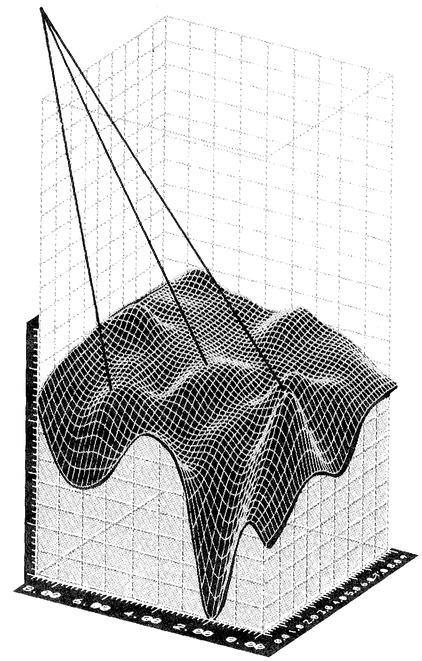

GPS — Satellites of Opportunity for Ionospheric Monitoring

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"Innovation" is a regular column in GPS World *featuring discussions on recent advances in GPS technology and its applications as well as on the fundamentals of GPS positioning. This month we feature an article on the use of GPS satellites to monitor the ionosphere. The author is Dr. David Coco, a research scientist at the Applied Research Laboratories, The University of Texas at Austin. Coco received a BA in physics from Rice University and an MS and Ph.D from the Space Physics and Astronomy Department of Rice University. He has been involved in the design of a GPS ionospheric monitoring system and has directed the design evaluation of several GPS receivers.*

This column is coordinated by Richard Langley and Alfred Kleusberg of the Department of Surveying Engineering at the University of New Brunswick. We welcome your comments and suggestions of topics for future columns.

Ionospheric scientists used radio transmissions from the first Sputnik satellite launched in 1957 to measure the number of electrons in the ionosphere. Ever since those first measurements, they have continued to take advantage of radio transmissions from a wide variety of satellites to gain a better understanding of the ionosphere. Ionospheric scientists often call satellites whose main objectives are not ionospheric research "satellites of opportunity," because they present a convenient opportunity to investigate the ionosphere at a relatively low cost.

GPS satellites represent the latest generation of satellites of opportunity for ionospheric scientists, and a number of groups are using these satellites to monitor the ionosphere. In this column we will discuss briefly how GPS is used for ionospheric monitoring and how such measurements ultimately may benefit the navigation and surveying communities.

INVESTIGATING THE IONOSPHERE

The ionosphere is the region of the atmosphere from roughly 50 to 2,000 kilometers above the earth's surface where ionized particles with equal numbers of electrons and positive ions control the behavior of radio waves. Thus the distribution and behavior of ionized particles in this region are important to all communication, navigation, and surveillance systems that use radio waves, including GPS.

The ionosphere can be investigated using ground-based techniques, such as incoherent scatter radar, or space-based techniques. Space-based techniques include both direct *in situ* measurements of the local ionospheric environment from satellite instruments and indirect measurements. The indirect measurements usually probe the region between the satellite and the ground using radio transmissions from the satellite. Each of these techniques has its own unique advantages and disadvantages, and usually measurements from both are required to provide a comprehensive view of the ionosphere.

In the past, two primary techniques — Faraday rotation and differential Doppler — have been employed to use satellites of opportunity to measure ionospheric properties. The Faraday rotation technique uses VHF signals from geostationary communication and weather satellites to measure the number of electrons between the satellite and the ground in a column with a cross-sectional area of one square meter. This quantity is referred to as the *total electron content* (TEC). The differential Doppler technique usually uses polar orbiting satellites, such as Navy Transit navigation satellites, to measure the change in TEC during the satellite pass. Both of these techniques have made important contributions to ionospheric science during the past 30 years.

