IONOSPHERIC CORRECTIONS FOR TIMING APPLICATIONS

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ABSTRACT

The group retardation effect of the electrons in the earth's ionosphere can seriously limit the accuracy of time transfer by radio waves relayed via satellite. The dual frequency approach used in the GPS satellite system eliminates this potential problem, but other techniques, such as the use of models of the ionosphere, can only partially remove the ionospheric time delay error. Since the ionosphere is a dispersive medium the best approach to removing this error source is to directly measure the time delay at two, sufficiently widely spaced, frequencies as the dual frequency GPS system does automatically. If one does not have access to dual frequency GPS capability, various other techniques can be used with varying degrees of success in correcting for ionospheric time delay.

Work currently being done in the ionospheric research community should help increase the capability of the time transfer community to make corrections for ionospheric time delay effects on time transfer by satellite. 1) Research is continuing on improving theoretical models of ionospheric behavior, especially during disturbed conditions when the largest deviations from median model time delay values normally occur. 2) A network of stations making real time measurements of the time delay of the earth's ionosphere is in its preliminary phase and, when completed, will provide qualified DoD users with real time updates of the time delay corrections over large regions of the globe. 3) Work is in progress on development of what is expected to be inexpensive code-free receiving systems using the dual frequency signals from the GPS satellites to directly measure ionospheric time delay in multiple directions simultaneously to allow greatly improved corrections for ionospheric time delay. These code-free GPS receivers should provide an excellent correction for the effects of the ionosphere on time transfer by satellite.

Predictions of the magnitude of the current solar cycle are for a nearly record high cycle, with the maximum to be reached in late 1989, or early 1990, and staying high for several years thereafter. The implications for ionospheric time delay errors are for very high values for the next several years, with daytime ionospheric time delay values at 1.6 GHz from several tens of nanoseconds, to well over one hundred nanoseconds along the slant paths normally used with simultaneous satellite viewing for pairs of stations.

INTRODUCTION - TOTAL ELECTRON CONTENT

The accuracy of time transfer by means of radio frequency signals via satellites can be limited by the number of free electrons in the earth's ionosphere encountered along the path from the earth to the satellite. The magnitude of this effect is:

$$t = \frac{40.3}{3 \times 10^8 \times f^2} \int N \, dl$$

where f is the system operating frequency in Hertz, and N dl is simply the total number of electrons encountered along the path, or the Total Electron

Content, (TEC), along an equivalent column having a cross section of one square meter, from the earth to the satellite.

The greatest contribution to TEC comes from the F2 region of the ionosphere. A typical daytime, mid-latitude, high solar maximum electron density profile is illustrated in Figures 1A and 1B. The curve in Figure 1A is the log of N_e plotted versus height as normally shown by ionospheric workers. Since the TEC is represented by the area under the curve of a linear plot of N_e versus height, a more representative plot is illustrated in Figure 1B, where the abscissa is in linear units of electron density, rather than a logarithmic plot. Note that most of the contribution to TEC ocurs near the peak of the F2 region, which is fortunate, as ground-based ionosondes have been used since the 1930's to make continuous, routine measurements of the density at the peak of the F2 region. Ionosondes measure foF2, which is related to N_{max} by: $(foF2)^2 = 80.6 * N_{max}$ where foF2 is in MegaHertz, and M_{max} is in units of 10^6 el/cc.

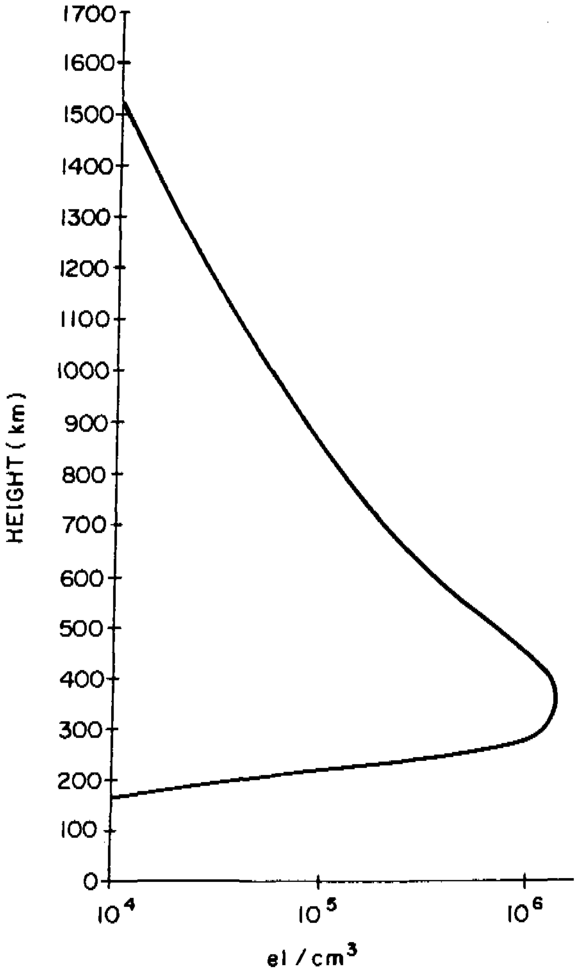

Figure 1A. Electron density (log scale) versus height.

