o + N(5.0) + \text{Chart Reading (mm)}/10 \qquad (2)$$

where TEC_o is a constant which accounts for the local magnetic field strength and the angle of intercept between the wave and the magnetic field line, i.e., the angular rotation of the "X" ray. N is the number of excursions across the polarization channel. The actual chart reading (in mm) is then divided by 10 and added to the preceding terms to yield the TEC (TEC_m in the equation) measurement in units of 10^{16} electrons/m^2. A significant limitation to the use of the Faraday technique for TEC measurements is caused by imperfect models of the electron content of the ionosphere above 1000 km. The model imperfections can introduce measurement errors as high as 14% [7]. Nonetheless, the simplicity of the technique and the unsophisticated equipment required, coupled with comprehensive geographical coverage, can add a valuable dimension to synoptic ionospheric studies.

The Group-Path-Delay Technique

This method of measuring TEC is more complex but considerably more precise than the Faraday technique [7]. More elaborate transmitting and receiving equipment is required because two widely separated frequencies are used rather than a single frequency as is used in the Faraday method. However, one important advantage to this method (the group-path delay) is that it is influenced little, if any, by the earth's magnetic field. In addition, a more complete picture of the TEC between the satellite and ground is possible, since the Faraday technique can only approximate the number of electrons above 1000 to 2000 km [7].

Refractive effects, described in Section D, result in a slowing of the speed of an electromagnetic wave as it passes through an ionized medium. For radio waves in the frequency ranges encompassing the lower HF, VHF, and UHF, this reduction in speed can be related to the TEC of the ionosphere by the following equation:

$$\Delta t = \frac{40.3}{c\, f^2} TEC \qquad (3)$$

where: Δt is the time difference (in nanoseconds) between the travel time of the signal and the travel time that the wave would have in a vacuum; c equals the speed of light in a vacuum (3×10^8 m/sec); and f is the system operating frequency. A typical time delay for a radar operating at 430 MHz might range from 10 to 1000 nanoseconds [7]. Equation (3) can be applied when two radio signals, widely spaced in frequency, are used. The amplitude modulation of the two frequencies is required (see Section C). For example, on the ATS-6 satellite a strong radio signal (a carrier) is generated at a frequency of 360 MHz. A modulating frequency of 1 MHz is added to this carrier. Thus, in addition to the carrier wave at 360 MHz, sidebands are created at 359 and 361 MHz. The same process is used for a carrier at 140 MHz, producing sidebands at 139 and 141 MHz. The receiver system removes the modulating frequencies from the two carriers and determines the difference in propagation time (group-path delay) between the two carriers (Δt). This time delay can be input to Equation (3) to yield the TEC measurement. The intercomparison of the group-path delay for TEC measurements is not seriously influenced by the local magnetic field strength or the zenith angles of the waves. A more definitive account of this technique is provided by Davies, et al, [3].

Variations in TEC

Any phenomenon which alters the ionospheric electron content will influence, to some extent, the polarization, the group speed, the amplitude, or all three properties of a traversing radio wave. Since the electron content is highly dependent on ionizing radiations from the sun, there are marked variations diurnally, seasonally, as well as longer-term variations directly related to the level of solar activity (the 11-year cycle). Other variations result from geomagnetic storms and short-term changes due to X-ray emitting solar flares. Many other variations are observed which are less understood. The remainder of Section E will be concerned with describing some of the more common variances.

a. Cyclical Variations in TEC. Diurnal TEC curves vary somewhat depending on the season. A typical summertime curve during quiet and geomagnetic conditions will exhibit a rather smooth minimum just prior to local sunrise (Figure 16). The electrons are present in the F-region of the ionosphere in small quantities, but are almost entirely absent in the E- and D-regions. A well-defined maximum will normally be observed at local noon. (Note: These times refer to the point where the satellite signal penetrates the ionosphere, the sub-ionospheric point, which may be several hundred miles distant from the receiving location).

