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Air Force Studies Board
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National Research Council (U. S.).

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Statement of Task

The Committee on Accuracy of Time Transfer in Satellite Systems will do the following:

1. Evaluate and determine adequacy of corrections for relativistic effects in present Air Force programs to performing their mission, e.g., global positioning system (GPS).

2. Estimate or evaluate the accuracy needs for correction of relativistic effects for future Air Force missions.

3. Determine adequacy of present methods for meeting those needs and recommend programs, if needed, to improve the accuracy of time transfer in satellite systems.

The Committee will provide the Air Force Systems Command with a final report giving its findings and recommendations for use by the Air Force Systems Command for its future course of action.

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CONTENTS

I. INTRODUCTION ● 1

II. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS ● 4

- 2.1 Handling of Relativistic Effects ● 5
- 2.2 Near-Term Improvements in GPS ● 5
- 2.3 Recommendations for Sub-Nanosecond Accuracy and Long-Term Improvements ● 6
- 2.4 Time Transfer: An Opportunity to Study Relativistic Effects ● 6

III. CLOCK SYNCHRONIZATION IN THE GPS: A PRIMER ● 7

IV. RELATIVISTIC EFFECTS IN GPS: VALIDITY OF CURRENT TREATMENT ● 11

- 4.1 Relativistic Effects ● 11
  - Time Dilation ● 11
  - The Sagnac Effect ● 12
  - Gravitational Redshift ● 13
- 4.2 Treatment of Relativistic Effects ● 13
- 4.3 Criticisms of the Treatment of Relativistic Effects ● 15
  - Points 1 and 2 ● 16
  - Point 3 ● 17
  - Point 4 ● 17

V. MAXIMIZING THE POTENTIAL OF GPS ● 19

- 5.1 Time Discipline in the System of Ground Station Timing ● 20
- 5.2 Auxiliary Monitoring Stations ● 26
- 5.3 Separation of Satellite Position and Clock Errors ● 26

VI. FUTURE NEEDS FOR TIME TRANSFER ● 32

- 6.1 Separation of Satellite Ephemeris and Clock Errors: The Long View ● 32
- 6.2 Compensating for Signal Propagation Effects ● 35
- 6.3 Performance and Reliability of Frequency Standards ● 39
- 6.4 Tightening of Requirements as Technology Permits ● 41

VII. TIME TRANSFER: AN OPPORTUNITY TO STUDY RELATIVISTIC EFFECTS ● 42

- 7.1 Relativistic Effects at the Sub-Nanosecond Level ● 42
- 7.2 Tests of the Postulates of Relativity ● 43
- 7.3 Rigorous Relativistic Analysis of Time Transfer ● 44

APPENDIX A
BACKGROUND TO CATTISS: A CHRONOLOGY ● 47

APPENDIX B
COMMITTEE ACTIVITIES ● 49

CHAPTER I. INTRODUCTION

The accurate transfer of time from point to point on and near the Earth is a longstanding procedure with important consequences, not only for the field of timekeeping, but also for such diverse fields as navigation and communications (both civilian and military), surveying and geodesy, and fundamental physics and astronomy. The precise determination of positions of ships at sea, oil-well rigs, commercial airliners, and intercontinental ballistic missiles, to name just a few, ultimately relies on accurate knowledge of time. Using timing to obtain precise locations of fixed points on Earth has important applications in surveying and geodesy. In military and civilian communications, the ability to determine the starting point of an encoded signal depends on accurate knowledge of the system time. Finally, a highly accurate global time system is important in many areas of fundamental science, such as very long baseline radio interferometry.

One system that depends on the concept of time transfer for navigational and positional purposes is the NAVSTAR Global Positioning System (GPS) of the U.S. Department of Defense (DoD). Although intended as a military satellite system for guiding and navigating the tools of warfare, it also has a variety of civilian uses (Kerr, 1985). The system consists of a constellation of satellites, currently numbering six (operational as of July 1985), ultimately numbering 21, in Earth orbits at about 11,000 miles altitude. Each satellite carries a set of atomic clocks. The present uncertainty of the system is 10 nanoseconds (ns) in time, or less than 10 meters (m) in position. Roughly speaking, the conversion from time accuracy to positional accuracy can be made using the speed of light, 300 meters per microsecond (μs), or 30 centimeters (cm) per ns.

At this level of accuracy, the effects of Einstein's theory of relativity are observable, and indeed must be taken into account to obtain accurate and consistent time and position measurements. At the altitude of a GPS satellite, the rate of an orbiting clock will differ from that of an identical clock on Earth by tens of microseconds per day as a consequence of the time dilation of special relativity (produced by the relative motion of the clocks) and of the gravitational redshift associated with general relativity (produced by the fact that the two clocks are in different gravitational potentials). There is an additional effect, explainable by special relativity, which if unaccounted for, would prevent a consistent synchronization of any system of clocks that circles the rotating Earth. Known as the Sagnac effect, it produces clock offsets that can be as large as 2 μs for GPS orbits.

These effects are well known, and standard procedures are used to take them into account both in GPS and in other time transfer systems. Nevertheless, in the late 1970s a number of investigators began to contend that these relativistic effects were not being handled properly. After several exchanges of correspondence, beginning in 1983, between people expressing this view and various Air Force personnel, a request was made to the Air Force Studies Board to convene a committee to resolve this question. The present study was initiated in May 1984. A parallel short study by the JASON group of Defense Advanced Research Projects Agency (DARPA) took place in July 1984; the leader of that study is also a member of the present committee.

Another goal of the study was to make recommendations for actions and research that would lead to improvements in the accuracy of GPS and other time transfer systems. The importance of improving accuracy cannot be overemphasized. Improving the precision to the 1 ns (30 cm) level, and possibly into the sub-nanosecond regime is not only intrinsically important to military communication and navigation, and to many civilian applications, it is also vital to the long-term autonomy of the navigational system. For instance, in the event of a loss of communication between the master control stations on Earth and the GPS constellation, the need for the spacecraft to maintain a certain navigational accuracy autonomously for as many as 100 days places stringent requirements on the initial accuracy and stability inherent in the system. As a consequence, the bulk of the deliberations of the committee was devoted to the important question of future improvements.

The structure of the committee's report is as follows: In Section II we summarize the main conclusions and recommendations of the study. Section III presents an elementary description of the GPS and the role of relativistic effects. Section IV provides a more technical discussion of the relativistic questions, and of the adequacy of the current method of handling them. Section V discusses in more detail the recommendations made in Section II for short-term or immediate improvements in GPS performance. Section VI discusses the recommendations of Section II for research on issues affecting improvements in the long-term and to sub-nanosecond levels. Finally, Section VII describes the opportunity in time transfer systems to study interesting relativistic effects. Appendices A and B detail the chronology of events and correspondence leading to the formation of the committee, and the activities of the study group. Appendices C, D, and E provide more technical discussions of some of the issues considered by the committee. Appendix F gives references.

CHAPTER II. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

An improvement of the current timing capability of the GPS is desirable, and possible at modest cost, and depends on several operational improvements and studies that do not seem to be difficult. A potential exists for nanosecond time transfer in the near future. Current operational techniques take into account all relativistic effects to two orders of magnitude below the 2 ns level. Beyond the 2 ns level many nonrelativistic problems can be expected well before the next class of relativistic effects is observed. We recommend studies to confront these potential problems.

Our conclusions and recommendations are divided into four groups, ranked in order of priority. The first two sets refer to immediate conclusions or to improvements that should be achievable soon (within five years). The third set is for study of improvements that may be possible over a longer term (10 years) or that will be needed if accuracy requirements become more stringent than the 2 ns level. The fourth set refers to the possibility of using accurate time transfer systems to study fundamental questions in physics, both for their intrinsic interest and as a foundation for future technological advances.

