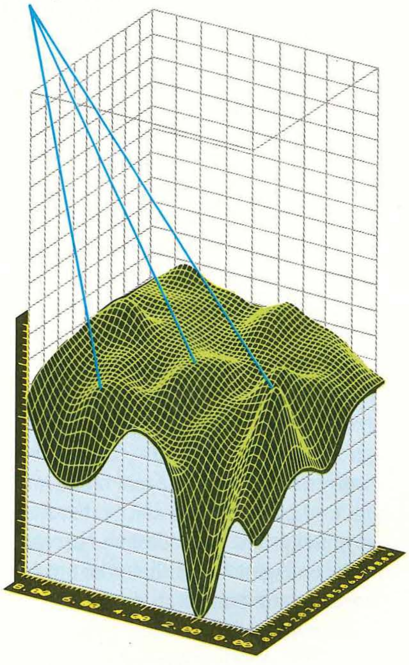

Effects of the Equatorial Ionosphere on GPS

Lambert Wanninger

Institut für Erdmessung,
Universität Hannover

When she was good, she was very, very good,
But when she was bad, she was horrid.

These lines from the familiar children's nursery rhyme might justifiably be used to describe the ionosphere. Under normal conditions in the mid-latitudes, the ionosphere is for the most part well behaved. GPS receivers can track the satellite signals from near horizon to horizon without difficulty, and the bias contributed by the ionosphere to pseudorange and carrier-phase observations can be readily removed by using dual-frequency observations. However, in the vicinity of the earth's magnetic equator, the ionosphere is at times quite "horrid," making life for the GPS user somewhat difficult. In this month's column, Lambert Wanninger, a research associate in the Institut für Erdmessung of the Universität Hannover in Hannover, Germany, describes the behavior of the equatorial ionosphere and how it affects the performance of GPS receivers.

"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. The column is coordinated by Richard Langley and Alfred Kleusberg of the Department of Surveying Engineering at the University of New Brunswick. We appreciate receiving your comments as well as suggestions of topics for future columns.*

GPS satellites broadcast their signals on two carrier frequencies. Simultaneous measurements of the pseudorange and carrier phase of these two signals differ mainly because of the presence of free electrons in the ionosphere. A dual-frequency GPS receiver or external data-processing software uses the differences in the measurements on the two frequencies to determine correction values and thereby remove the effect of ionospheric refraction from the data. Hence, it is widely believed that dual-frequency GPS observations solve all GPS user problems caused by ionospheric refraction. But this is only true for an undisturbed ionosphere in the mid-latitudes.

From the point of view of a GPS user, the earth's ionosphere consists of three major geographic regions (see Figure 1). The mid-latitude region exhibits the fewest disturbances, and one can fairly accurately predict the diurnal behavior of the total electron content (TEC) — the number of electrons in a column through the ionosphere with a cross-sectional area of one square meter — in a statistical sense. The auroral and polar regions are frequently the hosts for major disturbances such as severe phase scintillations. Their occurrence is highly correlated with magnetic activity and shows some diurnal dependence. We find the highest TEC values, the strongest large-scale gradients of TEC, and the worst disturbances in the equatorial region, which lies within a band about 30° on either side of the earth's magnetic equator and covers about 50 percent of the earth's surface.

In the April 1991 issue of *GPS World,* John Klobuchar wrote an "Innovation" article titled "Ionospheric Effects on GPS." He emphasized that the most disturbing effects are encountered in the equatorial region of the ionosphere in the years of high sunspot activity. A related article, "GPS — Satellites of Opportunity for Ionospheric Monitoring" by David Coco, appeared in the October 1991 issue. Coco's article dealt with the use of GPS to carry out observations of ionospheric electron content and ionospheric disturbances that ultimately may benefit the navigation and surveying communities.

We are now in the declining phase of the present solar cycle, which exhibited maximum solar activity from 1989 through 1992. The worst of it is over. After three years of experience with GPS in the equatorial region during this past period of maximum solar activity, we now better understand how this region of the ionosphere affects GPS. This article describes these effects and outlines measures that the user can take to handle or avoid them.

SCINTILLATIONS

Small-scale irregularities in the electron content of the ionosphere, with spatial extents from a few meters to a few kilometers, can produce both refraction and diffraction effects on received GPS signals. *Refraction*