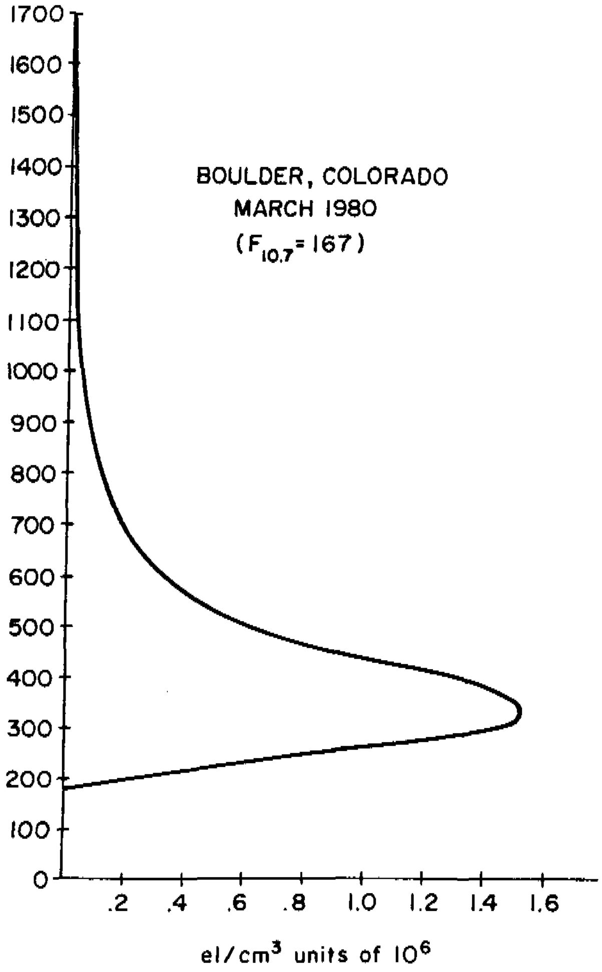

Figure 1B. Electron density (linear scale) versus height.

AVERAGE IONOSPHERIC MODELS

In the 1950's and 1960's, continuing to a more limited extent even today, upwards of 150 ionosondes were operated throughout the world to provide improved prediction capability for long distance high frequency propagation by means of ionospheric refraction. Various models of the critical frequency of foF2 were developed for this purpose, one of the more popular ones being commonly known as ITS-78 (Barghausen, et. al., 1969) after the report number which described the model. This model, among other things, characterized the 10 day average worldwide behavior of foF2 by Fourier temporal components and Legendre polynomial geographic coefficients ordered by mangetic, rather than geographic, latitude. The success of this experimental, data based empirical model, in representing the actual world-wide foF2 is due to the large amount of data available from ionosondes located in many regions of the world. Other characteristics of this models are discussed in Dandekar, 1982).

For the TEC parameter, data availability have been, and will likely continue to be, much more sparse. First, TEC measurements have been made generally by using measurements of Faraday polarization rotation using VHF signals of opportunity transmitted from geostationary satellite telemetry transmitters. A few lunar reflected Faraday rotation measurements in the late 1950's and early 1960's, and the TEC obtained from a few early, low orbit satellites did not contribute significantly to our knowledge of world-wide TEc behavior, at least not for modelling average ionospheric conditions. Only since the early to mid-1960's have TEC values been obtained on a more-or-less regular basis, but even today fewer than approximately one dozen stations regularly contribute TEC data, which can be used in TEC modelling purposes, to a world data center. The outlook for any world-wide model of TEC, made from direct measurements of TEC is poor, and will likely remain so for at least this current solar cycle maximum period of the next few years.

Fortunately, most of the contribution to TEC comes from near the F2 region density peak where models of foF2 are available. These foF2 models can be combined with some limited knowledge of topside ionospheric thickness obtained from topside ionospheric sounders and topside in-situ density measurements to produce a complete ionospheric height profile model. The most well known of these models is the one by Bent (Llewellyn and Bent, 1973), which uses ITS-78 coefficients for foF2 and topside exponential shapes from which the TEC is computed.

Other world-wide ionospheric electron density profile models, from which average TEC can be obtained, include the International Reference Ionospheric, (IRI), model, and the Penn State Mark III model (see Conkright, private communication). Several other models exist, but they are currently used only in by ionospheric researchers and are not generally available to users. All the models discussed here only attempt to represent the monthly average ionospheric profiles, though the Bent model is one which can be updated with real-time ionosonde and/or TEC measurements at up to several stations, to give a specification of the ionosphere over a nearby location.