2.1 Handling of Relativistic Effects

We conclude that there is no validity to the criticisms of the current methods of handling relativistic effects in GPS. These methods are theoretically valid to well below the 2 ns level, and have been verified empirically in GPS to 5 ns.

2.2 Near-Term Improvements in GPS

Improvement in accuracy of the present operational time transfer in GPS from the current 20 ns to 2 ns is desirable and possible without new technology. Recommended steps:

a. Establish a complete accounting of all clock rates and offsets in the ground system with respect to the DoD master clock to improve the clock and satellite position predictions, improve long-term autonomy, and provide immunity to reference-clock-switching transients.
b. Maintain at least one high-latitude monitor station (i.e., the present one in Alaska) for the next few years to help maintain time consistency.
c. For at least one satellite, make measurements that will allow a clear separation of satellite position errors from clock errors by means of distance determinations which are independent of the satellite clocks.

2.3 Recommendations for Sub-Nanosecond Accuracy and Long-Term Improvements

We conclude that it is important to make improvements in GPS operations leading to sub-nanosecond time transfer accuracy and to the capability for extended autonomous operation. The following steps are recommended to determine the feasibility of such improvements and to provide means to achieve them:

a. We recommend studies and experiments to determine the benefits in overall system accuracy and reliability caused by augmenting the current GPS monitor system by methods for independent distance determinations, such as by satellite-ground, two-way, or satellite-satellite links.

b. We recommend studies and experiments leading to improved methods for compensating for the tropospheric and ionospheric effects in the propagation of the navigation signals.

c. We recommend experiments and development leading to the coordinated use in space of clocks with higher stability and reliability.

d. We recommend systematic tightening of requirements as technology permits.

2.4 Time Transfer: An Opportunity to Study Relativistic Effects

Accurate time transfer systems present the opportunity to study interesting relativistic questions beyond the effects currently treated.

Although the performance of fundamental scientific experiments is not part of the Air Force charter, we emphasize the importance of the opportunities for basic research made possible by accurate time transfer systems such as GPS. In addition to its intrinsic scientific benefit, such research will provide the basis for further long-term technological development. Among the important items are:

a. To detect experimentally relativistic effects at the sub-nanosecond level.

b. To test the fundamental postulates of relativity, such as the isotropy of the speed of light.

c. To develop a relativistically rigorous treatment of time transfer to bridge the communication gap that has apparently existed between some relativity theorists and time transfer experts.

CHAPTER III. CLOCK SYNCHRONIZATION IN THE GPS: A PRIMER

The Global Positioning System is a group of satellites in nearly circular earth orbits that transmit navigation signals to users on or near the surface of the Earth. Users with suitable receivers can navigate to ~10 m accuracy in near real time. The complete system will comprise 21 satellites for nearly continuous coverage of the whole Earth with navigation signals. Currently (July 1985) there are 6 working GPS satellites in orbit.

The principle of operation is range determination by precise timing of signals. A GPS receiver determines its range from several GPS satellites by measuring the time of arrival of the L-band signals from satellite to receiver. A microprocessor in the receiver calculates its position by triangulation from the known satellite positions. Each GPS satellite carries several highly precise atomic clocks so that the time of transmission of the signals is known.

If a GPS receiver contains its own atomic clock which is separately synchronized with GPS system time, then the receiver can directly measure the times of arrival from 3 satellites and thereby determine its 3 spatial coordinates of position. (Each satellite broadcasts ephemeris data sufficient to determine its own position.)

If (as is usually the case) the receiver does not contain a synchronized atomic clock, it must also determine the precise time, and therefore the signal time of flight, by observation of 4 satellites and solution of 4 equations in 4 unknowns. The 4 unknowns are the 3 spatial coordinates of the receiver and the 1 time reference. The receiver can read out its position every 6 seconds, or even more frequently. A receiver may weigh less than 30 lbs and may cost under $3,000. In the future, a receiver based on a couple of chips may be available at greatly reduced cost and weight.

Determining position to an accuracy of 10 m requires that (1) the satellite positions be known to ~10 m; and that (2) the clock times be accurate to 30 ns.

No space qualified clock today can maintain an accuracy of 30 ns for more than a few days; moreover, the satellite orbit changes. Therefore it is necessary to update the information broadcast by each satellite about once a day. This is done by a ground station.

Confusion has arisen because the timekeeping requirements are so stringent that the relativistic concepts of time must be used to understand the nature of the received signals. We attempt here to explain these concepts as they affect GPS; a more technical discussion is given in Section IV.

Consider the operation of a clock relativistically. It is well understood that a clock moving with respect to a second clock will lose time with respect to that clock. This phenomenon, known as the "time dilation" or the "second-order Doppler" effect, has been experimentally confirmed. It is responsible for the observed increased lifetimes of unstable particles created in particle accelerators. It is also understood that a clock's rate relative to a second clock is affected by the gravitational potential in which the clock is found. A clock that is close to a massive body will run more slowly than an identical clock farther away. This effect, known as the gravitational redshift, is also well measured and thoroughly understood (Taylor and Wheeler, 1966; also Vessot <u>et al</u>. 1980).

Confusion has also arisen when the problem of synchronizing clocks is considered. Two clocks can be synchronized only when they are not separated. Separated clocks that read the same time in their own inertial frame, which is moving with respect to an external observer, can indicate different readings to that observer.

In the context of this report the question arises: Is it possible to synchronize clocks in separate orbiting satellites and have the time kept by these satellites remain directly related to clocks back on Earth? Suppose we wish to synchronize several satellites that orbit over the Equator. Imagine that we carry a standard clock from the Earth to one of the satellites and synchronize the satellite clock to the standard. We then move the standard from the first satellite to the second and synchronize that one. We proceed around the Equator synchronizing each satellite with the standard. When we have gone all the way around the Equator and arrive back at the first satellite we find that it is no longer in synchronization with the standard because the standard has been moving with respect to the first satellite and has lost time because of the relativistic variation in clock rates. There is nothing wrong with our physics in this example; it is merely our choice of synchronizing procedure that leads to the apparent paradox, and is an example of what has come to be known as the Sagnac effect, after the French physicist who discovered it in 1913 (Post, 1967). Among other things, it is the underlying principle behind the laser gyroscope. We could instead have added a correction each time we moved the standard clock to correct for the phase of the standard clock that we knew we would lose in moving. The reading of the standard clock plus the correction would then have exactly equaled the reading of the original satellite clock once the standard completed its entire path around the Equator.

The latter procedure is still not useful for navigation or for timekeeping. We wish the satellite clocks to keep time that is directly referenced to Universal Coordinated Time (UTC). We may thus envision the following procedure. Imagine a clock on the rotation axis of the Earth at the altitude of our satellites. This clock is not rotating with the Earth because of its position on the axis, so relativistic corrections due to rotation of the Earth do not affect it. We may then imagine slowly carrying a standard clock, originally synchronized with the axis clock, along any meridian to each of the satellites in turn. Each satellite clock is then synchronized with the axis clock. The time reading of the axis clock with respect to the UTC reference clock is known. Thus we have a procedure that can synchronize multiple orbiting clocks with UTC. In practice, synchronization is done with respect to a fictitious clock analogous to the axis clock of the previous example, and the amount of the offset applied to each satellite clock to achieve synchronization depends on the location of the satellite, the location of the master ground clock, and the path of the communication link between them by means of which the time information is transferred.

CHAPTER IV. RELATIVISTIC EFFECTS IN GPS: VALIDITY OF CURRENT TREATMENT

At the level of accuracy necessary for the GPS and to much better accuracy (~10^{-2} ns), one can treat relativistic effects by simply adding special relativistic (time dilation and the Sagnac effect) and the general relativistic (redshift) effects.