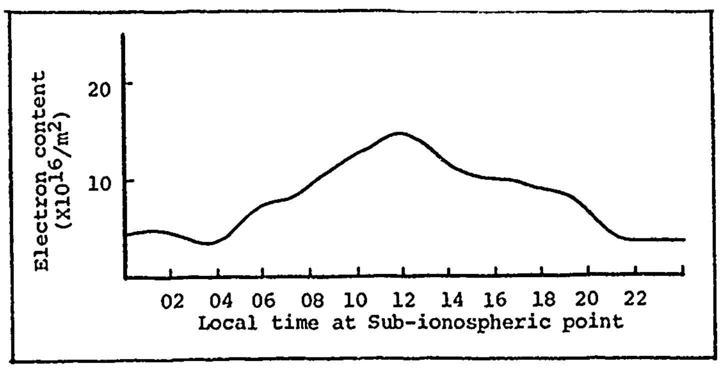

Figure 16. A Quiet Day Total Electron Content Curve (summer month). (Recorded at Athens, Greece on 21 June 1974.)

During the equinoctial months, at least over the middle latitudes, there is a tendency for the maximum to be shifted to the late afternoon hours. The maximum daytime TEC value is normally higher than the summertime value. Generally, too, a minor peak occurs near 0800 local time (Figure 17). During periods of high levels of solar activity, the daytime maximum TEC will be some 50% greater than during quiet periods. Finally, there is an overall greater TEC observed near the peak of the 11-year solar activity cycle coincident with the strongest ionizing solar radiations.

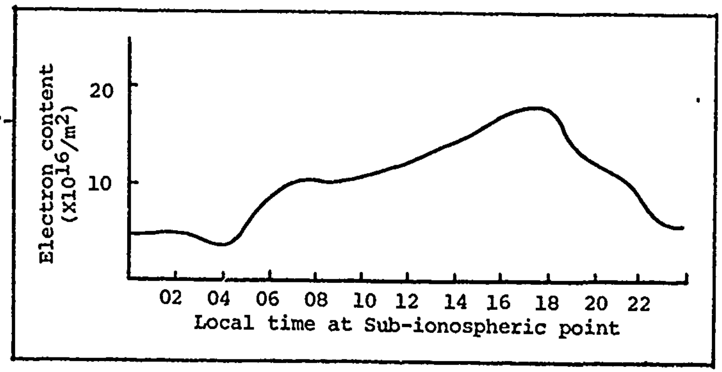

Figure 17. A Quiet Day TEC Curve (equinoctial month). Note the shift in time for the maximum value to the late afternoon hours. Also, as is typical, the maximum is greater than that of a quiet summer day. Usually a minor peak appears near 0800-0900 during the equinoctial months.

b. Geomagnetic Storm Variations. During geomagnetic storms the TEC exhibits strong variability. No two disturbed periods will show exactly the same pattern; however, certain similarities can be observed [11]. Figure 18 is an example of one disturbed period when changes in TEC were directly related to a geomagnetic storm; such changes have been observed at other times, however, for no apparent geophysical