Figure 2A illustrates the worldwide vertical time delay produced by the earth's ionosphere for solar maximum conditions in March 1980. Note that in the near-equatorial portion of the world there is a region where the mean vertical one-way ionospheric time delay is 50 nanoseconds. Major portions of the world have a vertical ionospheric time delay which exceeds 25 nanoseconds. In Figure 2B the worldwide vertical average time delay produced by the earth's ionosphere is plotted for solar minimum conditions. The highest vertical ionospheric time delay value is less than 25 nanoseconds, and only a small fraction of the world encounters a vertical time delay greater than 15 nanoseconds. The Bent model was used to generate the contours of TEC shown in Figures 2A and 2B, and is a reasonably good representation of actual worldwide average ionospheric time delay error.

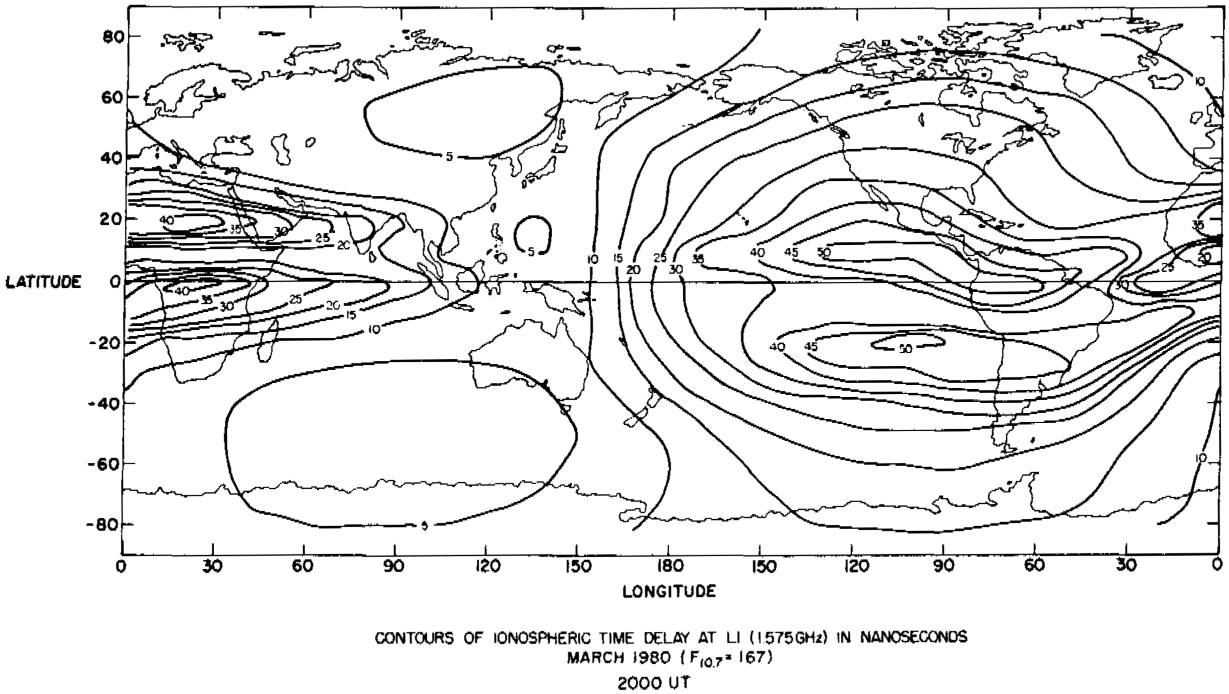

Figure 2A. Contours of Ionospheric Time Delay at L1 (1.575 GHz) in Nanoseconds Solar Maximum ($F_{10.7cm}$ = 167) ; 2000 U. T.