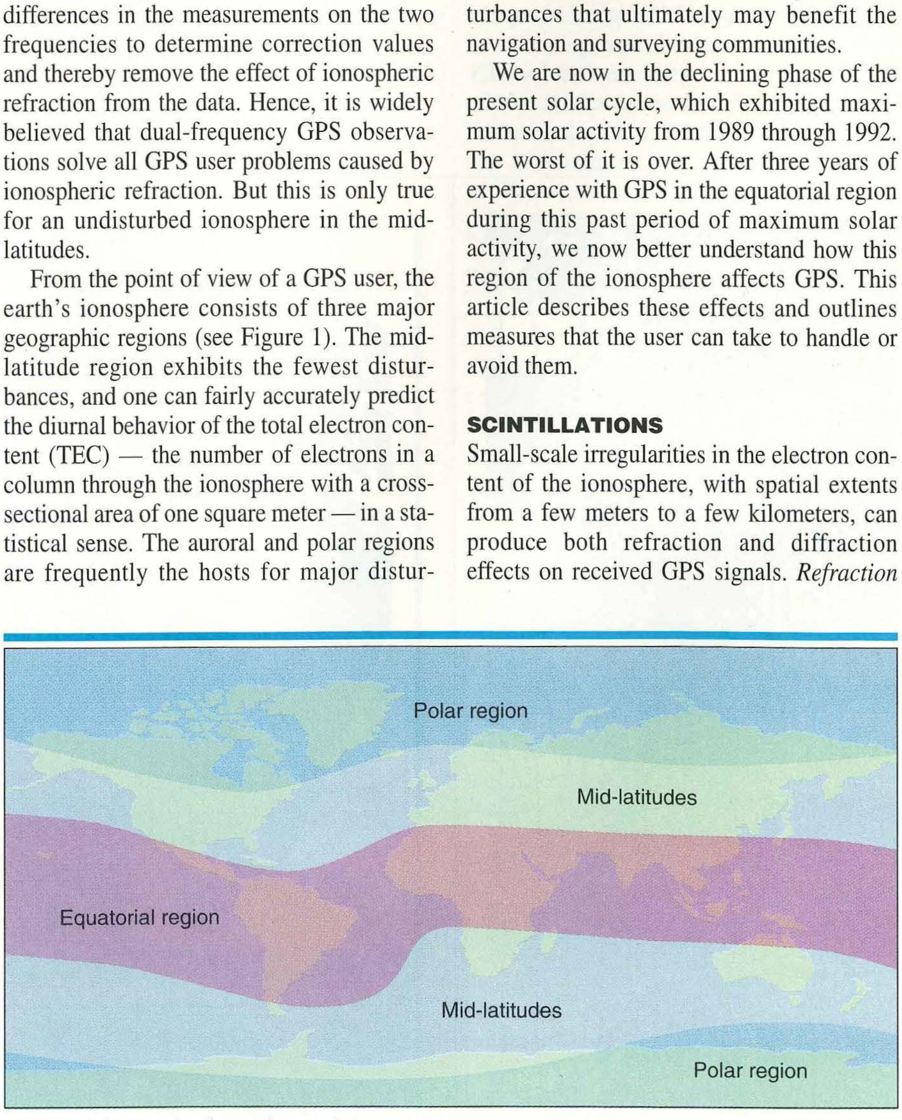

Figure 1. Ionospheric regions of the world.