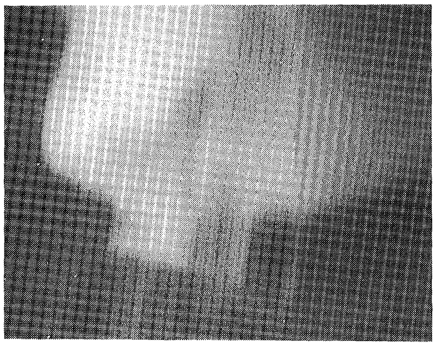
In the past few years, however, ionospheric scientists have been investigating the possibility of using GPS to monitor the ionosphere for two important reasons. First, the Faraday rotation technique will be increasingly difficult to apply in the future, because the new generation of geostationary satellites uses higher frequencies that are not suitable for ionospheric monitoring. Currently only two geostationary satellites (GOES II and III) can be used for ionospheric monitoring over the continental United States, and they will not be available much longer. Second, GPS is replacing Transit, and the older system will be phased out sometime in the near future. Although the orbital characteristics of GPS satellites differ from those of both of these systems, GPS does provide an excellent means of monitoring the ionosphere over a large region at a very low cost.

GPS IONOSPHERIC MEASUREMENTS

Most GPS receivers actually have two different means of measuring ionospheric TEC. The first method uses the difference of the P-code measurements from the L1 and L2 frequencies to generate a measurement of TEC. The second method, which is known as the differential Doppler technique, uses the difference of the carrier-phase measurements at these two frequencies to generate a measurement of the biased TEC. The phase-derived measurement is much more precise than the code-derived measurement but contains an unknown bias. This TEC bias arises from the fundamental ambiguity of the GPS phase measurement. Essentially, the phase measurement provides the change in the TEC from the beginning of the satellite pass (or since the last reacquisition) rather than the actual TEC. In practice, the code and phase measurements are usually combined to generate a single quantity that has the precision of the phase measurement with the phase bias determined from the code measurement.

Codeless receivers also are capable of measuring ionospheric TEC but require longer integration times. Their accuracy, however, is degraded at low elevation angles.

Although total electron content is the basic quantity available from GPS, ionospheric



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The aurora – evidence of a disturbed ionosphere – photographed from Søndrestrømfjord, Greenland.

scientists often use two other related quantities. The *phase scintillation spectrum* is the power spectrum of the TEC measurements (derived from carrier-phase measurements) recorded at a very rapid rate. The *amplitude scintillation spectrum* is the power spectrum of the signal amplitude measurements at either the L1 or L2 frequency, also recorded at a rapid rate. Both spectra require data rates of greater than about 10 Hz.

What do these measurements tell us about the ionosphere? First, TEC can be used to give an indication of the geographical, seasonal, and diurnal variations of the ionosphere. These regular variations result from a combination of solar radiation and transport of electrons from one region to another. Although scientists make ionospheric measurements throughout the world, two regions are of particular interest: the polar and equatorial regions. In the polar regions the ionosphere is highly irregular, and thus its behavior is difficult to model and predict. In the equatorial region the TEC is often quite large with large spatial gradients. The ionosphere in both of these regions often causes problems for communication, navigation, and surveillance systems (see Innovation, *GPS World*, April 1991), and, consequently, they are the places of primary interest to ionospheric scientists.

To illustrate the drastic difference between the typically smooth ionosphere of the mid-latitude region and the highly irregular ionosphere of the polar region, samples of GPS ionospheric measurements from these two regions are shown in Figure 1. The ionospheric measurements from Austin, Texas, show a smooth transition from low nighttime values to larger daytime values, while the measurements from Thule, Greenland, show an irregular pattern throughout the day. The different time segments are taken from different satellites in different parts of the sky, which explains the discontinuity between the segments.

In addition to regular variations of the ionosphere, rapid changes in TEC may indicate the presence of cloudlike structures within the background ionosphere. These structures, often called ionospheric irregularities, have sizes that range from meters to thousands of kilometers. The phase and amplitude scintillation spectra can provide important information on the structure and dynamics of these ionospheric irregularities.

THE IDEAL GPS RECEIVER

Almost any dual-frequency GPS receiver can be used to measure the ionospheric TEC, but several special features are desired to maximize the utility of the measurements for ionospheric scientists. Some of these features are also desirable for navigation and surveying users and, consequently, are found in many GPS receivers. Other features are peculiar to ionospheric applications and thus require specialized receiver designs.