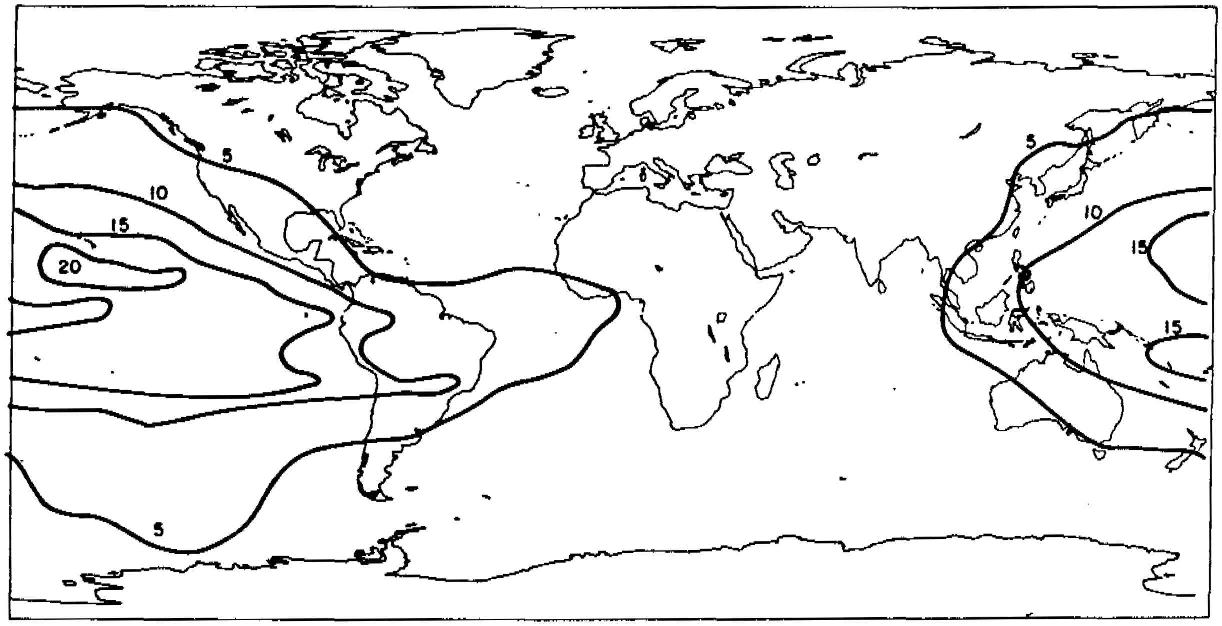

Figure 2B. Contours of Ionospheric Time Delay at L1 (1.575 GHz) in Nanoseconds Solar Minimum ($F_{10.7cm}$ = 70) ; 0000 U. T.

DAY-TO-DAY VARIABILITY OF IONOSPHERIC TEC

The day-to-day variability of ionospheric time delay for a mid-latitude station is illustrated in Figure 3 where a year's TEC data from Hamilton, MA is plotted versus local time in the form of 12 monthly overplots. Note that the annual highest values of daytime TEC do not occur during the summer months when the sun is at its highest elevation, but rather during the equinoxes. This is due to the effects of the heating of the neutral atmosphere with resulting greater loss rates from molecular species during the summer months. In Figure 3 one can also see the large day-to-day variability in the TEC values. The standard deviation of the actual TEC from its monthly mean behavior for most months is generally 20% to 25%, at least during the daytime hours when the absolute TEC values are greatest. Research is being carried out in the community of ionospheric physicists to attempt to understand and model, from first principles, the reasons for this large day to day variability. Geophysical effects which can modify the TEC from its monthly median behavior include: changing chemical composition at ionospheric heights, neutral wind variability, day to day changes in electric fields which drive ionization across the earth's magnetic field lines, and heat input into the high latitude ionosphere from magnetic storms which causes subsequent effects on TEC in the mid-latitudes.