4.1 Relativistic Effects

Time Dilation

A moving clock runs slow, as measured in the frame of reference of a stationary clock. This is known as "time dilation," and leads to the famous twin "paradox" of special relativity (this is not paradox but fact: A moving twin really is younger when he eventually comes back to rejoin the stationary twin). The magnitude of the effect is given in special relativity by the formula:

$$\Delta s = (1-v^2/c^2)^{\frac{1}{2}}\Delta t$$

where s is time as measured by the moving clock, and t is time in the reference frame of the stationary clock; v is clock velocity relative to the frame of the stationary clock and c is the speed of light. For purposes of GPS, the second-order approximation in an expansion in powers of (v/c),

$$\Delta s \approx \left(1-\frac{v^2}{2c^2}\right)\Delta t$$

is entirely adequate. The formulae are only valid in an inertial (i.e., non-rotating) frame of reference. In a rotating frame the physics is exactly the same, but the expression of the results is somewhat different. The difference is important because the Earth rotates and satellites orbit the Earth.

The Sagnac Effect

In a rotating frame, time dilation causes time transfer to be nonintegrable; that is, if a clock is transferred (even very slowly) around a closed loop, its reading at the end of the transfer will lag that of a stationary clock, sitting at the beginning/ending point of the closed loop, by an amount

$$\Delta s \approx \frac{2\omega A}{c^2}$$

where ω is the angular velocity of frame rotation, and A is the surface area of the loop, projected into a plane perpendicular to the axis of rotation. This is called the Sagnac effect (Post, 1967). Here only terms up to second order in 1/c have been kept, which is again entirely adequate for GPS. The effect is nontrivial, and amounts to ~207 ns for clock transfer around the Equator of the rotating Earth, and 9.07 μs for clock transfer around a geosynchronous orbit or 7.20 μs for an equatorial GPS orbit (these last examples are purely hypothetical since orbiting clocks have never been synchronized this way). Since modern atomic clocks are often accurate to within a few nanoseconds per day, the Sagnac effect is taken into account in comparing clocks at different places on the Earth and in space (Ashby and Allan, 1979; Bureau International des Poids et Mesures, 1980). Laser gyroscopes depend on this effect for measuring ω. Recently the effect has been directly measured and confirmed on a large scale by use of GPS satellites to transfer time all the way around the world and back to the starting point (Ashby and Allan, 1984; Allan et al., 1985).

Gravitational Redshift

According to general relativity theory, a gravitational potential causes a clock to run slow. To an order consistent with the expansion of the time dilation ($v^2/c^2 \sim \Phi/c^2$), the effect is given by

$$\Delta s \approx \left(1+\frac{\Phi}{c^2}\right)\Delta t$$

where Φ is the gravitational potential, as measured relative to the fiducial clock.

4.2 Treatment of Relativistic Effects

The magnitude of time dilation and gravitational redshift effects for a GPS satellite in its 12 hr, nearly-circular orbit is $\sim 4.4 \times 10^{-10}$, or about 4×10^4 ns/day, a very significant amount.

In GPS these relativistic effects are taken into account (Spilker, 1978; Van Dierendonck et al., 1978) by two successive correction procedures: (1) the rate of each satellite clock is offset by a relative amount 4.45 x 10^{-10}. This correction approximately, but not exactly, removes the time dilation and gravitational redshift from the time signals received by a GPS user. (2) Residual corrections are then made in the software in each GPS user's receiver, based on correction parameters broadcast by each satellite, and in the case of the Sagnac correction, on the location of the user. This residual correction accounts for all relativistic effects in GPS, down to the specified system accuracy. The correction parameters are updated from the ground once a day. In principle this procedure is completely adequate according to relativity theory. Furthermore, many experiments have confirmed that the theory of general relativity is correct to a higher degree of accuracy than is currently required in GPS. Table E.2 summarizes the status of experimental confirmation of general relativity and its relevance to GPS.

A recent time transfer experiment using GPS satellites (Ashby and Allan, 1984; Allan et al., 1985) was able actually to test the standard Sagnac correction and to check its validity to ±5 ns.

It should be emphasized that experiments and tests are continually being carried out to improve operation of the system and to look for possible errors. For example, a test during February 1985 performed by the Naval Research Laboratory (NRL) found a "bug" in the National Bureau of Standards' GPS receiver software that prevented execution of the software for evaluating the residual gravitational redshift effects caused by the small eccentricity of the satellite orbits. The effect, amounting to ~10 ns, is much smaller than the Sagnac correction. A simple change in the receiver software solved the problem.

4.3 Criticisms of the Treatment of Relativistic Effects

Cohen and Skalafuris (1984) have made a proposal that contains a detailed critique of methods currently used to handle relativistic effects in GPS and suggests research to remedy the perceived defects in those methods. Their principal points are:

1. Cohen and Moses (1977) showed that a new effect exists in systems of rotating clocks, such that there would be a 9.07 μs error in global synchronization by means of clock transport of clocks in geosynchronous orbit.
2. Cohen, Moses, and Rosenblum (1983) showed that a similar but quantitatively distinct effect occurs for clocks synchronized by exchange of electromagnetic signals.
3. A time transfer experiment by Saburi *et al*. (1976) confirms the 9.07 μs effect of Cohen and Moses (1977).
4. The paper of Ashby and Allan (1979) on time transfer contains erroneous language as well as erroneous formulae. In particular, the important Equation (1) of the Ashby-Allan paper is wrong.

In addition, the proposal contains several statements about time transfer and GPS. Among the more relevant of these are:

a. GPS satellite orbits are chosen so that the principal relativistic effects cancel out.

b. Monitor control systems of GPS update each satellite's time signals to agree with UTC, as maintained by the U. S. Naval Observatory (USNO).

Our comments and conclusions on these points are given below.

Points 1 and 2

The effects treated by Cohen and Moses (1977) and those by Cohen, Moses, and Rosenblum (1983), are not new. They are equivalent to the Sagnac effect (Post, 1967) in special relativity, well known to physicists for over 50 years. A complete and general account of such effects, within the full context of general relativity theory was given in a standard textbook (Landau and Lifshitz, 1962). The papers by Cohen and Moses, and by Cohen, Moses, and Rosenblum appear correct, but they contain nothing new for the purpose of time synchronization of satellite systems such as GPS.

The treatment of these effects for clock comparisons was reviewed by Ashby and Allan in 1979; their formulas show in particular that clock transport synchronization, such as the one described in Section III, and electromagnetic signal synchronization require different correction terms. The Bureau International des Poids et Mesures (1980) has recognized these effects and the proper corrections for them in an official document.

These synchronization effects are <u>not</u> errors; rather, they are completely computable corrections. The treatment of these effects in GPS at present is entirely adequate in principle, to currently achievable levels of precision.

Point 3

This point is incorrect. Saburi *et al*. (1976) found a 9.439 μs offset between two distant atomic clocks. Offsets are accidents of history for clocks. There was no direct measurement of the Sagnac effect in this experiment; rather, the standard Sagnac correction was used without being tested. Comparison of time transfer by means of electromagnetic signals bounced off a satellite in a geosynchronous Earth orbit with time transfer by means of clock transport on the Earth's surface, with both measurements incorporating the usual Sagnac correction, yielded consistent results within measurement error (respective offsets of 9.439 μs and 9.50 μs).

As pointed out above, the time transfer experiment of Allan and colleagues using GPS satellites was also able to test the standard Sagnac correction and confirmed the standard treatment to ±5 ns.

Point 4

We have independently derived Equation (1) of Ashby and Allan (1979) and it is correct. We find no reason to believe that this paper is in any significant way erroneous.

It is true that the paper is not written in language similar to that of most textbooks in relativity theory, and somewhat different notation and terminology is used. Furthermore, some of the underlying assumptions and connections to fundamental theory are not spelled out as clearly as some theoretical physicists might hope. This is not surprising because most relativity textbooks are at most tangentially concerned with real world measurements and systems, while the Ashby and Allan paper (1979) is wholly so concerned. In our view the precise language or terminology is not very important; only the results and formulae are important. These appear to be completely correct, for any time transfer procedure on Earth or in near Earth space, down to the accuracy level that any present or near term system might achieve. The most significant ignored terms are at the first post-Newtonian level of successive approximation; this next generation of relativistic effects is discussed in Section 7.1 and Appendix E. For GPS, where system specifications are at the 20 ns level, and where ultimate system capability with upgrades would be near 1 ns, the paper is completely adequate.