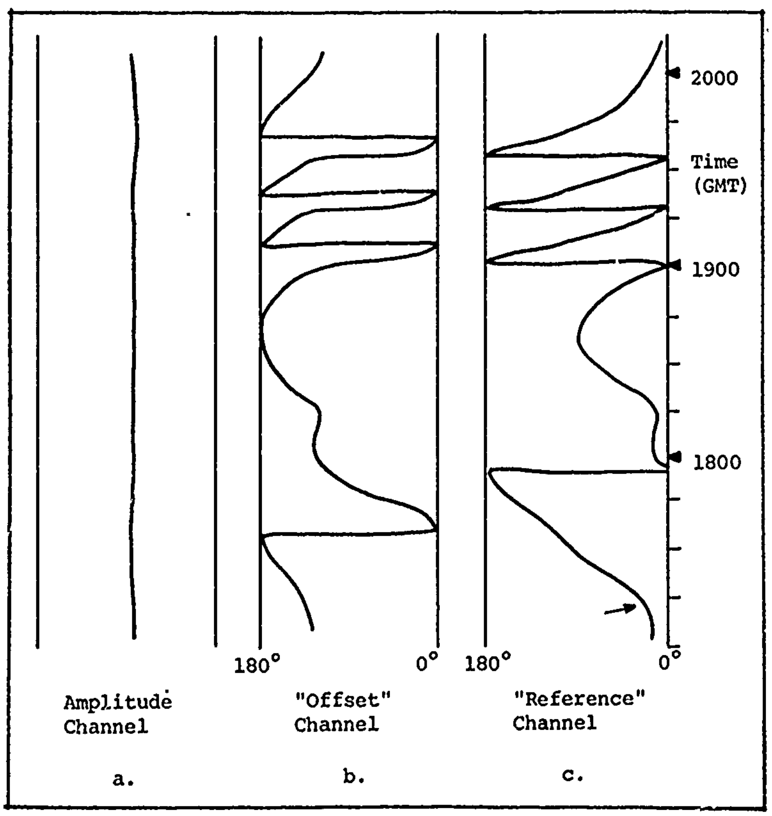

Figure 18. A Recording of Rapid Polarization Changes Observed at Athens, Greece on 15 September 1974. A geomagnetic storm began at 1342 GMT on 15 September 1974. A sharp increase in TEC began near 1700 GMT, reaching a peak near 1840. An extremely rapid decline then followed. Figures 19 and 20 are samples of the daily TEC curves prior to, and during this disturbance.

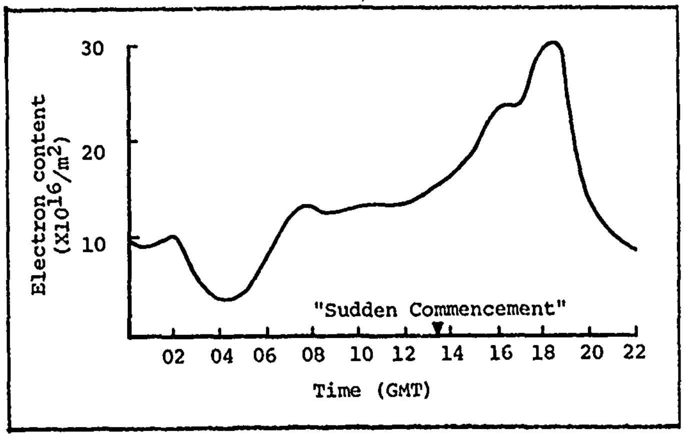

Figure 19. TEC Curve for 15 September 1974 Over Athens, Greece. A major geomagnetic storm began with a sudden commencement at 1342 GMT, followed in three hours by a sharp rise in TEC. This sharp rise is often observed with a sudden commencement of a magnetic storm over stations which are sunlit.

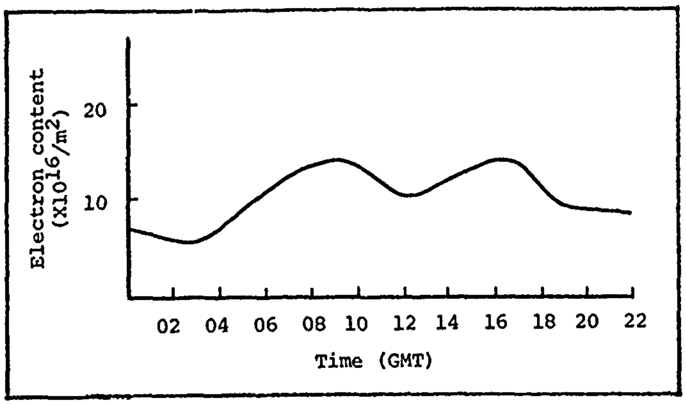

Figure 20. The TEC Curve for 16 September 1974 Over Athens, Greece. The geomagnetic field was severely disturbed. The pre-noon peak in TEC was slightly higher than normal, but the major peak late in the day was severely depressed as is common during disturbed periods.