The ability to track the P-code and the encrypted Y-code is highly useful in an ionospheric monitoring system. (The C/A-code cannot be used for ionospheric measurements because it is not on the L2 signal.) Codeless receivers can be used for ionospheric monitoring but provide a somewhat lower level of accuracy.

Interestingly, selective availability has no effect on ionospheric measurements, because the effects are the same on both frequencies and cancel upon differencing. However, antispoofing, which involves the encrypted Y-code, affects the GPS-based ionospheric measurement system in the same way that it affects other GPS systems – the system must have the basic capability of tracking the Y-code if it is to operate during times when antispoofing is in effect.

The ideal GPS-based ionospheric measurement system should also incorporate an antenna system that provides very low multipath noise for P-code measurements. This is especially important for obtaining accurate ionospheric measurements at very low elevation angles.

Another desirable feature is the ability to record carrier-phase data at a very rapid rate with a corresponding wide bandwidth. This characteristic is needed to produce phase scintillation spectra, which are used to investigate small-scale ionospheric irregularities. Data rates of 10–25 Hz are usually required, with bandwidths about twice this size. These wide bandwidths are sometimes found in receivers designed for navigation in highly dynamic environments, but it is rare to find a receiver that outputs the data at such a high rate. Typical navigation receivers have an output rate of about 1 Hz.

The signal amplitude for measuring amplitude scintillation spectra should also be recorded at a high data rate. This feature is rarely found in standard GPS receivers for the simple reason that it has no utility for navigation or surveying users. Most GPS receivers output a signal-to-noise value, which gives a relative measure of the signal amplitude, at about a 1-Hz rate with a bandwidth of 2 Hz or smaller. This data rate and bandwidth are much smaller than those required for ionospheric applications.

The ability to have the L1/L2 differential delay calibrated accurately is a final desirable feature for receivers used for ionospheric applications. This feature requires a bit of explanation because the concept is foreign to most GPS users.

The codes transmitted from GPS satellites at the two L-band frequencies are carefully synchronized so that they are emitted as simultaneously as possible. Absolute simultaneity is not possible, however, so the time difference between the transmit time at the two frequencies must be calibrated for ionospheric purposes. Differential frequency delays may also be present in GPS receivers because the L1 and L2 signals must travel through different hardware paths inside the receiver.

Both the satellite and receiver differential delays introduce error in the measurement of TEC. This error can be as large as 15 nanoseconds at L1, which is larger than a typical mid-latitude nighttime value of TEC. Thus, these differential delays cannot be ig-

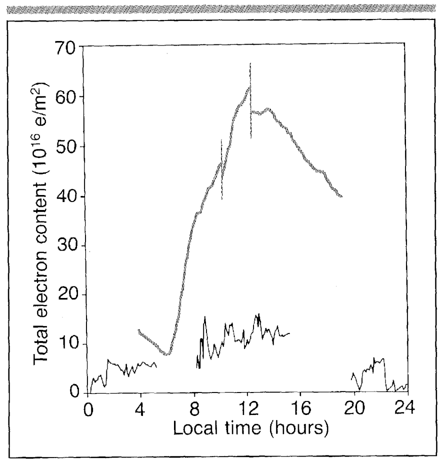


Figure 1. GPS ionospheric measurements for Austin, Texas, on August 30, 1989 (blue), and for Thule, Greenland, on October 10, 1988 (black)

nored. Fortunately, however, these delays are transparent to GPS navigation and surveying users as they are simply absorbed unnoticed into the satellite/receiver clock bias.

These differential delays must be carefully calibrated for ionospheric applications if very accurate, unbiased TEC measurements are required. Rockwell International, the manufacturer of the current generation of GPS satellites, performed a laboratory calibration of the differential delays before the satellites were launched. Prelaunch satellite calibration values are helpful in estimating the delays, but there is some evidence that the prelaunch calibration values may not be the same as the in-orbit delays. Research scientists at the Jet Propulsion Laboratory (JPL) and at Applied Research Laboratories, The University of Texas at Austin (ARL:UT) have recently shown that the combined satellite and receiver differential delays can be measured with a high level of accuracy while the satellites are in orbit. These differential delays present a challenge to the GPS ionospheric user but can be accurately measured with careful calibration.

