# Chapter 5



## MODERN TOTAL ELECTRON CONTENT MEASUREMENT TECHNIQUES

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ABSTRACT

Since the mid-1950s measurements have been made of the total electron content, (TEC), of the earth's ionosphere by various techniques, beginning with Faraday rotation of lunar reflected VHF radio waves. With the advent of artificial earth satellites, in 1957, Faraday rotation of VHF signals from low orbit satellites became a means of determining TEC versus satellite latitude. Beginning in the mid-1960s continuous measurements of TEC at one geographic location became possible using the Faraday rotation technique, from VHF telemetry signals of opportunity transmitted from geostationary satellites. The differential Doppler technique has been used since the early 1960s to correct automatically for ionospheric range-rate errors on low orbit navigation satellites, and beginning in the mid-1970s both differential group delay and differential Doppler have been used on a high-orbit satellite navigation system to correct for first order ionospheric effects on range and range-rate. All three techniques can be used to give measurements of relative TEC, but they each have different potential problems of calibration to obtain absolute TEC from the measured values.

Because measurements of TEC have largely depended upon using radio signals transmitted from satellites of opportunity, few attempts have been made to standardize the technique, to combine TEC data from many stations to improve TEC prediction capability, or to use TEC data directly to make realistic models of the topside ionosphere. Now the potential availability of suitable radio signals from various satellites for making measurements of TEC is undergoing a transition, and will provide new opportunities for making routine measurements of this parameter.

An improved knowledge of the behavior of TEC is becoming increasingly important as a means of doing research on ionospheric behavior, especially during disturbed ionospheric conditions. In addition, the time delay effects of TEC will become even a more important source of potential error in modern trans-ionospheric positioning systems as the required accuracy of modern satellite systems inevitably increases. Realistic models and methods for correcting for the time delay effects of the TEC on such modern systems require new TEC measurement capability. This paper describes the basic measurement techniques and various methods of making such measurements.

## 1. INTRODUCTION

There are basically three direct methods of measuring the total electron content of the ionosphere using radio techniques. These are: 1) Faraday rotation; 2) group delay; and 3) differential carrier phase. All of these techniques have been used in some form or other in making measurements of the ionosphere, or in systems which automatically correct for ionospheric time delay effects and its rate of change. All of these techniques have disadvantages in measuring absolute values of TEC; yet, these difficulties have been overcome so that many groups have made measurements of TEC from radio signals transmitted from various satellites of opportunity. In a few cases, satellite radio beacons have been launched specifically for making measurements of TEC, as well as for amplitude and phase scintillation, but these satellites have been relatively short lived, and have generally required more complex receiving instrumentation than has been easily obtained by many potential observers. Hence the TEC data base available from these dedicated beacon satellites is very limited in its geographic coverage. However, dedicated beacon satellites have provided important new information about the behavior of TEC from those regions of the world where observations were made. Davies, [1980] has reviewed the results from the dedicated ionospheric beacon on board the ATS-6 geostationary satellite. Fremouw, et. al., [1985], described the HILAT ionospheric beacon on a low polar orbiting satellite, and Fremouw, et. al., [1978], showed the first results from the Wideband low orbit dedicated beacon satellite experiment. A variation of the differential phase method of measuring relative changes in TEC to determine absolute TEC values was proposed by Burns and Fremouw, [1970], and was first attempted on the Wideband dedicated beacon satellite.

Measurements of the TEC of the earth's ionosphere are important for several reasons. The existing models of the topside of the ionosphere are not sufficiently accurate for system's designers or operators to use to make a state-of-the-art correction for the time delay effects of the ionosphere on their systems. Most of the attention in the ionospheric modeling community, both with empirical modelers, as well as with those who construct models from physical first principles, has been in generating and improving the bottomside ionosphere to satisfy the requirements of high frequency propagation. This concentration on the bottomside ionosphere has been because of the greater number of potential users of their models in high frequency propagation.

Now, with the increasing number of people involved in satellite ranging systems requiring high precision, those who use satellites for precise time transfer, radio astronomers who require a knowledge of the effects of the ionosphere on their measurement accuracy, and other applications groups, it is becoming more important to have continuous measurements of carefully calibrated values of TEC for these many applications. The improved models of TEC will then follow, but only when newer TEC data sets become available can the modelers be assured that their efforts are an improvement over existing TEC models.