reason [7]. This particular storm began with a strong "sudden commencement" at 1342 GMT on 15 September 1974. The reflection of this disturbance in the ionosphere began some three hours later in the form of an exceptionally sharp increase in TEC. Of special interest in this case is the initial sharp rise in TEC at 1714 GMT and the much sharper decline after 1840 GMT (Figures 18 and 19). The initial enhancement in TEC as shown in Figures 18 and 19 is often observed after the onset of a strong geomagnetic storm, while the ionosphere is still sunlit [11]. The shape of the curve during the ensuing 24 hours is also typical (Figure 20). In this example, the daytime curve for 16 September exhibits the double maxima characteristic of these latitudes during the equinoctial months, but the diurnal peak which appears late in the afternoon is considerably depressed.

c. Short-Lived Variations, Real and Spurious. As discussed earlier, any event which alters the electron content of the ionosphere will to some extent influence the signal-group speed, the polarization, the amplitude, or all. Spurious radio signals from sources other than the satellite can also appear on the TEC recorder, and care must be exercised to distinguish these false signatures from real ones. The first of the real changes associated with short-lived phenomena is the Sudden Increase in Total Electron Content called the "SITEC." As the name suggests, this phenomenon is marked by a sharp increase in electrons, and on Faraday equipment is apparent mainly on the polarization channels as an abrupt excursion to the left. It is the result of a large X-ray emitting solar flare. X-rays in the wavelength from 10 to 1030Å are absorbed in the E- and F-regions of the ionosphere and cause a rapid increase in electrons. This increase may range from 50% to 100% [9]. Figure 21 depicts a recording of a SITEC.

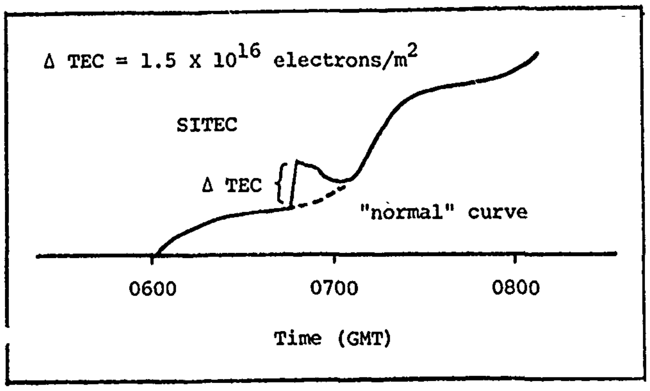

Figure 21. An Example of a Sudden Increase in Total Electron Content (SITEC), Recorded on the Polarization Channel on the Polarimeter at Athens, Greece. This SITEC was associated with a large, brilliant solar flare on 4 July 1974. The initial increase in TEC began at 0648 GMT and showed a nearly three-fold increase in ionospheric electron content as a result of the massive amounts of X-rays released by the flare.

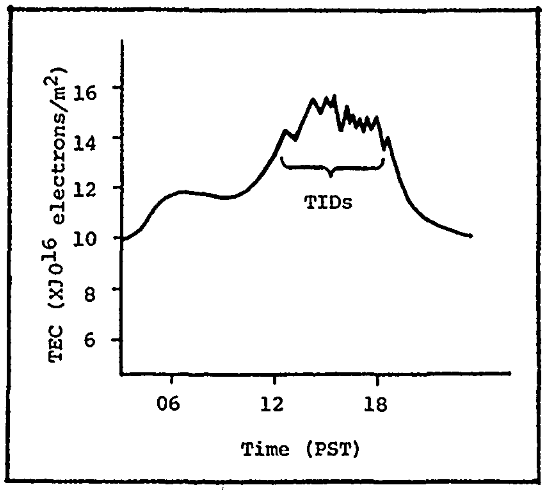

Figure 22. Fluctuations in TEC Due to Travelling Ionospheric Distributions (TIDs). These measurements were made at Ely, Nevada by the Stanford Research Institute, while monitoring the ATS-1 satellite on 5 June 1967.

Travelling Ionospheric Disturbances (TIDs) will also produce variations in the TEC over a specific location, the duration of which may range from several minutes to several hours [4],[13],[14]. An example of actual oscillations recorded during the passage of a train of TIDs is shown in Figure 22. The abnormality in the F-region known as Spread-F (described in Section B) gives rise to the phenomenon of "scintillation."

