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ACCURATE TIME AND FREQUENCY TRANSFER DURING COMMON-VIEW OF A GPS SATELLITE

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Summary

Even though the GPS is primarily a navigation system, if two clocks at known coordinates A and B are in common-view of a single GPS satellite, receivers at these two clock sites may coincidentally receive transmitted GPS clock times. By subtracting the received times of arrivals as measured by clocks A and B at the two sites while compensating for the propagation delays, one has an accurate measure of the time difference between clock A and clock B.

When all of the error contributions are assessed, it appears that 1 ns time stability and 10 ns of time accuracy should be achievable in measuring remote clocks--at distances of the order of a few thousand km. The primary error sources are as follows: uncertainties in the satellite ephemeris, differential ionospheric delays, uncertainties in tropospheric delay estimation, and uncertainties in receiver delays.

We have chosen this common-view approach because it provides an opportunity for a high accuracy (10 ns) relatively low cost receiver due to the common-mode error cancellation achievable.

Introduction

The fact that GPS time is based on atomic clocks, plus the fact that the GPS satellite ephemerides are accurately known, leads to some significant national and international time comparison opportunities. Even though GPS is fundamentally a navigation system, accurate time is also available.[1] It is assumed in this document that users wishing to measure or compare time on the earth will know their location to within similar uncertainties attributable to the time errors in GPS. The civilian or C/A (clear access)-code will always be available and can be used for general access system design.

There are four interesting methods to employ GPS for accurate time transfer or for accurate time and frequency comparisons (see Fig. 1):

First, Clock A and a GPS receiver are used to deduce from a GPS satellite's ephemeris, from clock A's location, and from received GPS time decoded from the same satellite, the time difference (Clock A - GPS time). This method is the simplest and least accurate (estimated to be better than about 100 ns with respect to GPS time),[2] but has global coverage, is in the receive-only mode, requires no other data, yields receiver prices that could be competitive on a mass production basis, and could service an unlimited audience. Also, GPS time will be referred to UTC(USNO) and will be known with respect to UTC(BIH), UTC(NBS), and other major timing centers.

Second, Clock A and Clock B at different locations anywhere on earth can be compared by making successive observations of the same GPS satellite clock, at least one of which will appear above their horizons with delayed view times of less than 12 hours. This is analagous to the clock flyover mode reported by J. Besson[3] and others. The time prediction error for the satellite cesium clocks to be used in the GPS satellites will be about 5 ns over 12 hours. Since the same GPS satellite clock will be viewed by both A and B, biases in the satellite ephemeris may tend to cancel depending upon geometry, etc. Accuracies of from 10 ns to 50 ns are anticipated. This method requires communication of the data between A and B, and hence the logistics may limit the customers.

Third (see Figures 1 & 2), two users with Clock A and Clock B at different locations, but in simultaneous common-view of a single GPS satellite clock, can take advantage of common mode cancellation of ephemeris errors in determining the time difference (t_A - t_B). The satellite clock error contributes nothing. Since the GPS satellites are at about 4.2 earth radii (12 hour orbits), for continental distances between A and B ($\lesssim$ 3000 km) the angle $\angle$ (A-Satellite-B) will be $\lesssim 10°$, and the effects of satellite ephemeris errors will be reduced by a factor of more than 10 over the first method. Using a fairly straightforward receiver system, an accuracy of about 10 ns in measuring the time difference (t_A - t_B) appears probable. This again requires data communication between A and B. With improved ephemerides and propagation delay characterization, the accuracy limit for this method appears to be about 1 ns. The receiver should be relatively inexpensive, and given the reasonable costs of data modems and the potential accuracies achievable via this method, it makes it very attractive and cost effective for national, and in some instances, for international time comparisons.

Fourth, a method being developed for Geodesy by JPL (Jet Propulsion Laboratory)[4] has baseline accuracy goals of about 2 cm over baselines of the order of 100 km. This method can be inverted to do time comparisons with subnanosecond accuracies. The two clocks A and B separated by about 100 km have two broadband receivers with tunable tracking antennae such that sequentially, 4 satellites can be tracked concurrently at A and B. The data are cross-correlated after the fact, the same as in long baseline interferometry, to determine location and time difference (t_A - t_B). The data density is high and the baselines are relatively short, but the accuracy is excellent.

It appears that as GPS becomes fully developed, GPS time may become operational world time. Methods 1, 2, or 3 above would yield significant improvements in national and international time comparisons. If commercial vendors take advantage of some of these methods, receiver costs could be made reasonable. The same basic receiver could be used in methods 1, 2, or 3; the main difference would be in the software support, modems, and local clocks. Method 3 (common-view) coupled with LASSO would provide an ideal future method for the generation of International Atomic Time, TAI, and of UTC at the nanosecond accuracy level. This method has the most attractive accuracy/cost ratio and is being pursued by NBS. The theoretical advantages and disadvantages are reported herein.

System Error Analysis

Errors Resulting from Satellite Ephemeris Location Uncertainty

The time transfer error is dependent upon the ephemeris or position error of a satellite. Common-view time transfer yields a great reduction in the effect of these errors between two stations, A and B, as compared to transfer of time from the satellite to the ground. Common-view time transfer is accomplished as follows:

1) Stations A and B receive a common signal from a satellite and each records the local time of arrival, t_A and t_B respectively.
2) From a knowledge of station and satellite position in a common coordinate system, the range between the satellite and each of the stations is computed, r_A and r_B respectively.
3) The time of transmission of the common signal according to each station, A and B, is computed by subtracting from the times of arrival, the times of propagation from the satellite to each of the respective stations, i.e., the time to travel the distances, r_A and r_B, are τ_A and τ_B (the range delays) and are given by $\tau_A = r_A/c$ and $\tau_B = r_B/c$ where c is the speed of light. This speed is subject to other corrections as are treated later.
4) Finally, the time difference, τ_{AB}, of station A's clock minus station B's clock at the times the signals arrived is:

$$\tau_{AB} = (t_A - \tau_A) - (t_B - \tau_B) = (t_A - t_B) - (\tau_A - \tau_B).$$