The world has approximately one hundred ionospheric sounders making routine measurements of the bottomside of the earth's ionosphere. Many of these stations report their important propagation parameters to one of the World Data Centers on an hourly, or a 24 hour summary, basis. These parameters are very important in predicting HF propagation paths on an hour to hour basis, and the 24 hour summaries are potentially very important in improving models of the bottomside ionosphere. Unfortunately, no equivalent network for making TEC measurements exists. There are perhaps no more than a twenty stations in the entire world where routine measurements of TEC are made, and only half of those stations report their data to one of the World Data Centers, either in near-real-time for improving prediction capabilities, or in summary form so that modelers can use the data to compare with their model improvement efforts.

Hopefully, the TEC measurement techniques presented in this paper will give the ionospheric research community sufficient additional information to begin to make measurements of TEC to aid in solving the problems of the day-to-day variability of the topside of the ionosphere. Also new TEC data from wide areas of the world, over sufficient time intervals, particularly during magnetic storms, and during various solar activity conditions, will be vital to ionospheric modelers in making realistic improvements to models, particularly of the topside, of the ionosphere. These improved TEC models will be of increasing importance to many trans-ionospheric propagation systems users in future years as their operational requirements for ionospheric time delay become more stringent. In this paper, first an outline of the possible methods of measuring TEC will be given, with a brief historical view of how each of these techniques has been used in the past. Then, potential methods of measuring TEC using new satellite signals of opportunity will be outlined.

## 2. FARADAY ROTATION

When a linearly polarized radio wave traverses the ionosphere the wave undergoes rotation of the plane of this linear polarization. At frequencies of approximately 100 MHz and higher the amount of this polarization rotation can be described by:

$$\text{OMEGA} = K/f^2 * \int B \cos(\theta) * N\, dh \quad \text{(radians)} \qquad 1.$$

where the quantity inside the integral is the product of electron density times the longitudinal component of the earth's magnetic field, integrated along the radio wave path. Many ionospheric workers have used this effect, named for Michael Faraday who first observed polarization changes in an optical experiment, to make measurements of the TEC of the ionosphere.

Since the longitudinal magnetic field intensity, $B * \cos(\theta)$, changes much slower with height than the electron density of the ionosphere, equation 1, can be rewritten as:

$$\text{TEC} = \frac{\text{Omega} * f^2}{K * B_L} \qquad 2.$$

where $B_L = B * \cos(\theta)$ is taken at a mean ionospheric height, usually near 400 km, $K = 2.36*10^{-5}$, and TEC is $\int N\, dl$.

Typical values of polarization rotation for northern mid-latitude stations monitoring radio waves from a geostationary satellite near their station meridian are given in Figure 1, as a function of system frequency and TEC. Generally, the equivalent vertical TEC is determined by dividing the slant TEC by the secant of the zenith angle at a mean ionospheric height. The equivalent vertical TEC is the one most often used for comparison purposes among sets of TEC data, due to various slant elevation angles at which satellites at normally viewed.

At 136 MHz the one way Faraday rotation observed from a geostationary satellite can be ten, or more, 180° half turns of linear polarization change. Since the measurement is made on a single frequency, there is an n * pi ambiguity in the total amount of polarization rotation; thus, the absolute TEC cannot be determined independently using this technique. The normal method of estimating this n * pi ambiguity is to compare the relative TEC determined from the Faraday rotation with values of $N_{max}$ obtained from an appropriately located ionosonde, during a time of night, when both the TEC and the density at the peak of the F2 region are low, and to rely on continuous polarization data for long periods, to insure the absolute calibration at other times. This method works well if careful attention is paid to obtaining continuous polarization data for long periods of time. Webb, [1973], described a method of resolving the n * pi ambiguity in 150 MHz two-way lunar reflected Faraday