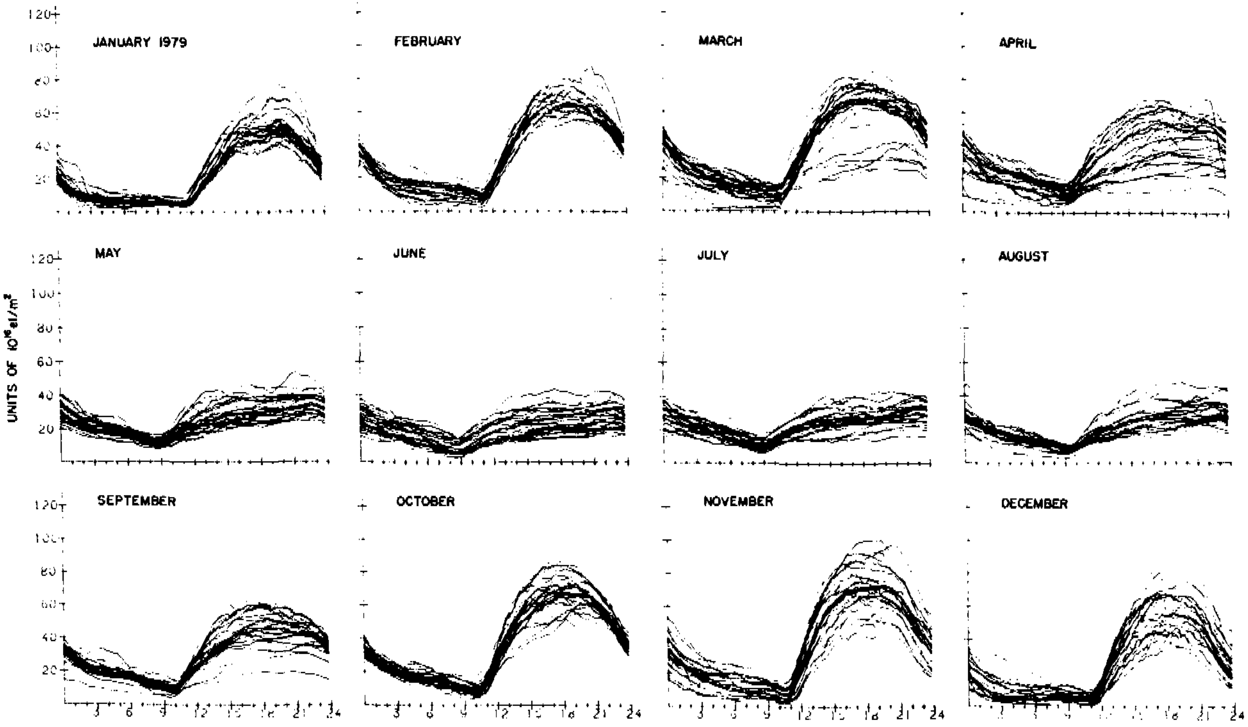

Figure 3. Monthly Overplots of Equivalent Vertical Total Electron Content for Hamilton, Massachusetts versus UT for 1979, (Near Solar Maximum).

SOLAR CYCLE ACTIVITY PREDICTIONS

The Ultra-Violet, (UV) flux from the sun is the major driver in long-term TEC behavior. However, short term changes in solar UV flux do not correlate well with day-to-day changes in TEC. Therefore, even if we had good direct measures of solar UV flux, they would not be very useful in solving the day-to-day TEC variability problem. However, long term changes in solar UV flux certainly would be helpful in predicting what magnitude of solar cycle effects to expect for the next solar cycle. Unfortunately, the state of the art of long term solar predictions is not as precise as one would like. The present solar cycle, number 22, is the current example of uncertainty in long term solar activity predictions. Figure 4 depicts the sunspot activity over the last approximate 200 years. While there is a general 11 year periodic behavior, the magnitude of each cycle is different. The largest cycle ever recorded peaked in 1958 and the second and third largest cycle peaks were in 1981 and 1949, respectively. One prediction for the current cycle is for a maximum sunspot number of approximately 150, with a peak as early as February 1990. However, even now in late 1988, this prediction is uncertain, with the range of maximum sunspot numbers going from 115 to over 200, (Hirman, et. al., 1988). The system user who requires long term ionospheric time delay predictions should be aware that the science of long term solar UV flux predictions is far from exact, and he must be prepared to keep updated on current monthly, or at least several day averaged, measured values if he wants to make the best use of models which give monthly average TEC.

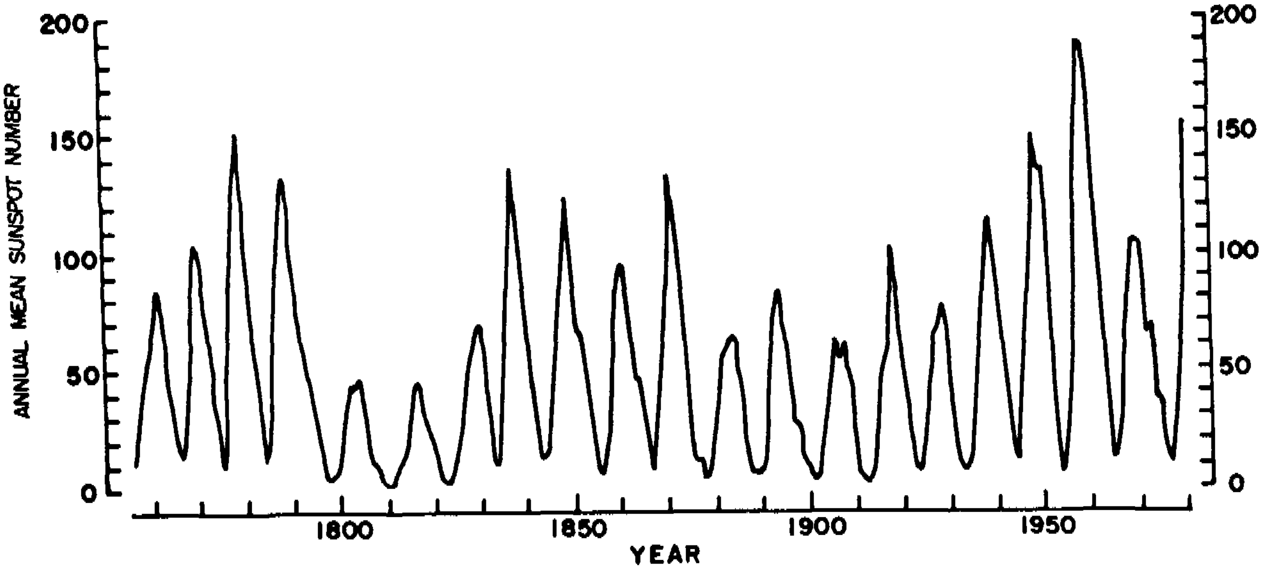

Figure 4. Mean Yearly Sunspot Numbers Since 1749.