Skalafuris et al. solicited comments on the paper of Ashby and Allan (1979) from two respected relativity theorists who have done distinguished work in mathematical relativity but who have little or no research experience with experimental tests of relativity theory, actual measurements in relativity, or in particular with precise time transfer. In unpublished 1983 letters, these two relativists expressed doubts about the adequacy of the Ashby and Allan treatment although they did not indicate any mistakes.

Many of their doubts can in fact be answered by appealing to the standard scientific literature on tests of relativity theory (see e.g., Will, 1981). For instance both relativists expressed doubt about the coordinate system used by Ashby and Allan; however, this coordinate system is just a special case of the PPN frame (cf. Will, 1981, Chap. 4), which is well justified and widely used in tests of relativity theory. One of the relativists raised the question of "frame-dragging" (Lense-Thirring effect) from the Earth's rotation as causing problems; however a short calculation shows that this effect is roughly 100 times too small to be of any consequence for GPS (See Section 7.1 and Appendix E). As a result of these apparent confusions, we perceive a need for a pedagogical article that will explain time transfer and GPS, not in practical terms in which they have been expounded up to now, but in the rigorous language of theoretical relativity (See Section 7.3).

Points (a) and (b) of the Cohen-Skalafuris criticisms are incorrect and illustrate a failure to understand GPS. First, the bulk of the relativistic rate effects between satellite and Earth clocks are cancelled by offsetting the rates of the satellite clocks, not by a particular choice of orbits. Second, system time of GPS is maintained separately from UTC, except for physical corrections to keep them from drifting more than 1,000 ns apart. Corrections are then transmitted in the navigation message to allow the user to determine UTC from GPS time to within 100 ns (Klepczynski et al. 1985).

CHAPTER V. MAXIMIZING THE POTENTIAL OF GPS

All future electronic systems that will operate over an extended area most likely will depend on precise time, because having a high-performance clock at a remote site enables one to make high-precision time of arrival measurements of remote signals (of importance for navigation and surveillance), and allows for the entry into very complex waveforms quickly and coherently. The latter is of great importance for communication systems, particularly military systems where jamming resistance depends on the degree of a priori knowledge of system time. At present there is a Navy requirement for GPS to allow timing to better than ±110 ns world-wide. This requirement easily can be met with present arrangements. In the future it is likely that higher accuracies will be needed, not only to improve intrinsic navigation and timing performance, but also to support long-time autonomy of operation. This includes requirements of the GPS itself. Such stricter requirements are expected to manifest themselves mostly as a greater capability for initial rate calibration. For example, assume that ±1 μs is required after 100 days. It is necessary to keep the rates of all clocks to within at least ±10 ns/day. For a calibration to be made in one day, it is therefore necessary to provide a resolution of the common time source to better than ±5 ns. For this reason the bulk of the committee's deliberations focused on means to achieve improved precision and performance in GPS and other time transfer systems.

Based on experience with the C/A code (the main code for civilian access) of GPS during its development phase, it can be stated that for operational use the system currently provides about ±20 ns world-wide (Allan and Weiss, 1983; Klepczynski et al. 1985). However, the potential exists for GPS to provide ±2 ns world-wide with the C/A code as it is presently provided.

5.1 Time Discipline in the System of Ground Station Timing

Figures 1(a) through (d) demonstrate some practical experience in keeping GPS time to within the specified 1 μs (110 ns with correction supplied in the navigation message) of UTC (USNO). Observations were made between 7 September 1984 and 2 January 1985 using an STI 502 time transfer receiver (C/A code and L1 frequency only). One can note the presence of large outliers (Fig. 1[a]), a rather regular fine structure that is due to a bias and periodic errors for each pass of 10-70 ns (Fig. 1[b]), and the power of filtering that allows estimates for the system time offset to