If the ephemeris of the satellite is off, the computed ranges from the stations to the satellite will be off an amount dependent on the way the ephemeris is wrong and the geometrical configuration of the satellite-station systems. The advantage of common-view time transfer is that the computed bias is affected not by range errors to individual stations, but by the difference of the two range errors. Thus, much of the ephemeris error cancels out. To see how this works in detail, suppose the ephemeris data implies range delays of τ'_A and τ'_B, but the actual position of the satellite, if known correctly, would give range delays of $\tau_A = \tau'_A - \Delta\tau_A$ and $\tau_B = \tau'_B - \Delta\tau_B$. Then the error in time transfer would be $\Delta\tau_{AB} = \Delta\tau_B - \Delta\tau_A$, where $\tau_{AB} = \tau'_{AB} - \Delta\tau_{AB}$ is the true time difference (clock A - clock B) and where τ'_{AB} is the computed time difference from the actual time of arrival measurements and ephemeris data. Thus, $\Delta\tau_{AB}$, the time transfer error due to ephemeris error, depends not on the magnitude of the range errors, but on how much they differ.

The error in time transfer, $\Delta\tau_{AB}$, as mentioned above, depends on the locations of the two stations and of the satellite, as well as the orientation of the actual position error of the satellite. Figures 3 through 18 at the end of the paper give $\Delta\tau_{AB}$ for some ground stations of interest with different discrete levels of error shown as contour graphs dependent on where the satellite is. There are four sets of contour graphs for each pair of ground stations; for current and future typical ephemeris errors,[4] and for whether the satellite is going north or south in its orbital plane. Within a particular graph, the contour level at a point corresponds to the root-mean-square value of $\Delta\tau_{AB}$ when the common view satellite is directly above that location. The current values of ephemeris error for the GPS satellites are estimated at about 10 meters in-track, i.e., in the satellite's direction of motion; 7 meters cross-track, and 2 meters radial.[5] This corresponds to 41.23 ns rms error (square root of the sum of squares/c). The projected values for 1985 are 7 m in-track, 3 m cross-track, and 0.6 m radial, corresponding to 25.46 ns rms error.[5] Notice that the rms errors make an elongated ellipsoid and are dependent on satellite direction. Thus, to compute the range errors to a given pair of stations for a given satellite location, one needs to know the satellite direction at that location. The satellite moves in a fixed plane in space with the earth rotating under it.

The program which computed the figures used an orbital plane making an angle of 63° with the ecliptic with the satellite moving west to east in the plane. As an approximation, the orbit was assumed circular at 4.2 earth radii (12 hour period). At a given latitude, the satellite direction in degrees east of north is determined by the orbital plane and whether the direction is northerly or southerly. Corrections for the earth's rotation need to be included. Thus, each figure was created by: 1) choosing a given pair of ground stations, a set of values for ephemeris error, and whether the satellite was moving north or south in its orbital plane; 2) for a given location on a map containing the ground stations, finding the satellite direction (a function of latitude only) and three independent position error vectors from the three different types of ephemeris error; and 3) approximating $\Delta\tau_{AB}$ for each of the independent position error vectors, then finding the square root of the sum of their squares for the total $\Delta\tau_{AB}$ at that location. In this way a chart of values of $\Delta\tau_{AB}$ was computed, which were then plotted in contour plots superimposed on a world map in cylindrical projection. Clearly, there are regions shown where the satellite will be below the horizon for one or both stations, so the maps are over-inclusive in this regard.

The $\Delta\tau_{AB}$ were approximated in the following way. Let us fix a coordinate system at the earth's center to define basis vectors. Then let $\underline{A}$ and $\underline{B}$ be the position vectors of stations A and B, repectively, and $\underline{S}$ the position vector of the satellite. Then the range vectors, pointing to the satellite from the ground stations, are:

$$\underline{R}_A = \underline{S} - \underline{A} \text{ and } \underline{R}_B = \underline{S} - \underline{B}.$$

Let e_A and e_B be the unit vectors in the directions of $\underline{R}_A$ and $\underline{R}_B$ respectively. Then the ranges are:

$$r_A = e_A \cdot (\underline{S} - \underline{A}) \text{ and } r_B = e_B \cdot (\underline{S} - \underline{B}).$$

If $\underline{S}$ is the satellite position according to its ephemeris, but the true position is $\underline{S} + \Delta\underline{S}$ then the new unit vectors, e'_A and e'_B, are the same as the old to first order:

$$e_A \cdot e'_A = 1 - \frac{\alpha^2}{2} + \cdots = \cos(\alpha), \text{ where } \alpha \text{ is the angle between } e_A \text{ and } e'_A.$$

So, to first order, the new ranges are:

$$r'_A = e_A \cdot (\underline{S} + \Delta\underline{S} - \underline{A}).$$

Thus, the range errors are approximately:

$$\Delta r_A = r'_A - r_A = e_A \cdot \Delta\underline{S} \text{ and } \Delta r_B = r'_B - r_B = e_B \cdot \Delta\underline{S}$$

so:

$$\Delta\tau_{AB} = (\Delta r_B - \Delta r_A)/c = \frac{1}{c}(e_B - e_A) \cdot \Delta\underline{S}.$$

We see that the time transfer error increases as the vectors pointing to the satellite from the ground stations become less parallel up to the maximum of $\sqrt{2}$ times the ephemeris error when they are perpendicular, down to zero when they are parallel. Because of the dot product, some interesting and very helpful situations may arise. For example, if the path of the satellite were at right angles to the line between stations A and B and were half-way in between the two stations, the effect of the ephemeris errors due to radial and on-track go to zero! Since the GPS satellites are so far out, 4.2 earth radii approximately, the direction vectors pointing to the satellite tend to be close to parallel, thus cancelling most of the ephemeris error in all cases where common-view is available.