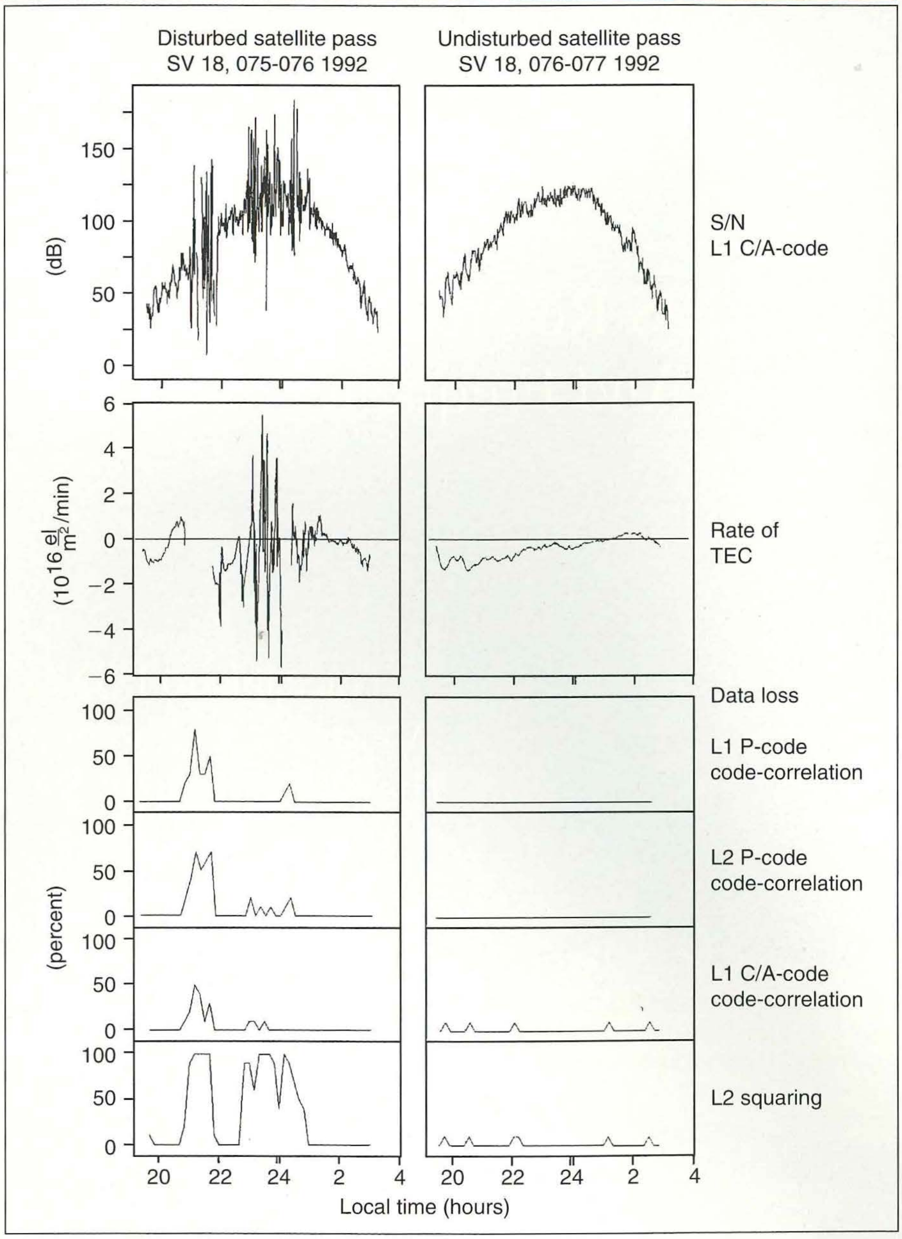

Figure 2. Effects of equatorial scintillations on GPS measurements from southern Brazil: amplitude scintillations, phase scintillations, and data loss.

changes the direction and speed of propagation of an electromagnetic wave while preserving the phase of the wavefront. *Diffraction,* on the other hand, results in the wavefront becoming crinkled, which, through mutual interference, gives rise to temporal fluctuations in the amplitude and phase of the signal at the receiver. Fluctuations due to either effect are called *scintillations.*

The region of equatorial scintillations extends 30° on either side of the earth's magnetic equator. The strongest effects are found at approximately 10° N and S. There is a clear diurnal variation: scintillations occur between sunset and midnight and occasionally continue until dawn. In addition to this diurnal variation, there is a seasonal dependence: in the longitude band stretching from the Americas to India, effects are strongest between September and March; from April through August, there is little chance of significant scintillations in this region. In the Pacific region, however, the situation is reversed. Furthermore, scintillation effects depend on the 11-year solar cycle. Their occurrence increases with an increase in sunspot numbers. From 1989 through 1992, during the maximum of solar cycle 22, they were especially strong. The occurrence and strength of scintillation effects will be minimal after 1994 and will continue at that level for the next 5 years or so. Around the year 2000, scintillation effects will increase once again.

The severest effects of small-scale ionospheric irregularities are signal fading and signal enhancement, collectively known as *amplitude scintillations.* As a result of these scintillations, the level of a GPS signal can drop below a receiver's lock threshold. This threshold depends on the bandwidth of the GPS receiver system and on the type of tracking channel. A code-correlation channel can maintain lock at lower signal levels than a squaring channel or a cross-correlation channel. Squaring the received signal results in a signal-to-noise ratio (S/N) roughly 30 dB lower than that obtained by code-correlation. Consequently, the data loss and the number of cycle slips caused by amplitude scintillations are larger for squaring channels than for code-correlation channels. The data loss can reach up to 100 percent during scintillation occurrence. Cross-correlating the L1 and L2 signals to obtain the ionospheric group delay also results in a low S/N. With such receivers, we can expect increased data loss and an increased number of cycle slips. However, detailed studies on the effects of equatorial scintillations on receivers with cross-correlation channels are still lacking.

Amplitude scintillations can be monitored by the interpretation of the time series of S/N values provided by geodetic-quality GPS receivers. Rapidly changing values indicate scintillation activity (compare the top two panels in Figure 2, which show the effect of scintillations on GPS data collected in southern Brazil). We can detect this sort of scintillation during the measurements because most geodetic receivers display the S/N values on their control panels. S/N values are also commonly stored in the raw data sets collected by geodetic receivers.

Phase scintillations result from sudden changes in ionospheric refraction or from diffraction effects. Because of these scintillations, the phase of both the L1 and L2 carriers can change by several cycles between two measurements spaced by as little as 10 seconds. Such perturbations complicate cycle slip detection and repair.

The rapid frequency changes in the received signal associated with phase scintillation effects can cause GPS receiver systems to lose lock. The range-rate errors can produce an apparent change in the Doppler frequency shift of greater than 1 Hz per second, which exceeds the tracking capability of many receivers. Under quiescent conditions, ionospheric refraction causes the L1–L2 phase difference to change slowly. In the case of phase scintillations, however, the phase differences can change rapidly by more than a few tenths of a cycle, so that L2 channels that are aided by L1 tracking data lose lock.