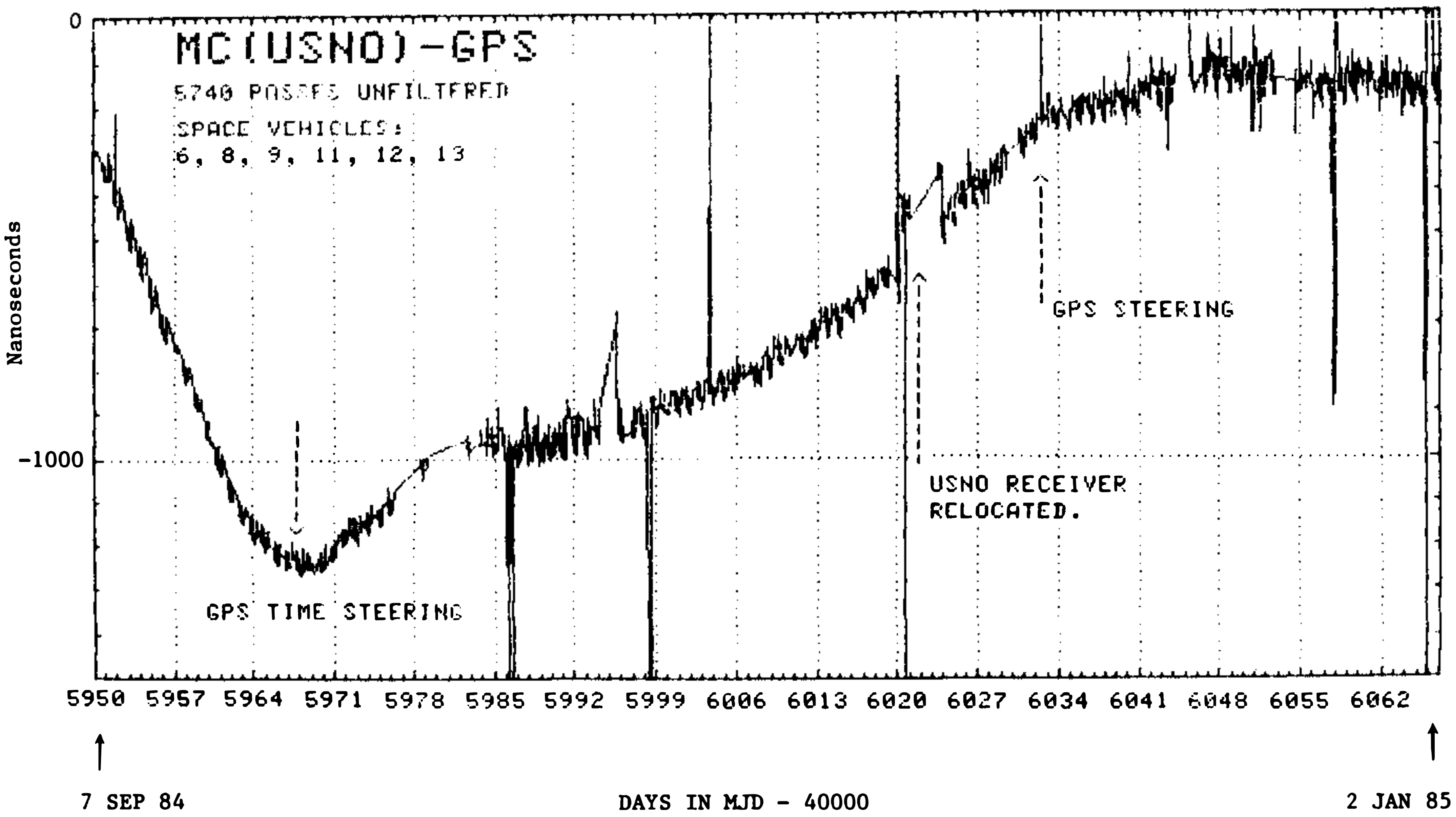
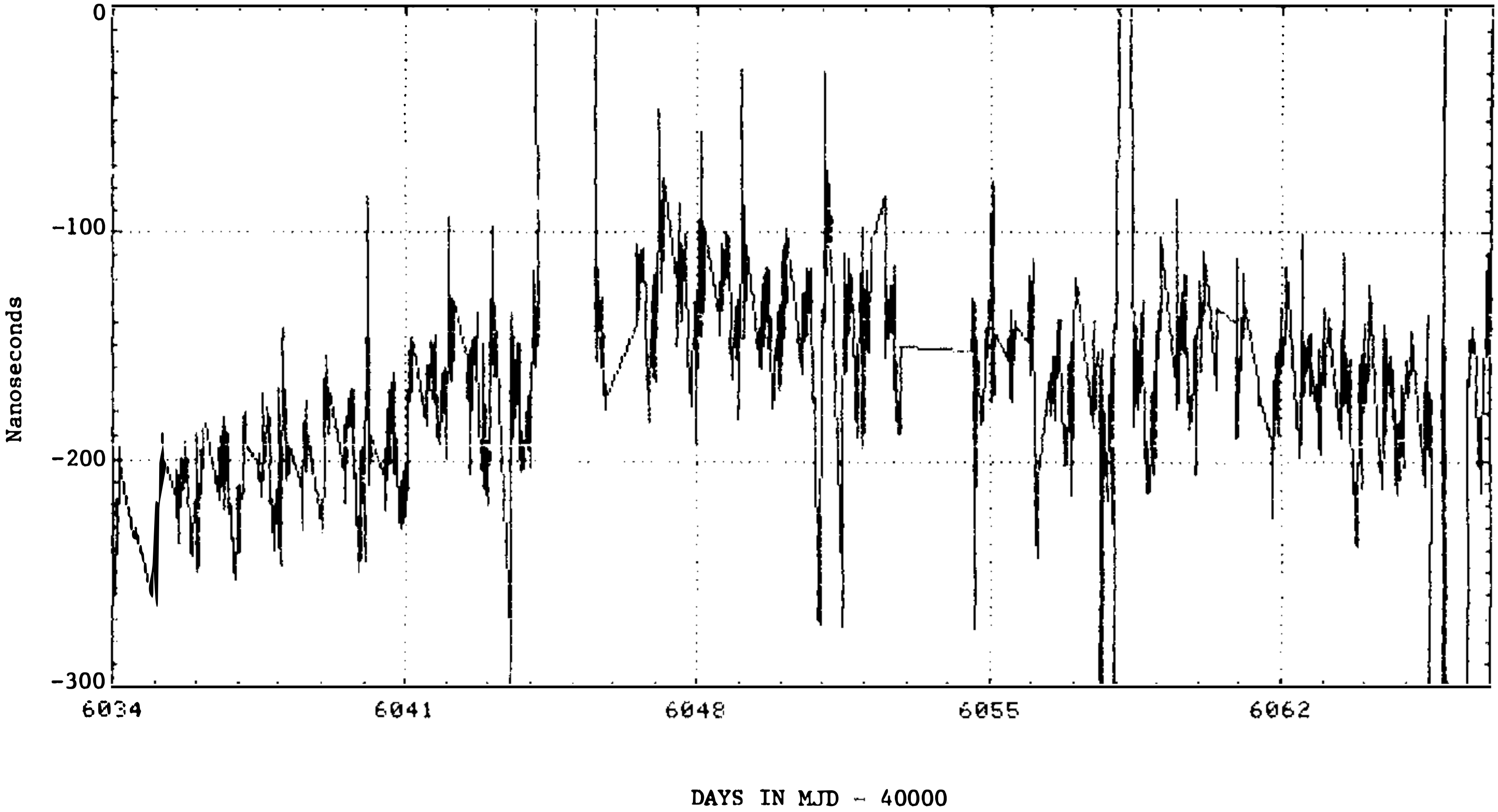
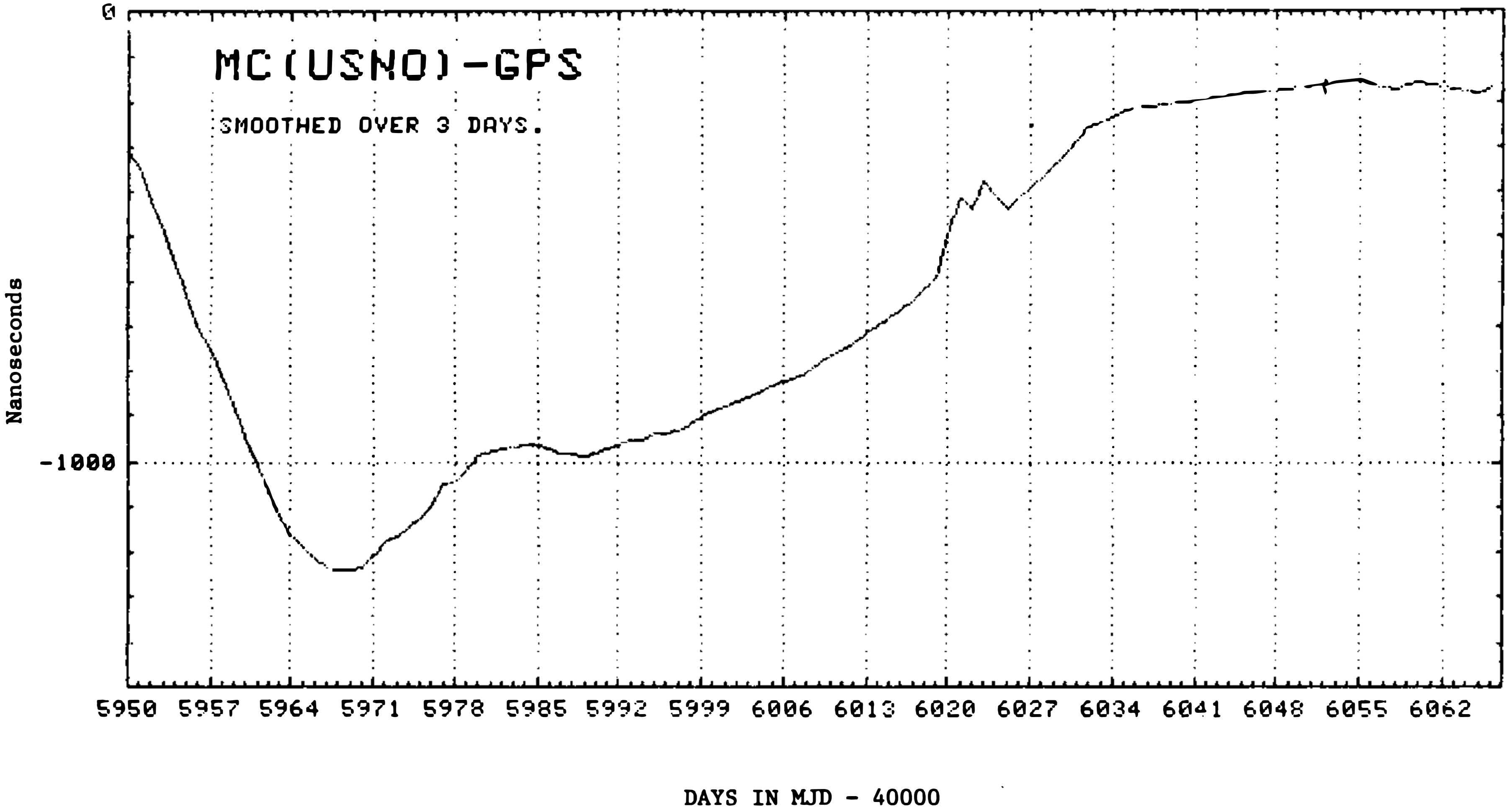