Errors Resulting from Ionosphere

The ionospheric time delay is given by $\Delta t = 40.3/cf^2 \cdot \text{TEC}$ (seconds) where TEC is the total number of electrons, called the Total Electron Content, along the path from the transmitter to the receiver, c is the velocity of light in meters per second, and f is the carrier frequency in Hz. TEC is usually expressed as the number of electrons in a unit cross-section column of 1 square meter area along the path and ranges from 10^{16} electrons per meter squared to 10^{19} electrons per meter squared. At the 1.575 GHz C/A carrier frequency for the GPS satellite system and for a TEC of 10^{18} electrons per meter squared, one computes the delay of 54 ns which is possible for low latitude parts of the world. For these low latitudes and solar exposed regions of the world, time delays exceeding 100 ns are possible especially during periods of solar maximum. Clearly, the TEC parameter is of great importance in the GPS system. Shown in Fig. 19 is a reproduction of a figure taken from a paper by J. A. Klobuchar,[6] this figure clearly shows during a solar maximum year, 1968, that the range of delays vary from about 5 to 40 ns, being maximum near the equator and near the noon path. Fig. 20 is also from Klobuchar's paper and shows the actual vertical electron content at Hamilton, MA looking towards the ATS-3 satellite for every day of the year, and here again one sees the variations from the order of 5 ns to 40 ns.

In studying these graphs, one observes two very important things: 1) the total delay at nighttime and/or high latitude is much smaller than at daytime, and 2) one notices that the correlation in absolute delay time covers much larger distances when one moves away from the equator and the vicinity of noon; the conclusion being that a significant amount of common-mode cancellation will occur through the ionosphere at large distances if all observations are made at either high latitudes and/or at nighttime. These cancellation effects, as can be seen from Fig. 20 over several thousand km, will cause errors of less than 5 ns. For short baselines less than

1000 km, this common-mode cancellation will cause errors of the order of or less than about 2 ns.

Clearly, this gives a definite direction as to how one should proceed using the common-view GPS time and frequency transfer technique proposed in this paper. Even though the total ionospheric delay may be very large at certain times and places, there are ways to pick and choose, which would allow one to get large amounts of common-mode cancellation and which would allow one to achieve with some care, time and frequency transfer accuracies approaching a nanosecond.

Beyond the common-mode cancellation, if one had access to the measurements of the total electron content, then clearly one could use the model to actually calculate the delay over the two paths of interest, or if the monitor stations for the TEC were nearby, given reasonable correlations from one monitor station to another, one could interpolate the TEC so that on an ongoing basis, the differential delay variations could be calculated again to the order of a nanosecond. Also, if one used both the L_1 and L_2 frequencies from the GPS satellite, the TEC could be calculated.

Errors Resulting From Troposphere

In transferring time between ground stations via common-view satellite, one records the time of arrival of the signal and computes the time of transmission by subtracting the propagation time. The propagation time is found by dividing the range to the satellite by the velocity of light. However, moisture and oxygen in the troposphere have an effect on the velocity of propagation of the signal, thus affecting the computed time of transmission and therefore, the time transfer. This effect is dependent on the geometry, the latitude, the pressure, and the temperature, and may vary in magnitude from 3 ns to 300 ns.[7] However, by employing reasonable models and using high elevation angles, the uncertainties in the differential delay between two sites should be well below 10 ns. Later on, if needed, the magnitude of the troposphere delay can be calculated with uncertainties which will approach a nanosecond.

Error Considerations in Receiver Design

Since the primary goal of the NBS receiver design is accuracy in time and frequency transfer, the approach taken tends to be somewhat different than perhaps may be considered in a navigation receiver. The fundamental concern is that whatever time delay exists within the receiver that it be extremely stable (of the order of a nanosecond). This, of course, can be most easily accomplished if the total additional delay (beyond cables) is minimized through the receiver. We also are working toward minimum parts cost, while still providing full automation in capability. In addition, we are designing into the current units being built by NBS, self contained microprocessor control and a (1 ns) time interval counter.

The total receiver will have high accuracy, is designed to be very stable, and will be totally automated and self-contained. This allows one to take maximum advantage of appropriate seeing time of the satellites, minimize ionospheric delay and delay variations; to maximize the common-mode cancellations between two sites. We estimate a total receiver delay, excluding cables, to be less than 30 ns and the receiver stability to be less than 2 ns. Receivers can be straightforwardly calibrated in a side-by-side mode as to the differential delay, and since one uses the concept of common-mode between two sites, only the differential delay is important for accurate time and frequency transfer between sites A and B.

Current and Future System Accuracy Potential and System Cost

When one combines all of the possible errors from any of the potential error sources, one obtains an absolute accuracy of time transfer of better than 10 ns, and a time stability of the order of a nanosecond. This means that on a 24 hour basis, one could measure absolute frequency differences between remote sites to a few parts in 10^{14}. We anticipate a front end parts and assembly cost (not including development costs) of well under $10,000. This includes the computer and automatic control system as well as a 1 ns time interval counter; but, of course, does not include the necessary testing documentation and costs incurred by a vendor if they were to develop and put into production such a system. The concept being developed has the significant advantage that the main costs will be front end costs as the system should be unintensive after being set in operation. It also has the significant advantage over two-way satellite systems, in that it is in the receive only mode, which should allow a much larger user audience for this kind of receiver as well as avoiding all of the problems of FCC clearance, etc. for having a transmitter, which is necessary for a two-way satellite system. There have been some discussions that because of the excellent signal-to-noise on the C/A code that the signal strength would be degraded, so that adversary users would be denied the full accuracy of the system. From a time and frequency point of view, this would not be a serious problem if there was a degradation in signal-to-noise, because one could simply do averaging and since there is plenty of time to average over a pass, this should still give comparable accuracy results.

The future accuracy potential is quite exciting because there is significant anticipated improvement in the accuracy of the ephemerides for the satellites, and that error contribution should be reduced considerably. The ionospheric delay can, in fact, be calibrated at or below the nanosecond level, and the tropospheric delay can also be modeled to a few nanoseconds. As we gain more experience with receiver design and total delay and delay stability, it is believed that its accuracy can also be improved to the nanosecond level or below. Ultimately, over the next several years this common-view approach could be developed with accuracies of the order of a nanosecond.

Conclusions

In conclusion, we have shown that one-way satellite transmission from a GPS satellite in common-view at two sites allows one to do accurate time transfer to 10 ns or better. This accuracy is achieved because of common-mode cancellations of several contributing errors in the system. The system furthermore has the potential to achieve accurate time transfer of the order of a nanosecond. The estimated stability of the receiver delays and all contributing error delays should yield stabilities of the order of 1 ns, which means that on a 24 hour basis, frequency transfer can occur with an accuracy of about 1 part in 10^{14}. Two prototypes are being built at the National Bureau of Standards to test these ideas.