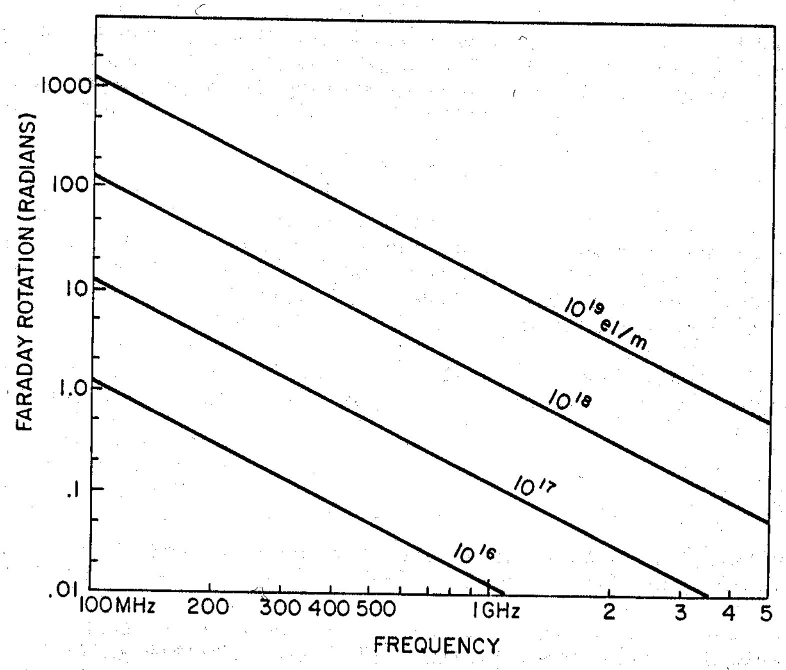


Figure 1. Faraday rotation vs frequency for various values of TEC.

rotation measurements using a fit against solar 2800 MHz radio flux.

Relatively inexpensive methods of measuring Faraday polarization changes from VHF signals transmitted from geostationary satellites of opportunity have been described by Titheridge, [1966], who used a physical rotating yagi antenna, and by Antoniadis, et. al., [1974], who developed an electronic means of generating an equivalent rotating antenna. Eis, et. al., [1977], described many aspects of determining absolute values of TEC from Faraday rotation from VHF radio waves transmitted from geostationary satellites.

The Faraday rotation technique, monitoring radio transmissions from 136 MHz telemetry beacon transmitters on geostationary satellites has been the standard technique in the past for making TEC measurements. However, modern geostationary satellites, with transponder traveling wave tube amplifiers at higher frequencies, have become so reliable that they no longer have the requirement for an independent beacon transmitter; thus, they no longer carry VHF telemetry beacon transmitters.

Effective in January 1990, the World Administrative Radio conference has re-allocated the 136-137 MHz portion of frequency spectrum to the Aeronautical Mobile Service for use on a primary basis, and has recommended that consideration be given to deleting all secondary allocations from the 136-137 MHz band. Thus, even though the geostationary satellite VHF beacon transmissions are only at the one watt power level, and are transmitted from a platform approximately 40,000 km from the earth, it appears that soon the era of making TEC measurements from VHF signals transmitted from geostationary satellites will be at an end. This need not be the case, as the approximate 1 watt transmissions from VHF telemetry signals from a space platform, at geostationary satellite distance from the earth, certainly would not interfere with the Aeronautical Mobile Service. Also, modern techniques of transmitting pseudo-random-noise encoded signals would easily allow the joint use of this portion of the spectrum. Any potential future satellite ionospheric beacon designers need not be concerned about the potential for interfering with other active radio frequency spectrum users, if modern signal transmission and processing techniques are used.

The past approximate 25 years of VHF telemetry transmissions has allowed many observers to make TEC measurements using the Faraday rotation technique. Since this era appears to be drawing to a close another technique will likely be used for future measurements of TEC.

## 3. DIFFERENTIAL CARRIER PHASE

As a radio signal traverses the ionosphere the phase of the carrier of the radio frequency transmission is advanced. The amount of this carrier phase advance, also called phase path decrease, can be expressed as:

$$\text{Phi} = \frac{1.34 * 10^{-7}}{f} * \text{TEC} \quad \text{(cycles)} \qquad 3.$$

where f is the system operating frequency in Hertz, and TEC is in units of electrons/$m^2$ column. In practice, the amount of this phase advance cannot readily be measured on a single frequency, unless both the transmitter and the receiver have exceptional oscillator stability and the satellite orbital characteristics are well known. Usually two, coherently derived, frequencies are required for this measurement.