FIGURE 1 DIFFERENCES BETWEEN GPS TIME AND UTC (USNO),
7 SEPTEMBER 1984 to 2 JANUARY 1985

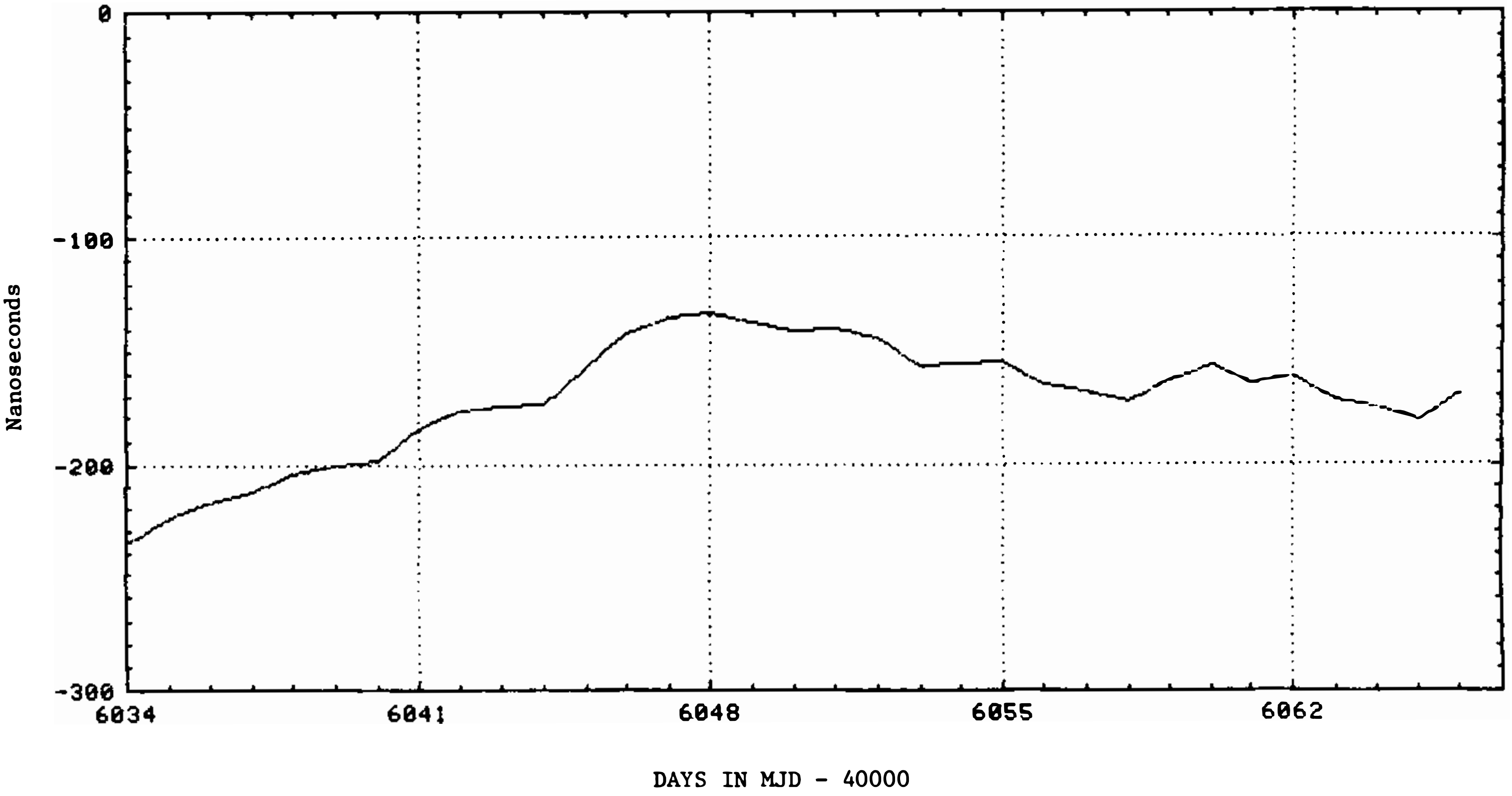
a) UNFILTERED PASSES



b) MAGNIFIED PORTION OF FIG. 1a



c) DATA SMOOTHED OVER 3 DAYS



d) MAGNIFIED PORTION OF FIG. 1c

about 10-20 ns (Fig. 1[c, d]). One can also note the effect of deliberate system time steering that introduces rate changes in system timing on the order of 10^{-13}. During the 117 days of observation, two deliberate rate changes were introduced (Fig. 1[a]). It is clear that the time transfer accuracy obtainable with GPS depends very much on the stability of the system reference because the corrections uploaded into the satellites are actually predictions that are valid commensurate with the system clock stability. The actual performance of the system reference clock up to now is only mediocre for a cesium clock compared to what is seen in similar clocks at the USNO and in many terminals of the Defense Satellite Communications System (DSCS). Several cases are known in the DSCS in which the remote clock stayed within 0.5 μs for more than a year without any steering. The main reason for the poor performance of the GPS ground clocks has been their adverse operational environment.

Many deficiencies in Fig. 1 can be remedied with relatively simple measures that will improve performance to state-of-the-art capabilities. Every time the ground station clock that serves as the system reference clock suffers a frequency change, this change propagates errors throughout the system, not only in the form of erroneous clock corrections but also as errors in the satellite ephemerides. A strict emphasis on time discipline will improve the clock and ephemeris predictions. By discipline we mean a complete accounting of all clock rates and offsets in the ground system with respect to the DoD Master Clock (USNO). Internal accounting alone is not good enough for long-term autonomy. A forthcoming Interface Control Document ICD-GPS-202 will provide most of the tools to establish time discipline. What is missing is only a command emphasis on this timing aspect which up to now has been wrongly considered by the operators as a benefit only for the USNO. For example, the monitor stations do not even provide clock outputs for checking and calibrating of their clocks using other means, such as traveling clocks or DSCS terminals nearby. Conversely, such clock outputs, if available, would also be a great benefit to other timed systems nearby.

5.2 Auxiliary Monitor Stations

For the next several years the existing high-latitude monitor station in Alaska should be maintained. The coverage of this station will greatly improve the internal consistency of the ground system because that station can see more satellites simultaneously than can the other stations.

5.3 Separation of Satellite Position and Clock Errors

The separation of satellite position or ephemeris errors from clock errors is an inherent problem in a purely passive monitor system. The high-precision separation of clock read-out from position estimation is vital for the improved accuracy needed for autonomous operation in the event of interruption of communication with the Master Control Stations. It is also needed for any later use of more stable clocks. The read-out resolution in the current system does not justify the use of more stable clocks since they cannot be read with a precision commensurate with their intrinsic capability. For these reasons we recommend studies and experiments to establish the means to separate satellite ephemeris errors from clock errors.

To explain the intimate connection between clock and ephemeris errors in GPS-type systems, we first describe the mathematical model used to process the data acquired in the GPS. This model is sometimes called a "Kalman filter."

The Kalman filter is like a simulation. It models the significant physical phenomena that represent the process of interest. The filter behavior tries to emulate the time history of the system starting from an initial state, and to predict what sensors will measure in the future. In comparing this prediction with the actual measurements, it finds an error that can be used to correct its state. With very good measurements and with mild unmodeled disturbances to the process, one can generally make corrections to the filter quickly. By contrast, when the measurements are noisy and the process is well modeled, the errors can be nearly ignored and it takes a long time for a filter to respond and correct its state. The navigation process of GPS involves knowledge of both the satellite ephemeris and the behavior of its clock. The intrinsic physics of these processes are quite independent. However, the measurements available consist of arrival times of one-way signals containing information on the emitted time as read by the satellite clock. From these two times an effective range, called "pseudorange," can be inferred. But because the pseudorange involves the time and position so intimately, differences between the expected measurement from the satellite and the actual measurement cannot distinguish between an error in the clock and an error in the ephemeris. Thus when there is a difference in the predicted and the measured values the filter corrects the behavior of both proportionately according to the process noise allocated to each in the filter model.