We can easily detect phase scintillation in continuous single-station, dual-frequency phase data. A suitable observable is given by the gradient of ionospheric refraction between two epochs separated by, for example, one minute. (The ionospheric refraction to within a constant bias is deduced by scaling the difference between the L1 and L2 phase measurements as expressed in units of distance.) Time series of this rate of TEC (RoT) observable contain the complete ionospheric information included in dual-frequency phase data. On the one hand, the RoT values are determined by the TEC and its spatial and temporal changes. On the other hand, these values depend on the movement of the satellite as seen from the observation site. RoT time series are especially useful for the detection of disturbances. A smooth curve indicates an undisturbed satellite pass. Phase scintillations caused by sudden changes in ionospheric refraction appear as spikes (see the middle pair of panels in Figure 2). A phase scintillation index can be computed as the root mean square (rms) over detrended parts of these time series. Any dual-frequency receiver could compute and interpret such an index while operating either in static or in kinematic mode, and if scintillations were detected, the receiver could provide an appropriate real-time warning to the GPS user.

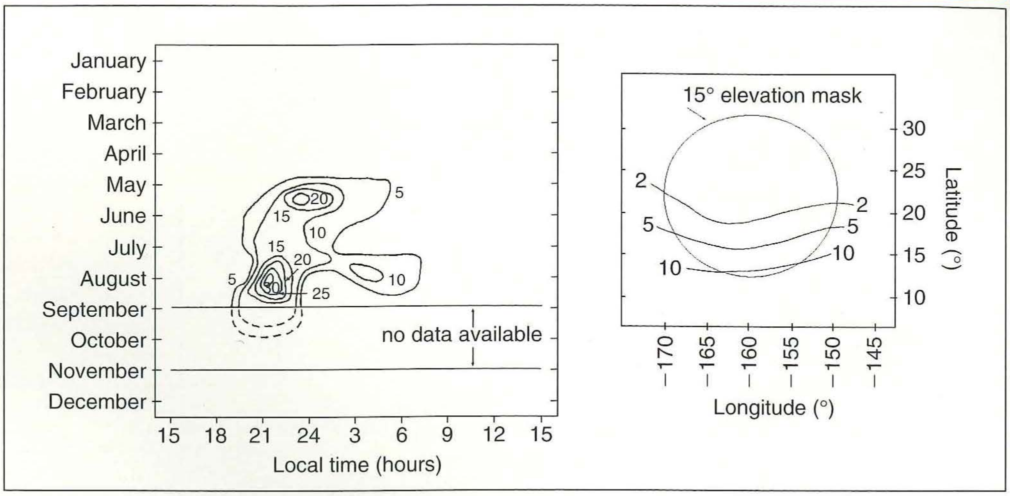

Figure 3. Percentage occurrence of phase scintillations as observed with GPS at Kokee Park, Hawaii, in 1992. Left: temporal variations. Right: spatial variations.

The severest scintillation effects on the performance of GPS receivers occur in the equatorial region. The navigation community operating in this region needs to be aware of the potential for significant data loss. The surveying community is affected even more. Under scintillation conditions, surveyors also must cope with an increased number of cycle slips, whose repair is often impracticable. Although an improvement in receiver technology might somewhat reduce the effects of amplitude and phase scintillations, it could not eliminate them completely. With the introduction of antispoofing (AS), the situation will be further aggravated. Under AS, most civil dual-frequency users will be forced to employ receivers with cross-correlation or squaring channels, which are more affected by scintillations than code-correlation channels. The unavoidable conclusion is that GPS is not necessarily an "all-ionosphere" positioning system.

Although equatorial scintillations can be much stronger than high-latitude scintillations, they have one positive characteristic: their occurrence is limited to nighttime hours and certain months of the year. At least in the case of surveying applications, the scintillation effects can be avoided by careful selection of the observation times. Obviously, this prescription won't be of much help to most navigational users of GPS.

MONITORING SCINTILLATIONS

The effects of equatorial scintillations on GPS observations can be observed best with GPS itself. An example with data from Hawaii will demonstrate the usefulness of scintillation monitoring for the planning and performance of GPS surveys.

Hawaii is located at approximately 20° N magnetic latitude, lying underneath the equatorial region of the ionosphere. Though the main scintillation activity takes place at about 10° N and S of the magnetic equator, we can also expect effects to be seen in Hawaii. Data from the permanent GPS tracking station at Kokee Park, Hawaii — a station in both the Cooperative International GPS Network (CIGNET) and the International GPS Geodynamics Service (IGS) (see "Geodynamics: Tracking Satellites to Monitor Global Change" in the February 1993 issue of *GPS World*) — are available for the whole of 1992, with the exception of a data gap from mid-September to mid-November. Because the analysis for this example used data in Receiver INdependent EXchange format (RINEX), only phase scintillations — no amplitude scintillations — could be detected. When raw data are converted to RINEX format, much of the S/N information gets lost as the S/N value is projected onto the interval 1–9.