Scintillation results in the rapid fluctuation of signal amplitude and is often accompanied by diffuse, but rapid changes in polarization of the signal. The rate of scintillation is fairly rapid and may persist on a given satellite-to-earth path for several hours. Sporadic E may have a slight affect on the amplitude (a slight decrease) of the signal, but polarization changes are unlikely [8]. The Sporadic E layer may be dense enough to deflect a small part of the satellite's signal, but the layer is generally only a kilometer or so thick. The population of the thin Sporadic E layer is a very small fraction of the total number of electrons encountered by the satellite signal.

Spurious signals recorded on TEC equipment may originate from any of a number of different sources, both natural and man-made. Among the natural sources is the sun. Strong solar flares will often generate radio noise across a wide band of radio frequencies including HF, VHF, and UHF. Such a radio burst at 136 MHz was recorded on the Faraday equipment at Athens, Greece on 23 September 1974 at 1204 GMT (Figure 23). This radio burst was also recorded on the solar radio telescope. It was assumed to have originated from an active solar region which had rotated over the west limb of the sun a few days earlier. Nearby thunderstorms may also inject natural radio noise into the TEC-receiving antennas. Such a case was observed with the approach

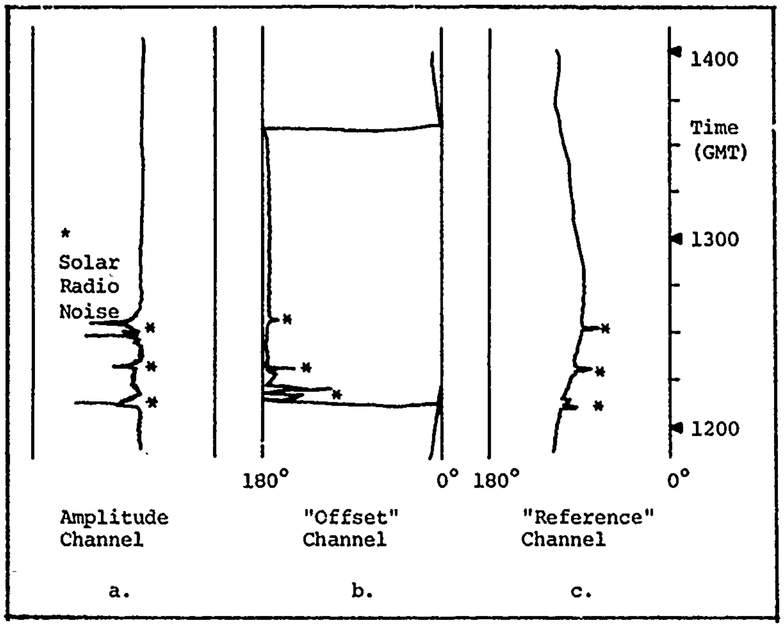

Figure 23. Actual Recording of a Strong Solar Radio Burst Superimposed on the Signal Received from SYNCOM III Satellite at Athens, Greece. This series of radio bursts occurred between 1204 and 1233 GMT, 23 September 1974. Note the strong increase recorded in amplitude, coupled with confused changes in polarization.