There is some selectivity in the correction of the state because the model predicts a certain type of behavior for the clock and a different expected behavior for the ephemeris. There is a further separation of corrections for clock errors from ephemeris errors because each ground station receives a satellite signal that was emitted in a slightly different direction relative to the orbit. Thus the ephemeris error contributes a different amount to the pseudorange for different ground stations. The remaining coupling produces clock behavior estimates with ephemeris characteristics, and vice versa.

The GPS ephemeris-clock Kalman filter processes a lot of tracking data from monitor stations to solve simultaneously for many parameters that describe the state. For example, a partition of 4 satellites and 4 monitor stations involves the following 59 parameters:

4 satellites		
position, velocity	6	
clock	3	
radiation pressure	2	
	11	x 4 = 44
4 monitor stations		
clock	2	
troposphere	1	
	3	x 4 = 12
polar wander and earth rotation		3
Total		59

The three clock parameters fit the phase of the onboard frequency standard with a second order polynomial in time; they therefore represent phase bias, frequency bias, and frequency drift. The force from solar radiation pressure is modeled rather elaborately, taking into account the direction of the sun-vector and satellite attitude. The two parameters for radiation pressure represent a scaling factor of the modeled force and an unmodeled force in the direction of motion of the satellite ("intrack" direction).

The dynamical equations of the satellites are most conveniently written in inertial coordinates, while most users navigate in earth-fixed coordinates. The transformation between these two coordinates cannot be assumed fixed because of the precession and nutation of the Earth's rotation axis, the variation of this axis with respect to a solid Earth, and the variation in the rotation rate of the Earth. Hence the effects of rotational irregularities must be included in the model.

Satellites are tracked whenever they are above a fixed chosen elevation angle at the monitor stations. The accuracy of the orbit determination process is gauged by monitoring continually the measurement residual (which is the actual input to the Kalman filter). The real-time ephemeris accuracy is believed to be on the order of 2 m radial, 7 m intrack, and 5 m crosstrack. These accuracies can be improved by a factor of 2 with post-fitting. The satellite clock phase accuracy is of the order of the radial error, which corresponds to about 10 ns, and is expected to grow linearly with time because of clock rate offsets. System time, which is defined by one of the clocks in a monitor station, is also steered to within 1000 ns of UTC.

While it is of little significance to navigation users, there is one fact that is of interest to the time transfer community and atomic clock experts: the three satellite clock parameters - phase, frequency, and frequency drift - exhibit correlated diurnal cyclic behavior after proper detrending. Calculations suggest that the cyclic variation in temperature and the radiation environment of the orbit should not cause this cyclic behavior in the clock, nor is there any other known physical source of clock disturbance that could produce the periodic effects. This cyclic behavior is puzzling and leads to speculation that such a phenomenon is generated within the Kalman filter through one or a combination of the following:

a. Ephemeris-clock coupling. Since the pseudorange measurement does not distinguish between clock phase error and line-of-sight position error, the filter in its search for a solution in the state space compensates for one error source with that of the other, since it has insufficient data for discrimination.
b. Coupling of clocks and ephemeris of different satellites through the monitor clocks whose phases appear in all pseudorange measurements and are also being estimated.
c. Presence of unmodeled or inadequately modeled forces. For example, the satellite travels in and out of the regions with the highest electron and proton density in the magnetosphere several times a day. Satellite charging (and change in its charge state) could induce small varying magnetic forces as it traverses these regions. The error in radiation pressure modeling is not unimportant. The error is of the order of 10^{-9} m/s^2 and could accumulate to 3.7 m in a day. The effect of errors in geopotential coefficients is of comparable magnitude.

There are other ways to determine GPS satellite orbits besides the direct use of pseudorange measurements. All of them provide for the separation of ephemeris and clock error and are of two types: those that use the existing navigation signals and those that do not. The first require no modification of the satellites. In the second category are radar tracking and laser ranging. Radar tracking does not require any modification of the satellites but is not expected to provide sufficient measurement sensitivity to be of interest here. Laser ranging offers one possible solution. Ranging accuracy of 1 cm should soon be routine with lasers. This is to be contrasted with the limitation imposed by the environment on the current L-band ranging accuracy. The L1/L2 2-frequency ionospheric correction amplifies the single-measurement random error by a factor of 1.55, resulting in a residual uncertainty of 30 cm. (Signal propagation effects are discussed in Section 6.2).

Unfortunately, to implement laser ranging throughout GPS requires considerable change in the configuration of the satellites and in their operational interface with tracking systems. For this reason we recommend measurements and experiments using at least one satellite that can clearly separate clock errors from ephemeris errors to demonstrate the gain in the accuracy to be achieved by such a separation. We expect that such experiments will show that the periodic variations described above are really caused by errors in the ephemeris, not by periodic frequency variations in the clocks. Such a demonstration would permit appropriate modifications in the Kalman filter that would yield immediate improvements in accuracy. Moreover, the separation of clock and ephemeris errors is so vital to high-accuracy operation of GPS, especially in the sub-nanosecond regime, that we will return to this issue in our discussion of long-term improvements in Section 6.1.

CHAPTER VI. FUTURE NEEDS FOR TIME TRANSFER

6.1 Separation of Satellite Ephemeris and Clock Errors: The Long View

Any attempt to operate a global navigation and time-transfer system at or below the 1 ns level will operationally require the clear separation of satellite position errors from clock errors. We strongly recommend that the current GPS monitor system be augmented by means that will allow such a separation and that coordinated studies and experiments be carried out to determine which methods will best achieve this goal in the long term. Several methods that have been under consideration are:

a. Use of Existing GPS Signals:

1. **Improved use of pseudorange measurements**
2. **Doppler tracking of the carrier phase**
3. **Carrier phase ranging by resolving ambiguities**
4. **Very Long Baseline Interferometry (VLBI)**

b. Two-way Ranging:

1. **Satellite transponder**
2. **Laser ranging**

(possibly with additional on-board event timer for clock read-out)

c. Ranging Between GPS Satellites

Pseudorange measurements can achieve sufficent accuracy to give sub-nanosecond clock comparisons provided that care is taken to minimize multipath problems and that the orbits are determined by other methods. It also may be possible to use pseudorange measurements to aid in resolving phase ambiguities. Carrier phase methods make use of the carrier frequency that underlies the coded message. In Doppler tracking, the changes in phase of the signals from different satellites as a function of time are used to determine the satellite orbits. The carrier phase ranging method also uses the carrier phase signals from different satellites, but an attempt is made to resolve the ambiguities in whole numbers of cycles. If this resolution can be achieved, the method will lead to improved orbits and accurate clock differences. Like the carrier phase methods, interferometric techniques treat the GPS satellite as a radio source and determine its orbit by measuring the difference in phase of its radio signal as received at the ends of a known baseline.

Two-way methods are attractive because solutions can be obtained in real time, but can involve potentially expensive modifications in the satellites. The use of a transponder is a considerable burden for the satellite design, which could be overcome by using an on-board event timer to measure the difference of the ground signal arrival time and the reference for the emitted pseudo-random noise (PRN) wave form. The measurement could be made available via telemetry. Not only would this allow accurate ranging with low power but also would give an independent clock read-out capability. The major disadvantage of such a scheme would be its high vulnerability to jamming and spoofing, unless the uplink is also done with spread spectrum methods. Laser ranging has several advantages, including lower sensitivity to atmospheric water vapor, but suffers from the problem of cost. The retroreflector and event timer design can be made invulnerable to spoofing and jamming by means of a simple shutter under program control. If retroreflectors alone are carried on the satellite, the clock comparisons can be made from the carrier phase or pseudorange signals, once the ranges are determined accurately.