Acknowledgements

We are indebted to our sponsor SAMSO and the several competent contributors to the development of Global Positioning System, in particular, to Dr. John A. Klobuchar and to Albert Bierman; to Dick Davis and Al Clements and their great initiative in the receiver design concepts, which will be published after prototypes have been built and tested. We also wish to express our indebtedness to Dr. G. M. R. Winkler, Mr. James L. Jespersen, and Dr. S. Jarvis for very helpful suggestions in the text.

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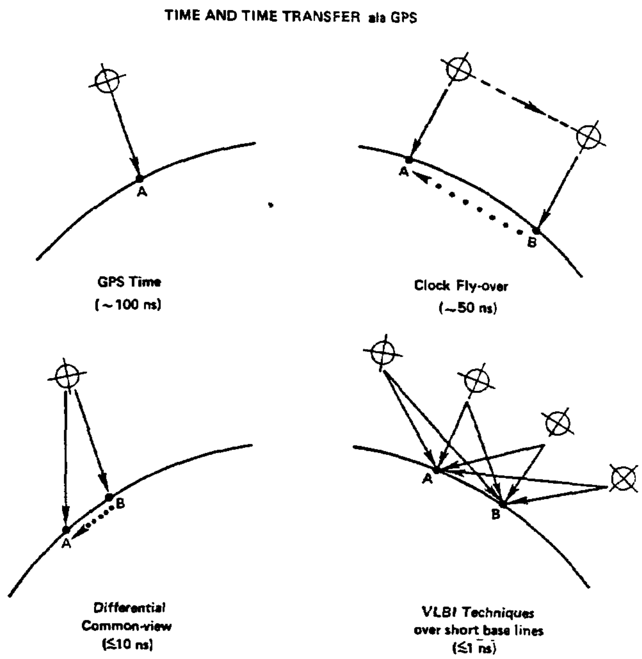


Figure 1. Four methods of time transfer and their approximate accuracies using GPS:
Upper left, using data from the satellite to find GPS time and comparing a local clock with the GPS time scale.
Upper right, using one satellite to decode GPS time at two different locations and times to compare both clocks with the GPS time scale and hence with each other.
Lower left, measuring the time of arrival of a common signal from a satellite at two locations to compare the computed time of transmission according to the two clocks and thus compare the clocks.
Lower right, recording signals from four satellites at two stations to determine locations and time differences.

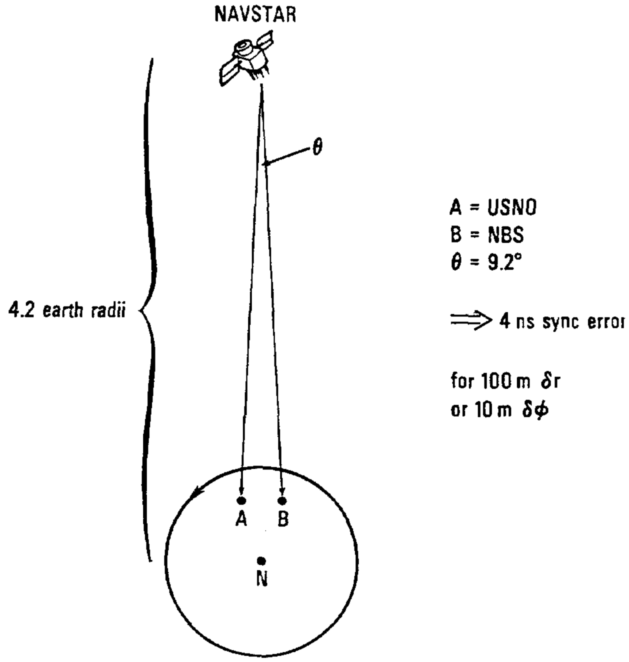


Figure 2. Time transfer via a satellite in common view of two ground stations indicating that fairly large errors (100 m = 333 ns radial error or 10 m = 33 ns in-track or cross-track error) in satellite ephemeris can cancel to a few ns time transfer error.

Figures 3-18. Contour graphs of the error in common-view time transfer for various choices of ground stations, satellite direction, and ephemeris error. The odd-numbered figures use current ephemeris error estimates: 10 m in-track, 7 m cross-track, and 2 m radial corresponding to 41.23 ns rms (square root of the sum of the squares divided by the speed of light). The even-numbered figures use error values projected for 1985: 7 m in-track, 3 m cross-track, and 0.6 m radial corresponding to 25.46 ns rms. The satellite direction is always northerly in the "a" figures and southerly in the "b" figures. The ground station locations are marked with an "x". The contours in a given figure are spaced for equal error values with error increasing as one goes from dotted to dashed to solid to dotted lines. Figures 3a, 3b, 4a, and 4b are examples of all four combinations; the odd numbered "a" figures and the even numbered "b" are deleted thereafter because their contour may be inferred from studying Figures 3a, 3b, 4a, and 4b along with the station combination of interest.

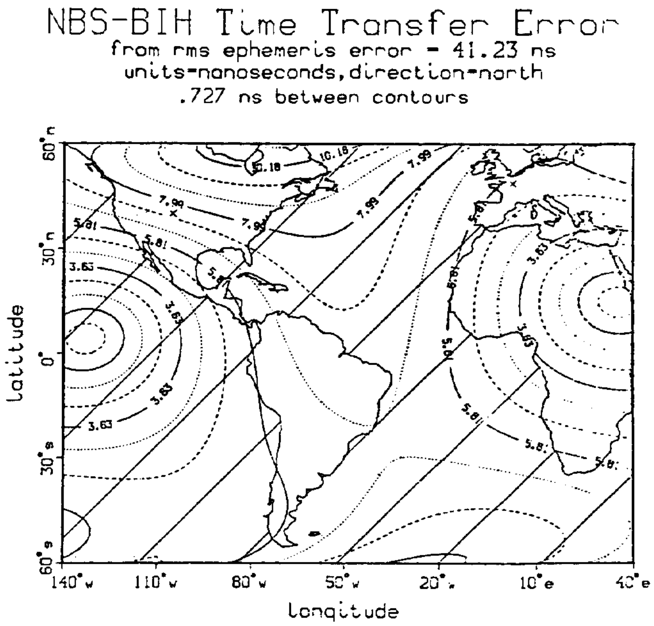


Figure 3a.