If two, coherently derived, frequencies are indeed transmitted from a satellite, the differential phase shift between the two frequencies can be measured. That differential measurement is related to TEC by:

$$\text{Delta (Phi)} = \frac{1.34}{f_L} * 10^{-7} * (m^2 - 1)/m^2 * \text{TEC (cycles)} \qquad 4.$$

where $m = f_H / f_L$. The U. S. Navy TRANSIT system, described by Black, [1980], has used this technique for automatic correction for first order ionospheric range-rate error correction since the system was first launched in the 1960s. Even though the U.S. Department of Defense intends to terminate its control over the TRANSIT navigation system by the mid-1990s, due to the imminent completion of the high-orbit NAVSTAR Global Positioning System, (GPS), the installed number of commercial navigation receivers is very large, and it is likely that the TRANSIT satellite navigation system will continue to operate well into the 21st century. As of mid-1989 there were over ten TRANSIT satellites in orbit. Someone desiring to construct an ionospheric monitoring system using signals from the TRANSIT navigation signals should expect to have signals available for at least a decade.

It is possible to construct a relatively inexpensive dual frequency receiver, for measuring differential carrier phase between the 150 and the 400 MHz TRANSIT satellite carriers, by converting one of the commercially available 400 MHz, single frequency, consumer navigation receivers to dual frequency operation by using the local oscillator energy from the 400 MHz receiver in a simple 150 MHz secondary channel. By taking advantage of the existing phase locked loop of the 400 MHz channel, one can divide the audio frequency by the 8/3 ratio required to directly phase compare against the audio from the 150 MHz channel. Except during times of strong amplitude and phase scintillation, a simple, dual-frequency, receiver using, as a base, an inexpensive commercially available 400 MHz receiver, should work well. If a digital output is available, which has demodulated satellite orbital elements and ID information of the Transit satellite being monitored, an automatic Transit data collection system can be assembled. Leitinger, et. al., [1975], has described a technique for combining data from Transit passes received at two, or more, sites to resolve the ambiguity in absolute TEC from the differential phase data.

## 4. GROUP DELAY

The additional time delay, over the free space transit time, of a signal transmitted from above the ionosphere, to a user on, or near, the earth's surface, is given by Millman, [1965], and can be expressed as:

$$\text{Delta t} = \frac{40.3}{cf^2} * \text{TEC} \quad \text{(seconds)} \qquad 5.$$

where TEC is the total number of electrons along the path from the transmitter to the receiver, c is the velocity of light in meters/sec., and f is the system operating frequency in Hertz. The TEC is the number of electrons in a unit cross section column of one square meter area along this path. Figure 2 illustrates the additional time delay encountered by a radio wave, as it traverses the ionosphere, as a function of its frequency.

By measuring the group path delay independently at two, widely spaced frequencies, the TEC along the path from satellite to receiver can be measured directly. If two system operational frequencies are chosen, $f_1$, and a lower