MEAN MODELS VERSUS SPECIFICATION

It is one thing to make a model of monthly mean behavior of TEC, and several such models of the ionospheric F region exist which can be used for this purpose. It is quite another matter to be able to specify the actual TEC at the present time, or to predict it at a future time with an accuracy sufficient to satisfy time transfer needs. Depending upon the ionospheric correction accuracy required, one has several choices. These choices are:

1. Live with the ionospheric error; do nothing about it!
2. Correct for an approximate 50% rms ionospheric error by using the ionospheric algorithm designed for single frequency GPS system users.
3. Correct for approximately 75% of the rms ionospheric error by using a "state-of-the-art" ionospheric model, but with no attempt at updating with a real-time measurement.
4. Use a real-time ionospheric monitoring capability, but not necessarily measuring the time delay parameter directly, or making a measurement from the same direction, or from the same location as where the ionospheric correction is desired.

5. Incorporate a real-time ionospheric monitoring capability at an observation location to remove over between 90 to 95% of the ionospheric time delay error.

Let us take these five possibilities listed above in turn and discuss the implications of a user making any one of the above choices. Firstly, if a user completely ignored any possible ionospheric correction, he should at least become familiar with the price he is paying to neglect the effects of ionospheric time delay. That is, he should know when, and how much, the ionosphere is apt to be a major limitation to his time transfer accuracy. At least he should know that the ionosphere has a diurnal maximum in time delay, with that maximum occurring in the mid-afternoon period, the equinoctial values are larger than those during summer, and those within approximately plus and minus 15 to 20° either side of the geomagnetic equator are usually the world's highest. He should also know that during years of high solar activity the ionospheric time delay values are from three to four times higher than during solar minimum years, and that during times of high geomagnetic activity the largest deviations from average ionospheric time delay behavior generally occur. Armed with those few facts about the ionosphere, the user in this first category will at least know when to expect large errors from the ionosphere in his attempts to transfer precise time via satellite.

Since it is relatively trivial to include the single frequency GPS user ionospheric time delay algorithm into a time transfer system, perhaps the majority of people will first use this option. The algorithm was described by Klobuchar, (1987), and tests of its accuracy have been described by Feess and Stephens, (1987). Its use is recommended for those who can be content with an approximate 50% rms ionospheric time delay correction. The user must be aware of the significance of rms deviations from the algorithm, and their potential limitations to overall accuracy.

Choice number three given above is best illustrated by Figure 5 in which ionospheric error correction is plotted versus a measure of model complexity. Note that there is no scale on the abscissa in Figure 5, but model complexity can be related to computer assets required to run the model.