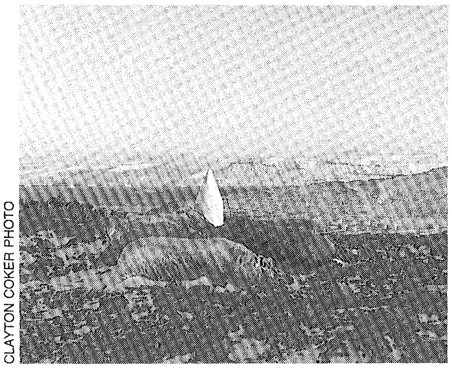
Although the technology is available, no single GPS receiver has yet been developed that incorporates all of these features, though one GPS receiver has been designed specifically for ionospheric measurements. This code-free receiver was developed by the National Institute of Standards and Technology to measure the P-code delay introduced by the ionosphere. Although it does not contain all the desired features, this receiver is a relatively low-cost solution to the problem of monitoring the total electron content of the ionosphere. In the past few years, ionospheric measurements have been made with several different off-the-shelf GPS receivers, some of which have been specially modified to incorporate some of the desired features. In the future, receivers incorporating many, if not all, of these features may be specially designed for ionospheric monitoring.

PAST EFFORTS AND FUTURE PLANS

An account of a few of the previous efforts, as well as some future plans, gives a feel for the scope of the different applications and agencies involved in using GPS to make ionospheric measurements. These efforts generally fall into three categories, among which there is considerable overlap: scientific campaigns to investigate the structure and dynamics of the ionosphere, GPS-based systems that are used to calibrate other systems, and experiments that investigate the effects of the ionosphere on GPS.

The first large-scale scientific campaign to use GPS to measure the ionosphere took place in 1981 on Ascension Island, which is located in the Atlantic Ocean near the equator. This campaign, a joint effort by the Air Force Geophysics Laboratory (AFGL) and Stanford Research Institute, was designed to measure near-worst-case equatorial ionospheric scintillations. Beginning in 1986, AFGL, ARL:UT, and other agencies participated in a series of campaigns using GPS to measure both TEC and scintillation in the polar ionosphere from two sites in Greenland.

Several agencies are using GPS ionospheric measurements to calibrate other space-based systems that are affected by the



CLAYTON COKER PHOTO

The antenna of the GPS-based ionospheric monitoring station at Thule, Greenland.

ionosphere. JPL is using GPS to measure TEC for calibrating the Deep Space Network, which is a worldwide network of NASA tracking stations. MIT Lincoln Laboratory uses GPS to assist in calibrating the ionospheric delay for Air Force satellites and other space platforms.

A worldwide, GPS-based ionospheric monitoring station network is being planned by the Air Weather Service of the Air Force and AFGL. It will consist of 17 stations, all reporting measurements to a central site in near–real time. This system, which is known as TISS (Trans-Ionospheric Sensing System), is designed to replace the current Air Force network, which uses the Faraday rotation technique to measure the ionosphere. This proposed network, shown in Figure 2, will be used by the Air Force for a wide variety of applications, including calibrating radars and space-based platforms.

In other cases, agencies have made ionospheric measurements mainly for the purpose of providing an understanding of how the ionosphere affects GPS measurements. The Norwegian Hydrographic Service has participated in several NATO-sponsored campaigns to characterize the ionosphere in the northern polar region; the University of New Brunswick has made a series of measurements in Canada; ARL:UT has monitored the mid-latitude ionosphere; and Ohio State University has collected ionospheric data in Antarctica.