Figures of the percentage occurrence of phase scintillations were produced with the help of the phase scintillation index described earlier. Of major interest to GPS users is the temporal distribution of the disturbances. If we assume a height of the small-scale irregularities of 400 kilometers, we can localize the scintillations. Figure 3 shows the temporal and spatial extent of the observed phase scintillations.

Figure 3 indicates that no phase scintillations were detected from January through April nor in November and December. The observed scintillation activity from March through September and October was not as severe as scintillation activity monitored in southern Brazil, which is closer to the magnetic equator. No significant data loss could be justifiably attributed to scintillation activity. The figures reveal that the main activity was limited to the period from sunset to local midnight, but on occasion scintillations continued until dawn. The geographical distribution of scintillation activity shows a decrease in activity with increasing latitude. The part of the ionosphere lying to the north of Kokee Park produced very few observed scintillations. Though only 12 percent of the observations were from signals that traversed the ionosphere south of 18° N latitude (based on an assumed ionospheric height of 400 kilometers), more than 50 percent of the detected scintillations occurred in this region. The paucity of GPS satellite passes south of

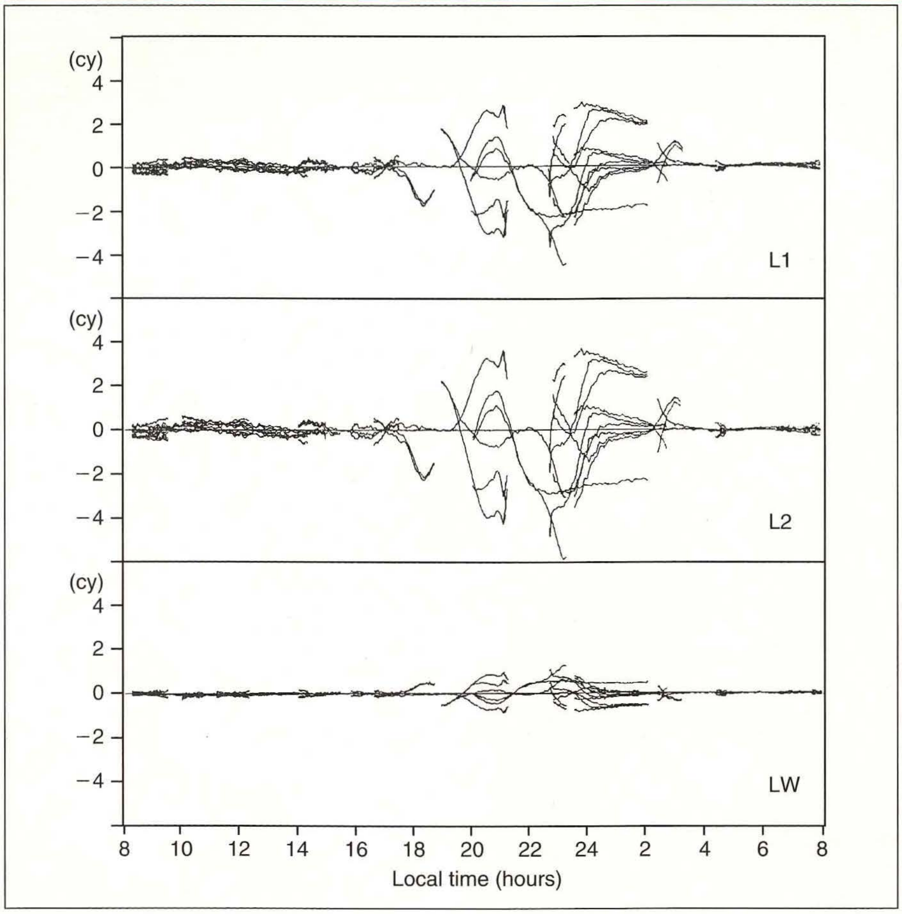

Figure 4. Double-difference phase residuals of all satellite pairs for full wavelength L1, L2, and the widelane linear combination, LW, from a 10-kilometer baseline in southern Brazil. Data collected on March 25–26, 1992, using an elevation mask of 15°.

18° N results in periods of up to some hours without any data from this region. This incompleteness explains some features of the scintillation occurrence map, such as the apparent late beginning of scintillation activity at approximately 21 hours local time (LT) in May and the apparent activity gap after midnight in August and September.

Despite the fact that the figure for the temporal distribution of scintillation occurrence is somewhat affected by the incomplete coverage of the sky with GPS satellite passes, it is of utmost importance to the planning of GPS surveys in the vicinity of Hawaii. We can assume that the temporal distribution in 1993 and also in subsequent years will be similar to that of 1992. Hence, with the help of this information extracted from permanent GPS tracking station data, we can easily avoid equatorial scintillations.