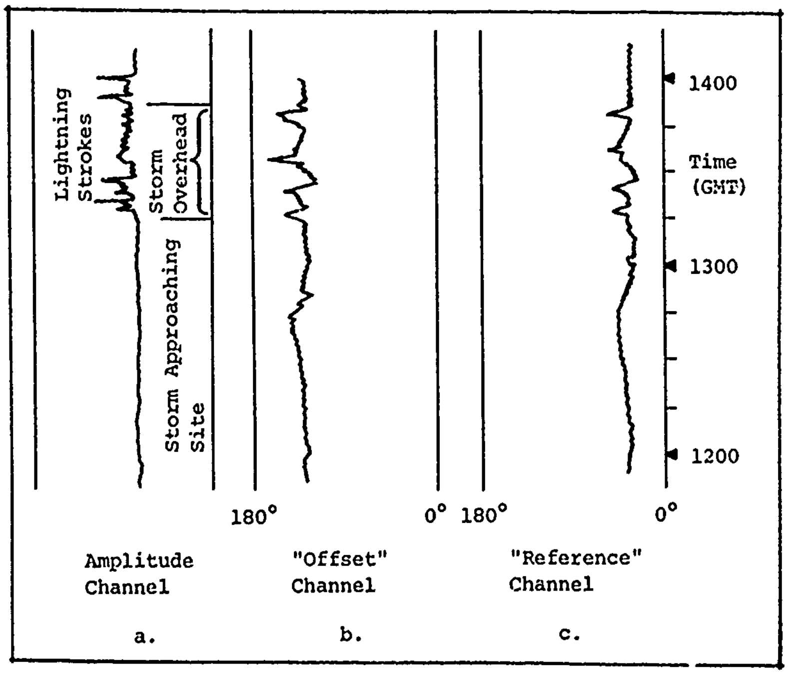

Figure 24. Noise Generated by a Thunderstorm. As the storm approached the site, steadily increasing amplitude changes were recorded. The polarization changes were confused or "random," but appeared to preceed the lightning strokes by a few seconds.

of a large thunderstorm to the TEC antenna at Athens in early September 1974 (Figure 24). Of particular interest in this example was the apparent increase in the electron counting rates (as deduced by the slight polarization increase) just prior to the radio emissions associated with the lightning flashes in the storm. This small increase may have been associated with the tremendous electrification within the storm itself, or in the ionosphere well above it. Man-made signals are often observed to "ride in" on the satellite signal into the TEC antenna. A spurious signal, assumed to have originated from a satellite passing close to the propagation path from the satellite SYNCOM III, is shown in Figure 25. The detection and identification of any of the foregoing phenomena will depend on their intensity and duration as well as on the sensitivity and location of the receiving antenna. As further experience is gained with the equipment, other phenomena may also be identified.

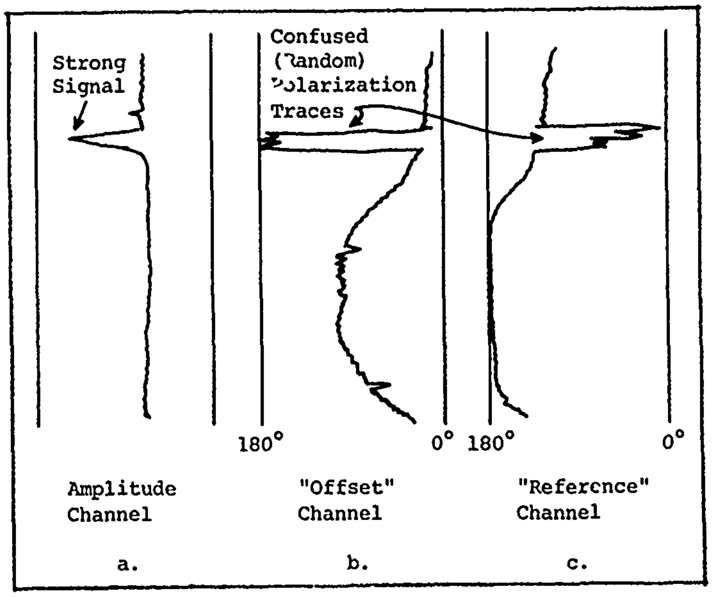

Figure 25. An Example of an Externally Generated, Man-made Radio Signal. The extraneous signal was presumed to have originated in another satellite transmitter, as it passed through the receiving antenna's field of view.

SECTION F — SUMMARY

The ionosphere presents some intriguing and challenging problems to systems which must transmit electromagnetic signals through it. The gross effects of the ionosphere, along with those of the geomagnetic field, are explainable in terms of relatively simple physical processes. Variations in the medium itself do not lend themselves to easy analysis due to their randomness and complexity. The phenomena of refraction and radio signal speed retardations lead to serious errors in the detection and tracking of objects in the higher levels of the earth's atmosphere. These effects may be somewhat compensated for through the timely and accurate measurements of the total electron content of the ionosphere over numerous geographic locations and the input of these measurements into realistic ionospheric models. While the grosser changes in the total electron content of the ionosphere are of paramount significance to the ionospheric physicist and the systems manager, the identification of various short-lived phenomena can result in a greater appreciation for the energetic aspects of solar-flare activity and the near-infinite dynamism of the ionosphere.