BENEFITS FOR OTHER GPS USERS

What does ionospheric monitoring have to offer the GPS surveyor or navigator, for whom the ionosphere is more often considered a nuisance rather than an object of scientific study? There are really two answers to this question. In the short term, ionospheric monitoring can help a typical GPS user understand and avoid anomalies that are related to ionospheric phenomena. In the long term,

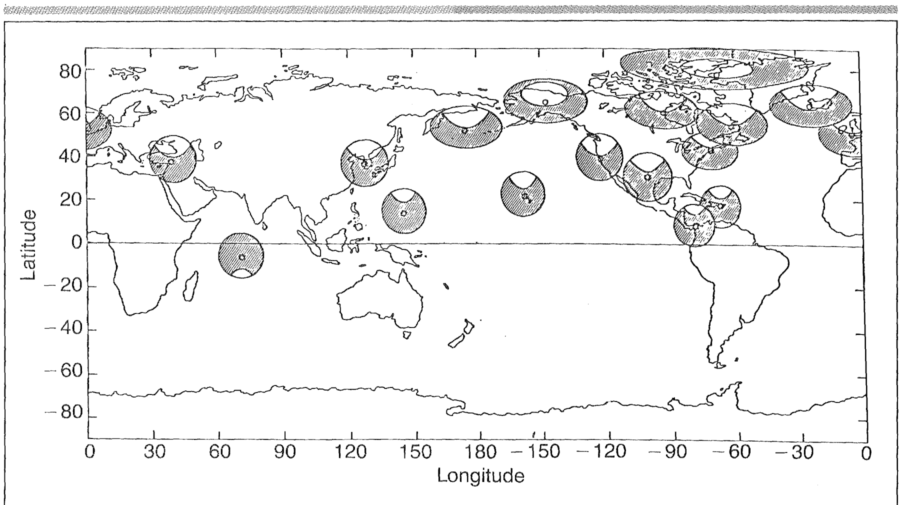


Figure 2. Proposed TISS geographic coverage. The shaded area around each station represents the portion of the ionosphere monitored at 350 kilometers altitude down to 15° elevation. The "hole" in coverage for each station results from the 55° inclination of the GPS satellite orbits.

ionospheric monitoring can help advance our basic understanding of the ionosphere so that dual-frequency receivers may not be required for all applications.

The potential impact of the ionosphere on GPS was discussed in detail in the April 1991 Innovation column. Note here, however, that GPS-based ionospheric measurements can often be an important tool for diagnosing system anomalies. For example, if a dual-frequency GPS receiver records numerous carrier-phase cycle slips and losses of lock in an equatorial region campaign, a review of the ionospheric measurements might provide important clues about the source of the problem. If the ionospheric measurements display a very irregular behavior, then the culprit may very well be the ionosphere. However, if the ionospheric measurements are reasonably smooth, then the user could probably rule out the ionosphere as the source of the problem and look elsewhere. The ionosphere is often blamed for system anomalies when this is not actually the case. A quick inspection of the ionospheric measurements is often very helpful in isolating and identifying the true source of system anomalies.

In the long term, ionospheric monitoring could contribute to the development of techniques that reduce, or even eliminate, the need for dual-frequency receivers for some applications. Currently, single-frequency GPS receivers rely on an ionospheric model that corrects only 50–70 percent of the ionospheric delay in a statistical sense. One technique proposed to get around this limitation is to use a regional network of dual-frequency receivers to monitor the ionosphere. The ionospheric measurements obtained from this network would then be used to develop a regional model of the ionosphere, which would in turn be provided to single-frequency receiver users in the vicinity of the network. This approach would allow single-frequency GPS receivers to remove a large portion of the ionospheric error either in real time or in postprocessing. Questions on the optimum number of stations, the maximum spatial separation of these stations, and the accuracy provided by a network of this type can only be addressed by long-term ionospheric monitoring studies.

The ionosphere is a critical link in the earth's environment for space-based navigation and communication systems, but there are still important aspects of this region that are not understood. Using signals from the GPS satellites, we now have an additional tool to study the complex physical and chemical processes that take place there.

ACKNOWLEDGMENTS

References have been omitted for the sake of brevity. Readers interested in further information on this topic should consult conference proceedings for the past few years for the ION Technical Meetings. Several colleagues contributed to this article: Jack Klobuchar of AFGL suggested this topic and made several helpful suggestions; Greg Bishop, also of AFGL, contributed Figure 2 and other items; Clayton Coker of ARL:UT processed the data for Figure 1; and Dr. Jim Clynch of the Naval Postgraduate School made several helpful suggestions. ■