Furthermore, we were able to show that in and near Hawaii, scintillation effects on receivers with code-correlation tracking channels resulted in negligible amounts of data loss. We may infer, then, that most GPS navigational applications are not affected by these ionospheric disturbances.

In 1992, there were only a few permanent non–Department of Defense GPS tracking stations in the equatorial region. With the ongoing establishment of IGS and other networks, the number of stations will grow. The data collected at these stations should be used to study ionospheric disturbances further and to test and improve GPS receiver performance under disturbed conditions.

HIGH TOTAL ELECTRON CONTENT

The equatorial anomaly regions, located about 10°–20° on either side of the magnetic equator, are the regions where the world's highest TEC values are encountered. Here, pseudorange and carrier-phase biases caused by ionosphere refraction can reach up to 100 meters for signals arriving at low-elevation angles. Errors remaining after dual-frequency correction do not exceed 10 centimeters and are usually much smaller.

In contrast to mid-latitude sites, there is often no single maximum in the diurnal variation of the electron content but rather two maxima: one around noon and one in the evening hours. The second maximum can even exceed the level of the first one. Moreover, an extremely large day-to-day TEC variability can occur in the afternoon and evening hours. Under these conditions, corrections of single-frequency GPS measurements using global ionospheric forecast models may be of little value.

LARGE HORIZONTAL GRADIENTS

In the case of relative positioning with GPS, it is not the TEC itself but the horizontal gradients of TEC that are most important. The largest horizontal gradients in the electron density are found in the regions of the equatorial anomalies. On the one hand, there are large gradients from the equatorial crest to the mid-latitudes and in the opposite direction to the magnetic equator (north–south gradients). On the other hand, minor gradients are caused by the diurnal cycle of the ionospheric electron content (east–west gradients). The large-scale gradients of the second daily TEC maximum usually exceed the gradients of the first maximum.

Using GPS data collected in southern Brazil, in the region of the southern equatorial anomaly, we observed horizontal gradients as large as 30×10^{16} electrons per square meter (el/m^2) per 100 kilometers in the north–south direction. However, the east–west gradients did not exceed 3×10^{16} el/m^2 per 100 kilometers. These gradients were observed after sunset in March 1992, that is, around the time of the vernal equinox. At that time of the year, extreme ionospheric conditions may be expected. By way of comparison, in the mid-latitudes, horizontal gradients seldom exceed 2×10^{16} el/m^2 per 100 kilometers. The effects of large TEC gradients on GPS positioning will be explained using this example from southern Brazil (which is illustrated by Figure 4).

For differential GPS (DGPS) applications, if the baseline is sufficiently short, we may assume that the ionospheric conditions above the two stations are highly correlated. In this case, the differential corrections computed for a remote station by a single-frequency receiver at the reference station include a correction for ionospheric refraction. After these corrections are applied, the remaining pseudorange errors are often less than 1 meter. However, in the presence of large-scale horizontal gradients, only a part of the ionospheric error at the remote station is included in the correction of the reference station. Because horizontal gradients of 30 × 10^{16} el/m^2 per 100 kilometers correspond to an L1 differential range error of at least 5 meters per 100 kilometers (depending on the elevation angle of the satellite), an additional positioning error of similar size can be expected. Consequently, in the equatorial region, DGPS accuracies are often poorer than those attained in the mid-latitudes.

We can draw similar conclusions for single-frequency static GPS surveying. Even when long observation periods are used, ionospheric gradients may cause significant position errors for short baselines because of the gradients' temporal stability. The processing of data from a 10-kilometer baseline in blocks of 1 hour showed coordinate errors of 1 centimeter (1 part per million [ppm] of the baseline length) before sunrise, of up to 5 centimeters (5 ppm) during the daylight hours, and of more than 30 centimeters (30 ppm) from the early evening hours until after midnight. This example demonstrates that in the equatorial anomaly regions, precise GPS surveying can be performed only with dual-frequency receivers.

But even with dual-frequency data, serious problems can occur in the data processing. Precise applications of GPS require the resolution of the integer ambiguities of the double-difference phase observable. Here again, it is assumed that the ionospheric effects at the two receivers are highly correlated and, in the case of short baselines, can be removed with differencing. In the presence of large-scale horizontal gradients, however, the ambiguity determination is affected considerably. Figure 4 shows double-difference phase residuals from the 10-kilometer baseline discussed in the preceding paragraph. These large residuals are almost all caused by large-scale horizontal gradients. We can see that those gradients mainly occur around the time of the second daily TEC maximum.

Maximum residuals amount to 4.6 cycles of L1 (1 cycle corresponds to a wavelength of 19.0 centimeters), 5.9 cycles of L2 (with a wavelength equal to 24.4 centimeters), and 1.3 cycles of the widelane linear combination (with an effective wavelength of 86 centimeters). The widelane residuals, for example, exceed 0.5 cycles for 6 out of 24 hours. The magnitude of double-difference residuals caused by ionospheric refraction is, in the first approximation, proportional to the baseline length. A baseline measured under the same ionospheric conditions and with the same azimuth but twice as long would experience effects about twice as large.