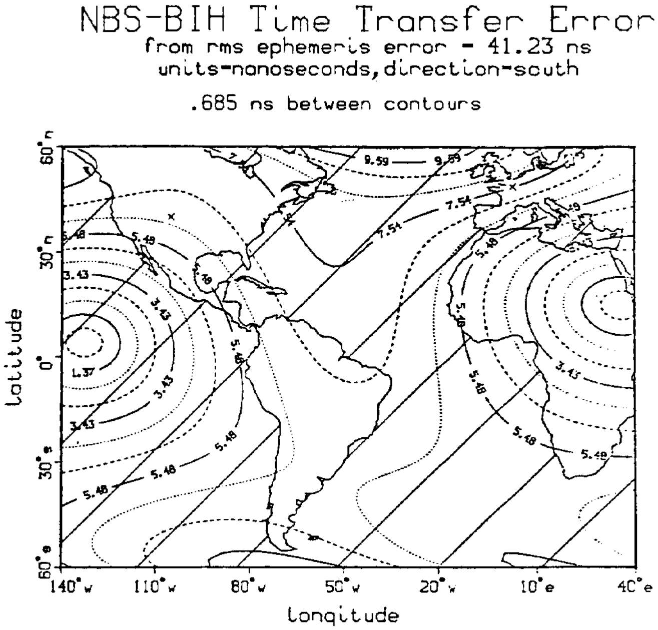


Figure 3b.

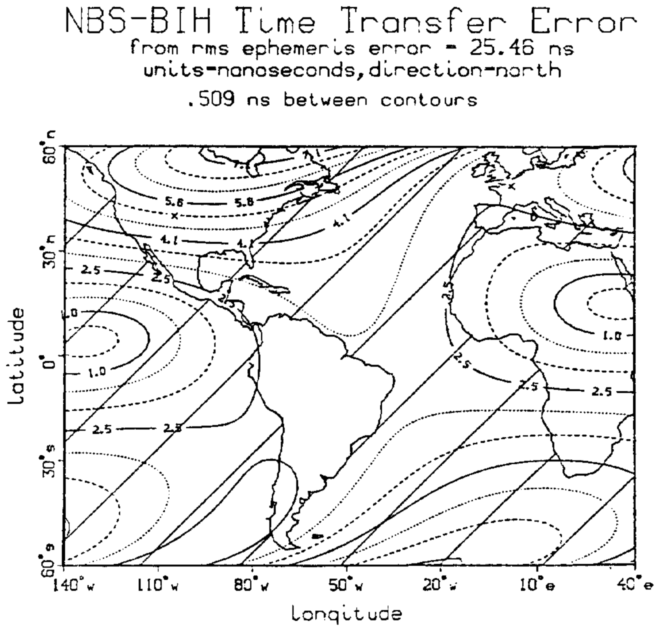


Figure 4a.

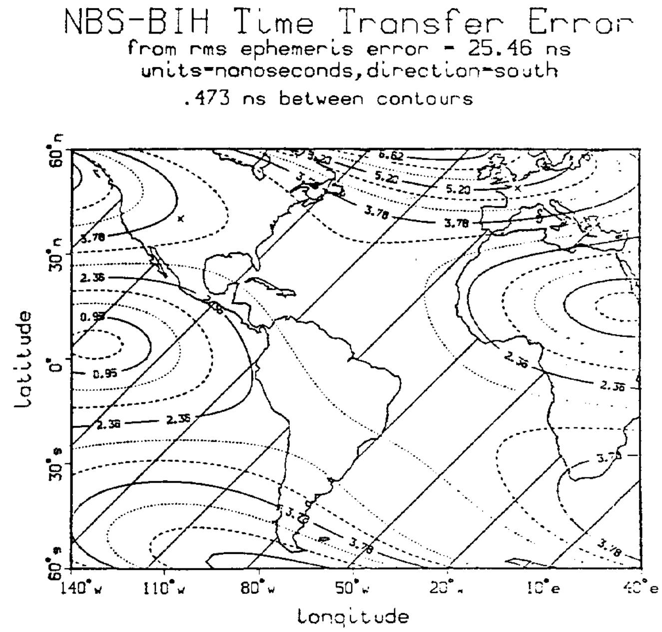


Figure 4b.

NBS-NRC Time Transfer Error
from rms ephemeris error = 41.23 ns
units=nanoseconds, direction=south
.200 ns between contours

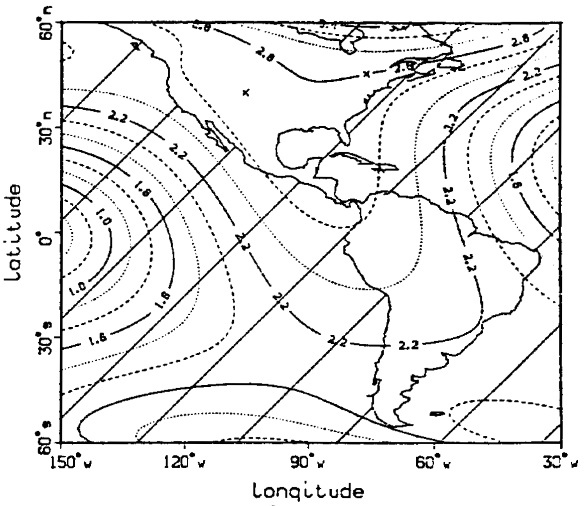


Figure 5b.