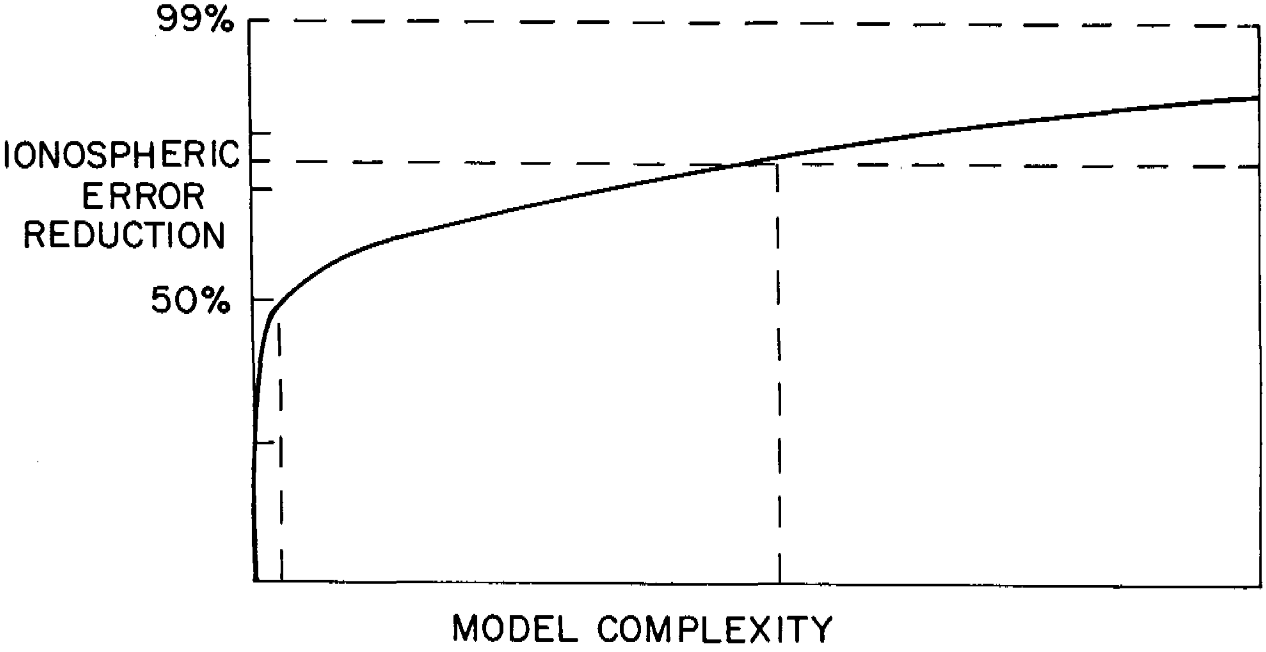

Figure 5. Ionospheric Error Reduction Versus Model Complexity.

For instance, the algorithm designed for a 50% rms ionospheric correction for single frequency GPS users is certainly not complex, yet it has been shown by Feess and Stephens, (1987), to give at least a 50% rms ionospheric error correction capability. State-of-the-art ionospheric models can be quite complex, and at present give only monthly mean ionospheric behavior without any near-real-time updating. Consequently, state-of-the-art ionospheric models can be expected to have as remaining errors any of the day-to-day deviations from monthly mean behavior, which are approximately 20 to 25%. By going from the simple ionospheric single frequency user algorithm, which gives an approximate 50% rms correction, to a state-of-the-art ionospheric time delay model, one adds a lot of model calculation complexity, yet only gains from 50% to perhaps 70-80% ionospheric error reduction. Some state-of-the-art ionospheric time delay correction models are available. These include the Bent Model, the International Reference Ionosphere, or IRI model, and the Penn State model. The first two can be obtained from the World Data Center-A, (Conkright, private communication), and the Penn State Model can be obtained from Nisbet, (private communication). The additional ionospheric time delay correction obtainable from any of these models, as compared with the model complexity, may make a user go to choices number 4 or 5 listed above.

If a user really needs to have the best currently available ionospheric time delay correction for his time transfer system then the thing to do is to make a dual frequency measurement of the actual ionospheric time delay along the actual satellite path of interest, such as the dual-frequency GPS system does automatically. Even with this technique one cannot expect to completely remove the effects of the ionosphere, but a correction exceeding approximately 95% of the ionospheric time delay can likely be expected. In order to make precise measurements of ionospheric time delay using two frequencies, their separation should be very wide, the transmitted carrier phase offsets must be known precisely, the receiving system must be carefully calibrated, careful attention must be paid to potential multi-path effects and the signal to noise of the signal must be high enough, or the integration time chosen long enough to make a precise measurement. It is doubtful that all these factors can be controlled accurately enough to make a 99% ionospheric error correction, but one in the mid 90% correction range is possible, if careful attention is given to these measurement details.

At least four groups are working on dual frequency, code-free receiving systems to make absolute measurements of ionospheric time delay using the GPS satellite signals. In a short time one of more such receiving systems, coupled with an ionospheric model to smooth over the necessary spatial distances between multi-satellite observations, may provide users with a correction for ionospheric time delay in the mid-90% range.

CONCLUSIONS

The total electron content of the earth's ionosphere can produce time delay errors in excess of 100 nanoseconds at the GPS L1 frequency. Models of the ionosphere vary in complexity, but even state-of-the-art models can correct, in general, for only 70 to 80% of the ionospheric time delay. The best correction for the effects of ionospheric time delay can only be made by an actual measurement along the same path as that along which the time transfer is being accomplished.

REFERENCES

Barghausen, A. L., J. W. Finner, L. L. Proctor, and L. D. Schultz, "Predicting Longterm Operational Parameters of High-Frequency Sky-wave Telecommunication Systems, ESSA Tech Report, ERL 110-ITS 78, 1969.

Conkright, R., private communication. For information on obtaining the International Reference Ionosphere, (IRI), or the Bent Model of the Ionosphere, contact Mr. R. Conkright, World Data Center-A, 325 Broadway, Boulder, Co. 80303.

Dandekar, B. S. "Ionospheric Modeling", AFGL-TR-82-0024, AD A115243, 1982.

Feess, W. A. and S. G. Stephens, " Evaluation of GPS Ionospheric Time-Delay Model", IEEE Trans. on Aerospace and Electronic Systems, Vol. AES-23, No. 3, pp 332-338, May 1987.

Hirman, J. W., G. R. Heckman, M. S. Greer, and J. B. Smith, "Solar and Geomagnetic Activity During Cycle 21 and Implications for Cycle 22", EOS, p. 962, October 18, 1988.

Klobuchar, J. A., "Ionospheric Time-Delay Algorithm for Single-Frequency GPS Users", IEEE Trans. on Aerospace and Electronic Systems, Vol. AES-23, No. 3, pp 325-331, May 1987.