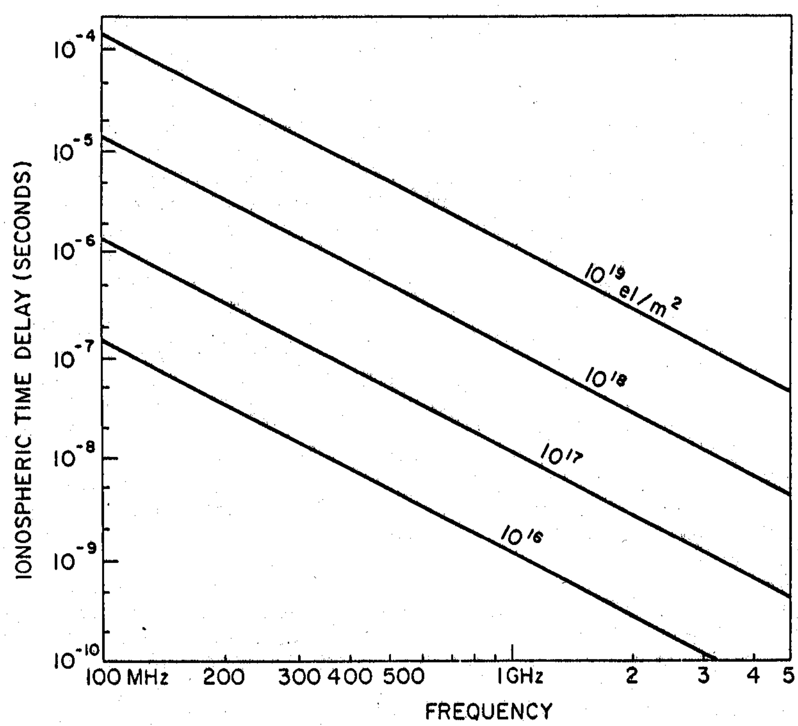


Figure 2. Time delay vs. frequency for various values of TEC.

frequency, $f_2$, from 5., above we obtain:

$$\text{Delta}_2\ t = \frac{K}{c} * \text{TEC}\ [1/f^2_2 - 1/f^2_1] \qquad 6.$$

$$\text{Delta}_2\ t = \text{Delta}\ t_1\ [f^2_1 - f^2_2] / f^2_2 \qquad 7.$$

where Delta $t_1$ is the ionospheric time delay at $f_1$.
For a direct measure of absolute TEC from the 10.23 MHz modulation phase delay at $L_2$ minus that at the higher frequency, $L_1$, we obtain:

$$\text{TEC} = 2.852 * 10^{16} * \text{Delta}_2\ t, \qquad 8.$$

A more detailed derivation of the equations for differential group delay and differential carrier phase advance can be found in Klobuchar [1985], section 10.8.

The Global Positioning System, (GPS), described by Denaro, [1981], and Parkinson and Gilbert, [1983], will consist of 21 satellites in 55 degree inclination, 12 hour sidereal orbits, such that a minimum number of four satellites will be visible to any user on, or near, the earth's surface, at all times. The GPS satellites transmit dual frequency, coherently derived, L-band signals, to automatically correct the first order ionospheric range and range-rate errors for navigation system users. The transmitted signals are the 120th and 154th harmonics of a standard 10.23 MHz frequency. These signals can also be used by ionospheric researchers to measure differential carrier phase and differential group delay, to make precise, absolute calibrated measurements of TEC.

The dual frequency, L-band signals transmitted from the GPS satellites are modulated with a pseudo-random noise code, having selective availability, so that the casual user cannot easily make ionospheric measurements from these signals. However, several groups, including MacDoran, et. al., [1984], have worked on either completely, or partially code-free, GPS receivers, for geodetic measurements, some with the potential for making ionospheric measurements. French and Gardner, [1986] discuss despreading a spread-spectrum signal without knowledge of the code, and at least two such receivers are presently close to commercial availability, [Osborne, (private communication), Allen, (private communication)]. In addition, the Jet Propulsion Laboratory is currently developing a dual frequency GPS receiver, called the ROGUE, Thomas, [1988], which will be capable of making ionospheric range corrections, for precise measurements required in NASA's TOPEX program. These new GPS code-free equipment developments bear close watching, as the future of modern TEC measurements will be greatly enhanced by successful, development of inexpensive receivers to make multi-direction differential group delay measurements from the numerous GPS satellites.

## 5. A MODERN GEOPHYSICAL BEACON CONCEPT

A major disadvantage in measuring TEC at individual ground stations, from radio signals of opportunity transmitted from satellites, is the need to have careful, uniform calibrations at all the stations, as well as timely availability of the data from each station. A concept has been proposed by Klobuchar and Hicks, [1989], in which a geostationary satellite would have an on-board beacon transponder which would simply receive signals from a potentially large number of low-power beacon transmitters on the ground. The signals received at the satellite would be re-transmitted to the earth on an S-band transponder frequency.

The low power ground transmitters would have both VHF and UHF pseudo random noise signals, separately coded for each station, and could carry low data rate geophysical information modulated onto the signals. For instance, meteorological or seismic information could be transmitted from each low power ground station, to a central data collection facility, via the geostationary satellite geophysical transponder. The complete band received at the satellite would simply be translated to one of the standard TV satellite transmit channels and could be received by a modest size antenna and receiving system similar to that currently used by consumer receivers of direct satellite TV transmissions.