NBS-NRC Time Transfer Error
from rms ephemeris error = 25.46 ns
units=nanoseconds, direction=north
.167 ns between contours

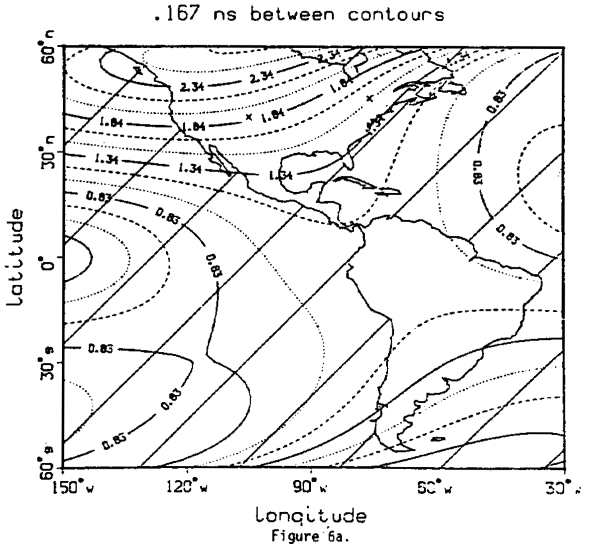


Figure 6a.

NBS-PTB Time Transfer Error
from rms ephemeris error = 41.23 ns
units=nanoseconds, direction=south
.609 ns between contours

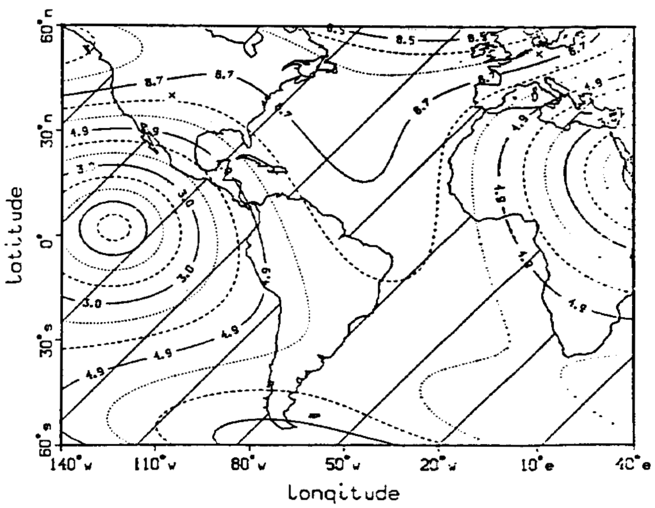


Figure 7b.

NBS-PTB Time Transfer Error
from rms ephemeris error = 25.46 ns
units=nanoseconds, direction=north
.477 ns between contours

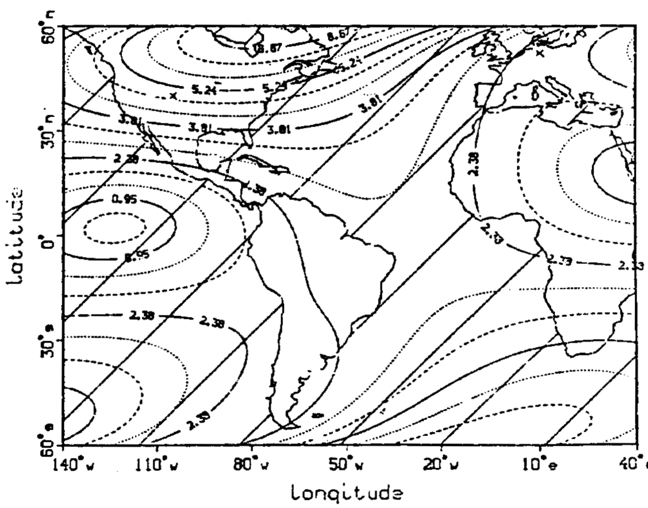


Figure 8a.

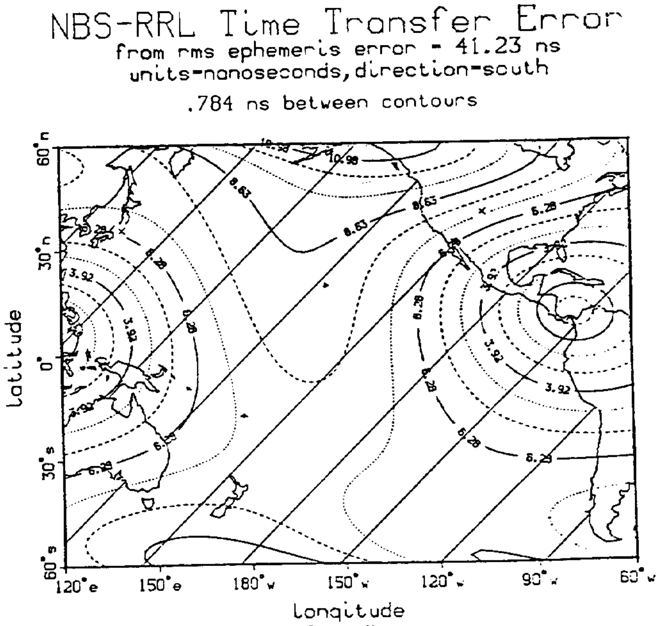


Figure 9b.

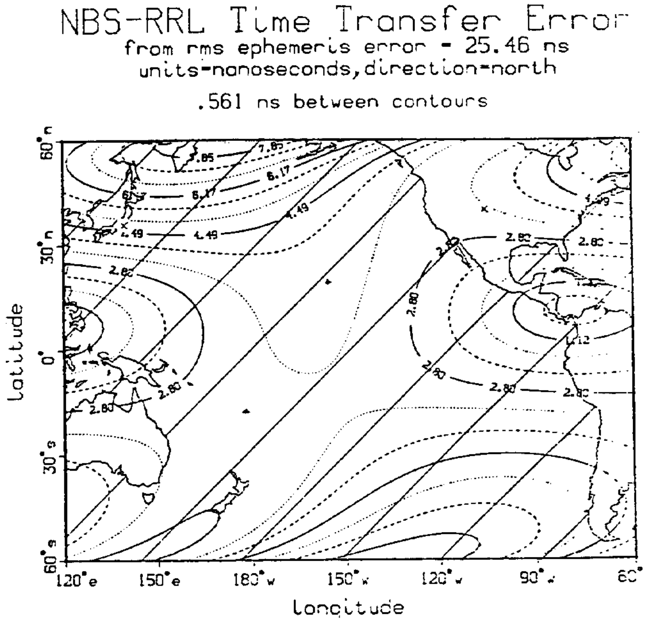


Figure 10a.