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Appendix A

DEFINITIONS

Angstrom: A unit of measurement equal to 10^{-8} centimeters. This term is commonly used to define electromagnetic wavelengths of less than one millimeter.

"Condensations" of electrons: Collections or aggregates of electrons in the Ionosphere. These collections are analogous to the condensation of moisture in the lower atmosphere which produces clouds.

Free electrons: Electrons which are removed from their parent atoms and are free to meander throughout the medium in which they are contained.

Geomagnetic storms: Fluctuations in the earth's magnetic field as a result of energetic solar particle radiations, or of interactions between the earth's magnetic field and the interplanetary field which originates in the sun.

High Frequency (HF): Radio waves in the frequency range from 3 to 30 megahertz (MHz). (Also referred to as "short waves".)

Ionization: The process whereby the electrons orbiting the nucleus of an atom are removed by the absorption of high energy radiation. The absorbed radiation may be electromagnetic or particulate.

Magnetic "Crochet": The name given the signature recorded on ground-based magnetometers coincident with some solar flares. Electrical current systems present in the E-region of the ionosphere become momentarily "hardened" during some energetic solar flares due to the creation of excess electrons via the ionization process.

Magnetometer: A ground-based instrument designed to detect indirectly changes in the earth's magnetic field. Changes in the electrical conductivities of the magnetosphere/ionosphere result in induced changes in earth surface electrical fields which are in turn sampled by the magnetometer.

Magnetosphere: The region surrounding the earth where the earth's magnetic field is stronger than the interplanetary field in which it is immersed. The magnetosphere provides a vast reservoir for the storage of energetic particles originating on the sun.

Nanoseconds: An interval of time equal to 10^{-9} seconds.

Neutral Atmosphere: A term used to collectively describe the un-ionized constituents of the earth's atmosphere. As these constituents are influenced by the gravity, the greatest neutral atmosphere density is found near the ground and decreases as one ascends.

Penetration Frequency: The lowest frequency radio wave which will penetrate an ionized medium such as the ionosphere. The penetration frequency is a function of the electron density of the medium. In the ionosphere, this frequency may range from as low as 1.5 MHz at night to as high as 18 MHz during the sunlit hours. The greatest penetration frequencies are observed in the ionosphere when the solar X-ray and extreme ultraviolet (EUV) radiations are the greatest.

Scintillation: A random, generally rapid, variation in amplitude of an electromagnetic wave (eliptical or radio) due to irregularities between the signal source and the observer. "Twinkling" starlight is one example of optical scintillation. Radio scintillations occur on signals from extraterrestrial sources due to irregularities in the ionosphere.

Short Waves: (See High Frequency)

Short Wave Fade (SWF): A term used to describe the phenomenon of absorption of High Frequency (HF) radio waves that occurs simultaneously with some energetic solar flares. Large amounts of X-rays in the very short wavelengths (1 to 10 Angstroms) are released with the flare and are absorbed in the lower ionosphere (50 to 90 kilometers above the ground), creating a large number of free electrons. These free electrons remove energy from traversing radio waves, and through recombination with neutral constituents, contribute the removed energy to the medium in the form of thermal energy. The SWF becomes common and is quite severe during periods of high solar activity and may result in prolonged outages on HF communications and detection systems.

Sinusoidal: The more or less smooth variation of a variable around a mean value or baseline, whereby a repetitive pattern is established. A sinusoidal function can be synthesized by the application of the sine function.

"Soft" X-rays: A term used to generally define electromagnetic radiations in the wavelengths from 10 to about 100 Angstroms. Shorter wavelength radiations (less than 10 Angstroms) are called "hard" X-rays.

Ultra High Frequency (UHF): Radio waves in the frequency range of 300 to 3000 MHz.

Very High Frequency (VHF): Radio waves in the frequency range of 30 to 300 MHz.