The centrally located, S-Band ground receiver would decode the modulation from each beacon transmitter, demodulate the low data rate geophysical information, and make the necessary differential carrier phase, differential group delay and Faraday rotation calculation for each ground beacon transmitter. All the ionospheric and other geophysical information from potentially over one hundred ground locations would then be available at one central station for immediate use in ionospheric and other geophysical predictions.

It is even possible that, through the clever use of signal encoding, such beacon transponded signals would not interfere with the normal use of a 6 MHz S-Band satellite transponder channel. Thus, a typical satellite transponder channel could jointly transmit a standard television signal as well as the geophysical information, received at the satellite, from over one hundred ground locations within view of the geostationary satellite.

## 6. IONOSPHERIC TOMOGRAPHY

The measured quantity from either the Faraday rotation, the differential Doppler, or the differential group delay, technique is just the one-dimensional value of TEC along a specific direction. Austen, et. al., [1988], showed that by using several TEC monitoring stations spaced below a low orbit satellite pass, one could obtain the two dimensional electron density versus height profile along the path of the satellite. Electron density profiles over a large geographic area are of potentially great importance to those who require information on the height profile of electron density, such as in high frequency propagation, in looking at the details of ionospheric variability during magnetically disturbed times, and in modeling studies, where assumptions of scale height of both the topside and the bottomside of the ionosphere shape can be verified using the tomography technique. Though only limited tests of this technique have been done thus far, it holds great promise as a modern, inexpensive method of determining electron density profile information over a large geographic region.

## 7. A SOFTWARE RECEIVER

With the ever increasing speed of modern digital computers, and their decreasing costs, a major portion of analog receivers and data collection can be performed, in a more general way, by the use of digital techniques. Chiralo and Spalla [1989] described a method in which, after suitable analog RF amplification and prefiltering is done to prevent aliasing, the signal can be digitally processed in a number of ways. These include mixing, additional filtering, phase and amplitude detection, phase comparison, spectral analysis, and other sampling and statistical computations. They illustrated a software approach to a VHF polarimeter, pointing out the relative low cost of duplicating such a receiver after the investment in initial development is completed.

The future of software receiver techniques in TEC measurements, from satellite signals of opportunity, is large. The potential advantages of a software receiver, over an analog system, include low cost, assurance of reproducible calibrations among the receivers, and great versatility of data collection and reduction.

## 8. TEC DATA REQUIREMENTS

The requirements for future measurements of TEC include the following:

1. Data taking from many locations throughout the world
2. Standardized digital format
3. Absolute calibration, rather than only relative measurements
4. Fully automated operation
5. Continuous data from each station
6. Availability of different data collection rates
7. Centralized, remote data collection at World Data Centers
8. Low or moderate cost
9. Data from many directions from each station

While some of these requirements seem contradictory, namely the low cost versus automatic operation, continuous data from many directions, in this age of modern, low cost computational facilities, and ever decreasing electronic component costs, it is possible to construct such a system. The dual frequency L-band signals of opportunity from the GPS satellites represent the best opportunity for future TEC measurements, providing inexpensive receiving systems are designed and fielded.

## 9. CONCLUSIONS

The routine measurement of the earth's total electron content is very important in studies of the physics of ionospheric F2 region behavior, especially as more interest focuses on the dynamics of the topside ionosphere. Coupled with nearby measurements of the bottomside ionosphere with modern ionosondes, the TEC can be used to yield a topside ionospheric profile shape factor. Normally several satellites can be viewed in different directions at once, thus yielding important information on the gradients in the ionosphere within approximately plus and minus ten degrees of earth center angle around the observing station.

TEC measurements also are becoming increasingly important in corrections to advanced ranging systems, precise time transfer by satellite, and in correction for radio astronomical measurements. Improved models of the topside ionosphere must rely on actual TEC data for their construction and verification. The projected availability of the constellation of 21 GPS satellites of opportunity, which can be used to make absolute TEC measurements, as well as precise relative TEC measurements, heralds the beginning of a new era in trans-ionospheric propagation measurement capability. The new technique of tomography, applied to constructing electron density profiles from TEC information from a number of stations, also shows great promise. Finally, newer generation software receivers, relying heavily of the use of computers, will add an important source of versatility to the existing measurement capability.

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