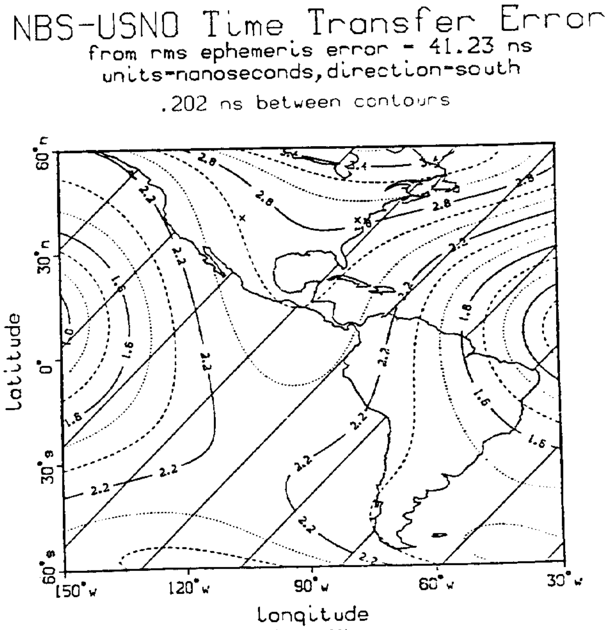


Figure 11b.

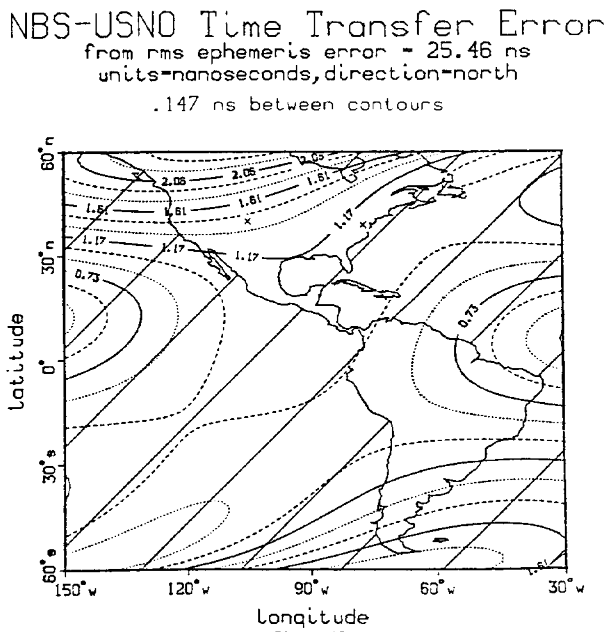


Figure 12a.

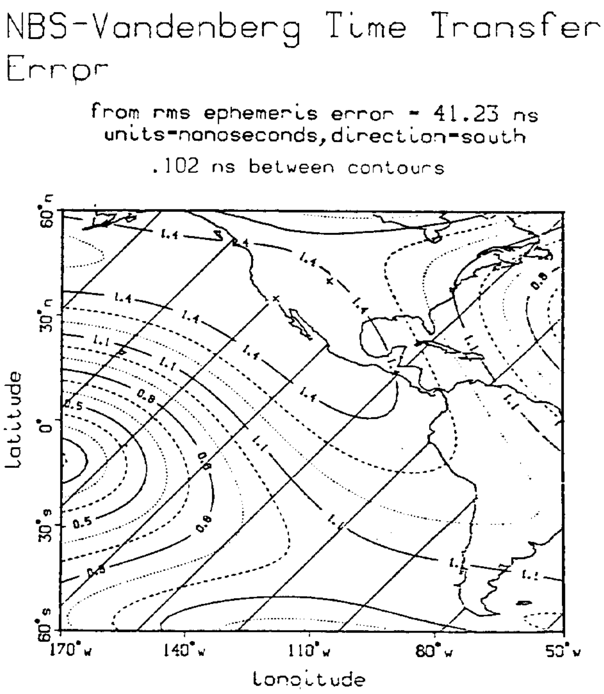


Figure 13b.

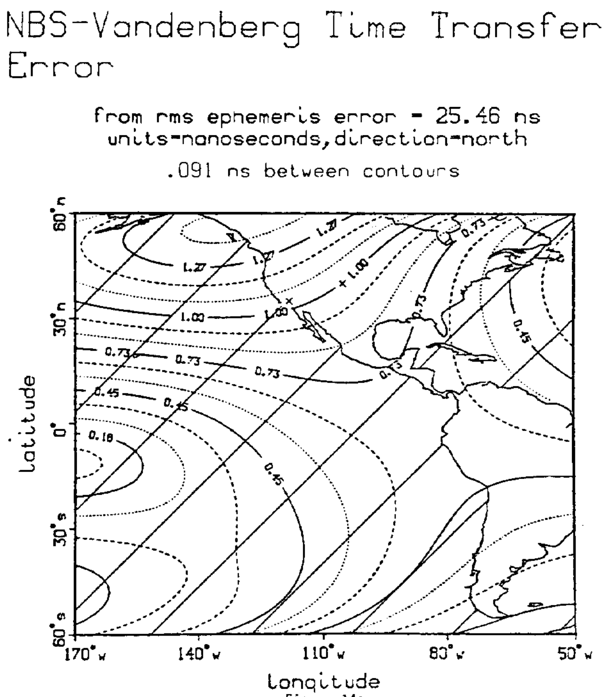


Figure 14a.

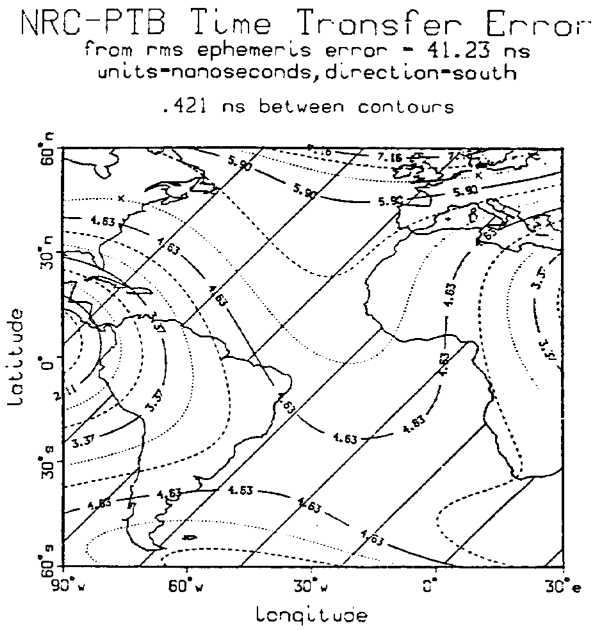


Figure 15b.