Llewellyn, S. K., and R. B. Bent, "Documentation and Description of the Bent Ionospheric Model", AFCRL-TR-73-0657, AD 772733, 1973.

Nisbet, J., private communication, For information on obtaining the Penn State Ionospheric Model, contact: Professor, J. Nisbet at Communication and Space Sciences Laboratory, Penn State University, 316 Electrical Engineering East, University Park, PA 16802.

QUESTIONS AND ANSWERS

PAUL CASPER, ATMOSPHERIC RESEARCH SYSTEMS: Do you have any idea what the ionospheric delay is at ten times higher frequency? Up at Ku-Band?

MR. KLOBUCHAR: Yes, its one over f-squared, so it is one one-hundredth of these delays.

DR. WINKLER, USNO: I think that you can do another thing in order to reduce the effects and the errors, and that is just to observe during the night. The relative errors during the night are, of course, proportionally smaller. I have another question.

MR. KLOBUCHAR: Wait a minute. Do you have night at both places all the time. If you are trying to transfer time between here and India, under common view, it would be impossible to have night at both places.

DR. WINKLER: But we are not interested in common view. Most of the DoD does not use it for the simple reason that they cannot communicate. But I do have a question and that is: The phase noise which we have observed on dual frequency from six seconds to sixty seconds is much greater than on a single frequency. We have ascribed that, not to a spottiness or a phase jitter due to the ionosphere, but due to the measurement uncertainty. Is that correct?

MR. KLOBUCHAR: That is correct in nice, comfortable mid-latitudes. There are times when you can get in the auroral and polar cap regions some pretty fast phase jitter. Most certainly your observations have been under quiet mid-latitude conditions and on a second-by-second basis you would have very slow variations.

DR. LAPACHELLE, UNIVERSITY OF CALGARY: We already have the multi-channel receivers that can make dual-frequency phase measurements, by squaring the L2 without decoding. We also call them codeless receivers. Of course this type of receiver is quite different from the L1-L2 cross correlation. This type of receiver allows us to measure the rate of ionospheric variation over time, If we combine this technique with the L1-L2 cross-correlation technique that we saw yesterday, then we have a very powerful machine that does not require decoding of the code, and yet does everything we want as far as the ionosphere. I have the following question. Can you comment on the effect of phase scintillation on carrier phase lock? There are problems with that not only in the auroral zone, but also probably near the equator. This loss of phase lock has already been experienced and could possibly cause a lot of problems, at least for navigation. Could you comment on the extent of this, when the sunspot reaches a maximum?

MR. KLOBUCHAR: Yes, you are certainly correct that in the equatorial part of the world and maybe in the high latitudes there are times that you can get such severe phase scintillation that you can lose lock. The program office became aware of this in '79 or '80 we went to Ascension Island to make some measurements with a, at the time state-of-the-art receiver. Ascension Island is right down near the peak of the anomaly of very high peak electron density. Sure enough, the receiver was in and out of lock a lot of the time. We also made measurements in Kwajalein Island over in the Pacific and similar kinds of things happened. You could get amplitude fades in excess of 20-25 dB. We reported this to the JPO and they made some changes on their receivers to allow the receivers to "coast" through these amplitude fades and to continue at the same cycle rate that they had as they entered the fades. That helped the problem to some extent. In the high latitudes, we have had three receivers working up at Thule, Greenland for the last couple of years and we don't see as severe effects. We see some changes in group delay or absolute time change that are great. We haven't ever lost lock yet, I guess, but we are not at solar maximum. The times when this occurs in the equatorial region are well known. It is very patchy and only occurs from local sunset to around midnight, but only in patches. I don't think that it will put anybody out of business unless they need to know it right then and there. Certainly JPO has stations all over this area. I asked them how they could tell where the satellites are when they are in this very strongly scintillating region and they said that they just have a little higher errors and average a little longer and discard data if it is too bad. They don't have a real time requirement. The time transfer community can do the same thing because their requirement is not real time either. The problem is different if you are a naval vessel that wants to launch a missile and needs positions right away. In the high latitudes, you don't have a simple diurnal variation like you do in the equatorial region where it starts up like clock work at sunset and goes on to midnight almost every night for six months of the year. The high latitudes are not as predictable, but the problem is not quite as severe there.

SKIP OSBORNE, ALLEN OSBORNE ASSOCIATES: Even though the spread between L1 and L2 isn't as great as you would like it, is there any advantage to using L3?

MR. KLOBUCHAR: No. It isn't on all the time and it isn't even as far apart as L1 and L2. They didn't do a bad job in selecting L1 and L2.

MR. OSBORNE: T sub g–is there anything that you recommend? It sounds like we are stuck.

MR. KLOBUCHAR:I think that we had better continue this off line since we are out of time.