In our example, all ambiguities could have been solved for correctly, because we had dual-frequency data extending over more than 24 hours. Ambiguity resolution for sessions of 1 hour during the period of the maximum gradients (18 to 2 hours LT) either yields incomplete solutions or incorrect ones. If the session length is reduced even further, which is suggested for rapid-static positioning, ambiguity resolution is impracticable for baselines of this length using data-processing software available today. Furthermore, ambiguity resolution of single-frequency data is completely impossible in the presence of these gradients.

The data processing of the Kokee Park GPS observations revealed that Hawaii lies at the northern boundary of the northern equatorial anomaly. Large-scale gradients between a low electron content in the north and a high electron content in the south could be observed almost every afternoon and evening. Strong gradients occurred from January to March and in November and December 1992; that is, they appeared in those months without strong scintillation activity. In southern Brazil, however, scintillations and large-scale gradients occurred on successive days in March 1992.

CONCLUSIONS

In the equatorial region, the GPS user needs to be aware of severe ionospheric conditions that are unknown or very infrequent in the mid-latitudes. The worst effects can be expected in the afternoon through midnight hours. Understanding the seasonal dependencies helps the GPS user to avoid them. Because we are now in the declining phase of the present solar cycle, smaller effects than described in this article can be expected for the next six years or so.

GPS receiver performance deteriorates in the presence of ionospheric scintillations. All types of receivers can, at times, experience considerable tracking problems with resulting data loss. The full-time implementation of AS will aggravate these problems for the L2 frequency.

Differential GPS applications are affected by large-scale horizontal gradients of the ionospheric electron content. These gradients cause large position errors and can prevent phase ambiguity resolution for single-frequency data. Although dual-frequency observations can effectively be used to make ionospheric corrections, in the presence of strong gradients, the determination of double-difference ambiguities becomes considerably more complicated, even for short baselines.

There are still many important aspects of the equatorial ionosphere that we do not understand. Permanent GPS tracking stations will provide valuable information on the regional and temporal distribution of the disturbing ionospheric conditions. GPS observations will also contribute to a better understanding of the complex physical and chemical processes in the ionosphere, which ultimately may benefit the navigation and surveying communities.

ACKNOWLEDGMENTS

The Brazilian GPS measurements could not have been obtained without the enthusiasm of Milton Campos and his talent for organization. Many individuals from Brazilian universities and from the Instituto Brasileiro de Geografia e Estatística (IBGE) contributed to the observations. The Hawaiian GPS data were made available by Scripps Institution of Oceanography. The work described in this article was supported with grants from the Deutsche Forschungsgemeinschaft. ■

For product information, turn to page 66 and see Manufacturers. *For reprints (250 minimum), contact Cheryl Byer, Marketing Services, (503) 343-1200.*

CALENDAR

JULY 14-15

Spectrum Needs for IVHS Applications
Burlingame, California. Sponsored by the Communications Committee of the Transportation Research Board, in cooperation with the Federal Highway Administration, IEEE Vehicular Technology Society, Society of Automotive Engineers (SAE), and IVHS America. Contact: TRB Spectrum Workshop, c/o Steve Weiland, Navigation Technologies, 10400 West Higgins Road, Suite 400, Rosemont, IL 60018, USA, (708) 699-7070, fax (708) 699-6556.

JULY 14-16

Intelligent Vehicles '93
Tokyo, Japan. In cooperation with IEEE Industrial Electronics Society, Society of Automotive Engineers (International and Japanese divisions), Dynamic Systems and Control Division of American Society of Mechanical Engineers, IEEE Vehicular Technology Society, IEEE Neural Nets Council, Japan Society for Fuzzy Theory and Systems, Robotics Society of Japan, and Society of Instrument and Control Engineers. Contact: Ichiro Masaki, Computer Science Department, General Motors Research Laboratories, 30500 Mound Road, Warren, MI 48090-9055, USA, (313) 986-1466, fax (313) 986-9356.

JULY 19-23

Fundamentals of GPS/GPS Seminars
Alexandria, Virginia. Separate sessions will cover fundamentals, advanced receiver systems, IVHS, and DGPS. Contact: Navtech Seminars, 2775 South Quincy Street, Suite 610, Arlington, VA 22206-2241, USA, (800) NAV-0885, fax (703) 931-0503.

JULY 25-28

Pacific Rim TransTech Conference
Seattle, Washington. Contact: Washington Department of Transportation, Federal Highway Association, (206) 753-6014, fax (206) 753-6218.

JULY 26-29

Intelligent Vehicle Highway Systems course
Ann Arbor, Michigan. Contact: University of Michigan, Conferences and Seminars, 112 West Quadrangle, 541 Thompson Street, Ann Arbor, MI 48109-1360, (313) 764-5305, fax (313) 764-2990.