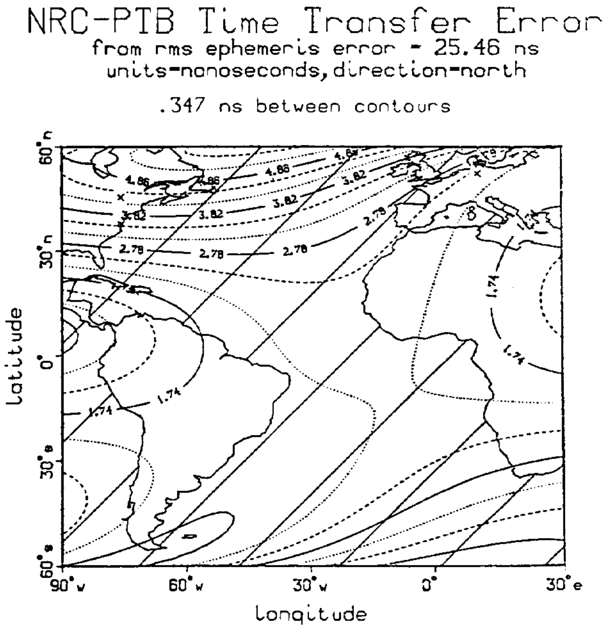


Figure 16a.

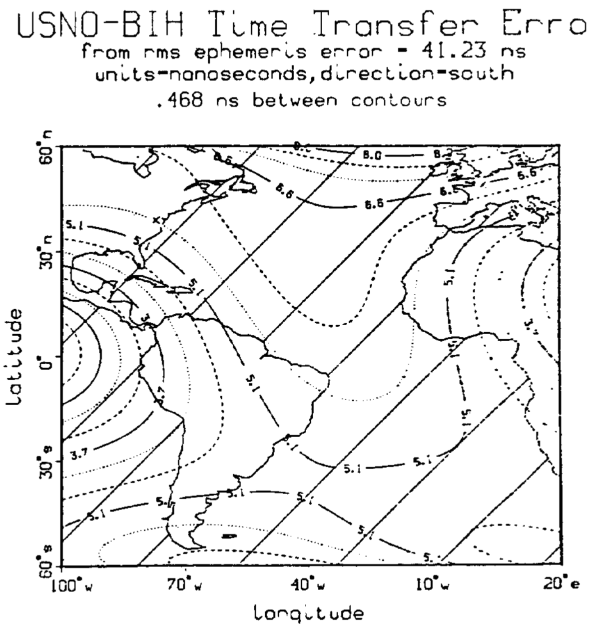


Figure 17b.

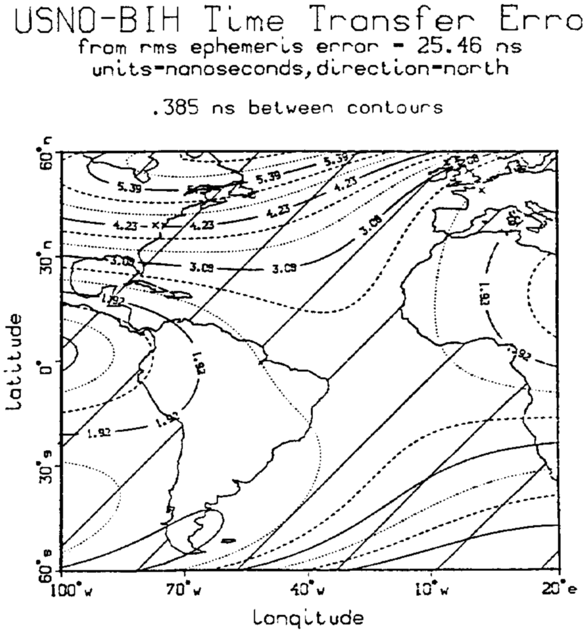
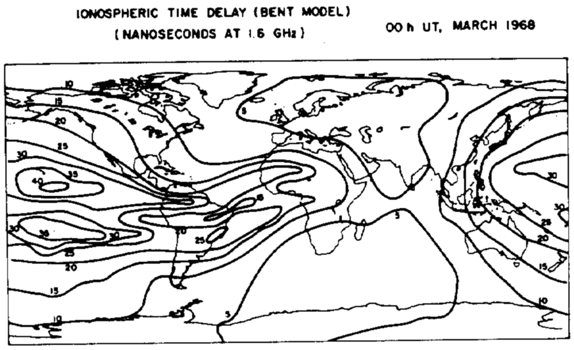
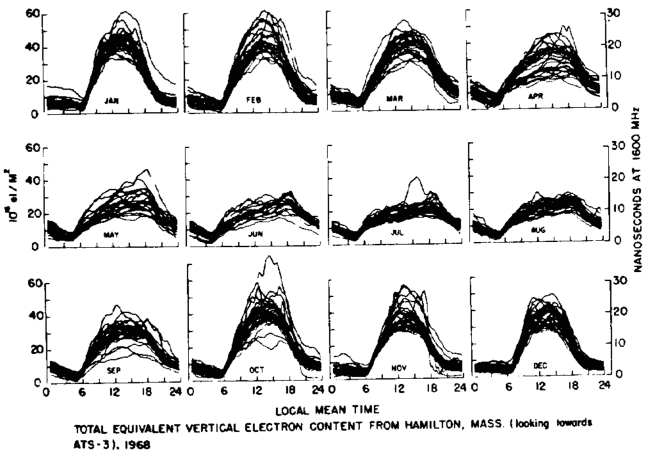


Figure 18a.



Worldwide average vertical ionospheric time delay at 1.6 GHz for 00 hours universal time March, 1968, an average solar maximum year.

Figure 19.



Monthly overplots of equivalent vertical TEC from Hamilton, Massachusetts for the year 1968, a solar maximum year.

Figure 20.