JULY 28-30

Ports, Inland Waterways, Intermodal Distribution, and International Trade
Portland, Oregon. Sponsored by the National Research Council's Transportation Research Board. Contact: Office of News and Public Information, 2101 Constitution Avenue, NW, Washington DC 20418, USA, (202) 334-2138.

AUGUST 2-6

GPS Seminars
Rancho Mirage, California. Separate seminars will cover fundamentals of GPS, GPS for engineers, evaluating DGPS, navigation systems integration, and integration of GPS with INS. Contact: Navtech Seminars, Inc., 2775 South Quincy Street, Suite 610, Arlington, VA 22206-2204, USA, (800) NAV-0885, fax (703) 931-0503.

AUGUST 4-8

Airshow Canada '93
Vancouver, British Columbia, Canada. Aviation tradeshow, symposium, and airshow. Sponsored by the Government of Canada, Western Economic Diversification Canada, the Government of British Columbia, and the B.C. Trade Development Corporation. Contact: Registrar, Financial Post Conferences, 3rd Floor, 333 King Street East, Toronto, Ontario M5A 4N2, Canada, (416) 350-6200, fax (416) 350-6201.

AUGUST 9-12

Future Transportation Technology Conference
San Antonio, Texas. Contact: U.S. SAE, (412) 776-4841, fax (412) 776-5760.

ADVERTISERS INDEX

Advanstar Marketing Services	*45*
Allen Osborne Associates, Inc	*55*
Ashtech, Inc	*5,30–31,68*
Ball Corporation (Efratom Division)	*49*
Bruttour International PTY. Ltd.	*10*
GARMIN International	*29*
GeoPlane Services Corporation	*63*
GPS World Magazine	*53*
IEEE Plans '94	*8*
Institute of Navigation GPS '93	*59*
M/A-COM, Inc	*17*
M/A-COM Antenna & Cable Division	*35*
Magellan Systems Corporation	*3*
Magnavox Advanced Products Systems Co	*7*
Micro Pulse, Inc	*4*
Navstar Electronics, Inc	*45,47*
NovAtel Communications Ltd	*43,67*
PCI, Inc	*11*
Racal Positioning	*9*
Resolution Mapping	*39*
Rockwell Collins Avionics & Communications Division	*65*
Rockwell Commercial GPS	*15*
Sercel	*13,37*
Sextant Avionique (Navigation Systems Division)	*41*
Spectra Systems, Inc	*46*
Stanford Telecom	*2*
TRAK Microwave Corporation	*33*
Trimble Navigation	*27*
Welnavigate, Inc	*19*

SEPTEMBER 13-17

26th ISATA Silver Jubilee Conference
Aachen, Germany. Coinciding with the Frankfurt Motor Show, the event will include technical visits and 10 simultaneous dedicated conferences. Contact: ISATA, 42 Lloyd Park Avenue, Croydon CR0 5SB, United Kingdom, +44 81 681 3069, fax +44 81 686 1490.

SEPTEMBER 22-24

ION GPS '93: The Satellite Division of the Institute of Navigation's Sixth International Technical Meeting
Salt Lake City, Utah. Contact: Phillip W. Ward, Navward GPS Consulting, 9629 Covemeadow Drive, Dallas, TX 75238-1819, USA, (214) 348-9446, fax (214) 348-9447.

MANUFACTURERS

Page 20. *Saving Lives: GPS and New Zealand's Armed Forces.*
This year, three RNZAF Andover C Mk 1 twin-engine tactical transports were fitted with commercial Skynav 5000 GPS sets from **Magellan**, San Dimas, California. In 1990, RNZN equipped two of its Wasp helicopters with GPS 100 units from **GARMIN International,** Lenexa, Kansas.

Page 28. *Urban Positioning with GPS: A Mobile Communications Field Measurement Application.*
The field measurement application used SVeeSix and Placer/DR receivers from **Trimble Navigation,** Sunnyvale, California.

Page 40. *GPS-Augmented Live Television Coverage of Persian Gulf Boat Races.*
TV2 Helivision/MetRoaTech customized, automatic pointing antenna and MetRoaTech's Telenav video/GPS encryption system were used with MX100 GPS receivers from **Magnavox,** Torrance, California, and a C-100 Compass Engine from **KVH Industries,** Middletown, Rhode Island.

Page 48. *Effects of the Equatorial Ionosphere on GPS.*
GPS receivers used in Brazil included the P-XII receiver from **Ashtech Inc.,** Sunnyvale, California and 4000 SLD and SST receivers manufactured by **Trimble Navigation Ltd.,** Sunnyvale, California. The Kokee Park, Hawaii data came from a Rogue SNR-8 manufactured by **Allen Osborne Associates, Inc.,** Westlake Village, California.

Manufacturer credits reflect the products used for the applications, as reported by the authors, at the time the articles were written.