Ranging between GPS satellites (crosslink ranging) is a concept originally developed to facilitate eventual system autonomy. The present system depends on daily update of satellite ephemeris and clock parameters from the master control station to maintain navigation accuracy. Without attention of the control segment, satellite clock phase error is expected to grow by at least 10 ns/day. Satellite position errors also grow with time, the most serious being the intrack error that reaches about 2 km in 100 days and about 10 km in 200 days. Radial and crosstrack errors follow daily oscillations whose amplitudes also grow in time, reaching 200 and 70 meters respectively in 200 days.

It has been shown by detailed simulation that with on-board processing of crosslink ranging data and appropriate autonomous housekeeping capability installed in the satellite, it may be feasible in principle to maintain original navigation consistency among GPS users with the satellites left unattended up to six months, although accuracy with respect to Earth coordinates may be seriously degraded. Crosslink ranging may also provide a means of separating ephemeris and clock errors.

As one example of an experiment in which two of these methods will be studied and intercompared, we mention the NASA Ocean Topography Experiment (TOPEX), which will make use of GPS to estimate the orbit of a low altitude satellite. Measurements will be made simultaneously from ground stations to GPS satellites and from the user-satellite to GPS (a variant of crosslink ranging) and then processed together with a double differencing scheme to eliminate error contributions from all clocks. Both the coded pseudorange navigation signals and reconstructed carrier phase measurements will be used (Lichten et al. 1985).

To repeat, we recommend systematic studies and experiments to determine which methods will lead to improved accuracy in both ephemeris and time.

6.2 Compensating for Signal Propagation Effects

In any time-transfer system the effects of the propagation of the signals through the Earth's atmosphere must be taken into account, and may produce important limitations on the ultimate accuracy of such systems. There are two general aspects to these propagation effects, systematic time and frequency shifts, and random effects that can be represented statistically. The random effects are represented in terms of their Fourier frequency spectrum, or in a more practical way, by the Allan variance, which is a measure of the variance of the distribution of frequencies seen in pairs of samples separated by a time interval plotted against that time interval. The solid lines in Figure 2 show the Allan variance of the performance of modern (1985) atomic hydrogen masers and the primary cesium standard at the U. S. National Bureau of Standards. Note that this plot is a measure of oscillator stability, not frequency accuracy.

The random aspects of noise, resulting from fluctuations in signal propagation through the Earth's troposphere, are shown in Figure 2 as a dashed curve. This noise degrades the cesium performance by a factor of

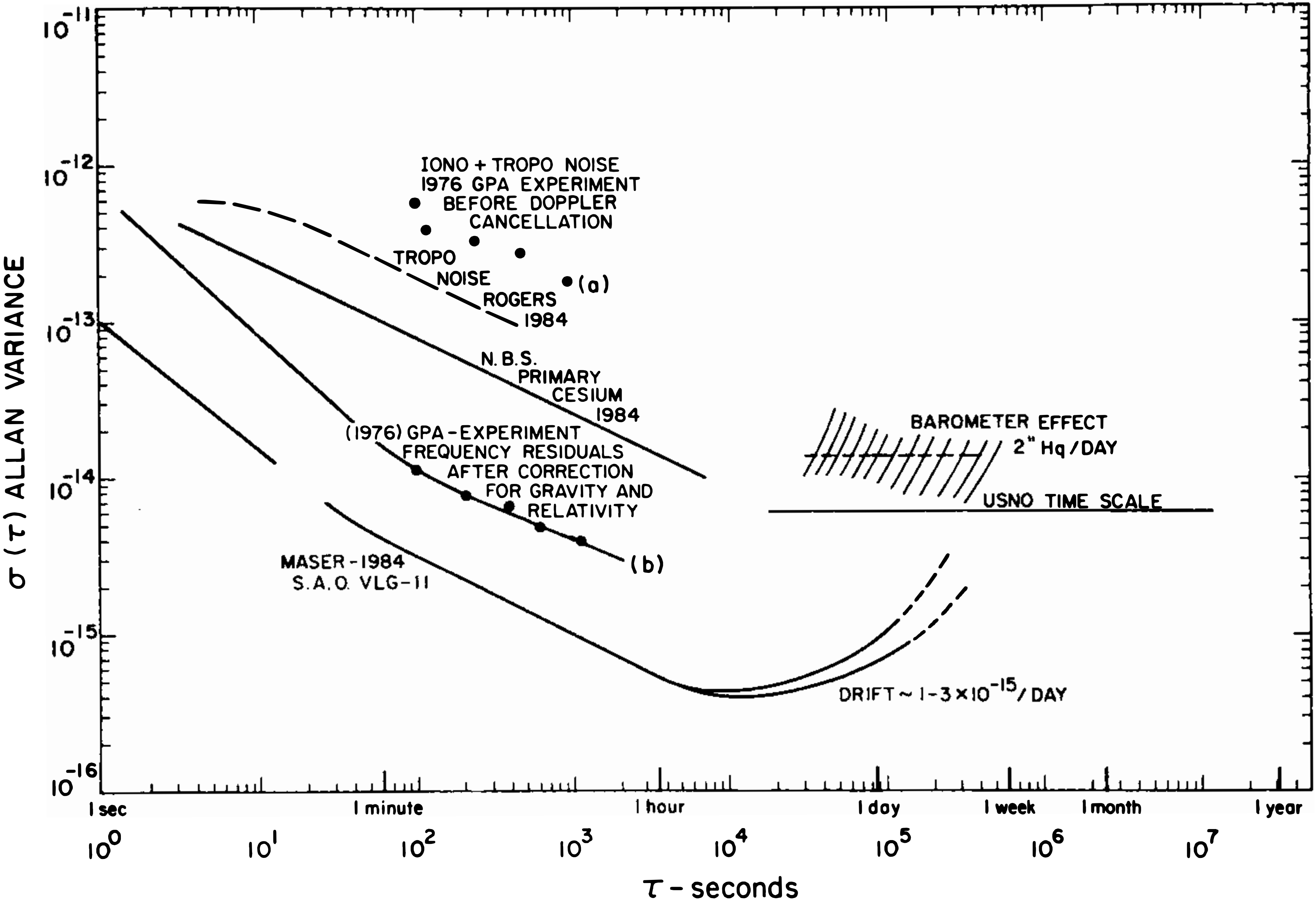


FIGURE 2 OSCILLATOR STABILITY AS MEASURED BY ALLAN VARIANCE vs. SAMPLING TIME

10, and that of hydrogen masers by a factor of 100. The long-term propagation effects owing to barometric pressure variations set a limit of about 1 part in 10^{14} in $\Delta f/f$ measurements made for time intervals of about 1 day. Tropospheric noise and systematics are largely independent of radio signal frequency except for molecular absorption bands, as described more fully in Appendix C. The tropospheric effects are the principial limitations to accuracy in all electromagnetic one-way propagation systems.

In contrast to the non-dispersive nature of the tropospheric path delay, the ionospheric propagation effects are highly affected by the frequency of the signals; both the path delay and the path itself are affected. Both the systematic and random noise properties depend on the number of electrons per unit area over the distance of the ray path (columnar electron density), a quantity that varies greatly with the level of solar activity and the time of day. This quantity is very unpredictable. The effects of both the ionosphere and the troposphere for signals at 2.2 GHz during the morning hours of June 16, 1976 (a period of minimal solar activity) are shown as a dotted curve (a) in Figure 2. Here we see that ionospheric and tropospheric instability is about 300 times higher than that of the hydrogen masers then in use.

The situation for coping with these propagation instabilities is far from hopeless. Generally, if it is possible to measure the propagation effect by a separate system, the propagation effects can be treated as systematic effects and removed from the data. If this process is done in real-time the compensation is very effective for fluctuations whose time constant, t, is greater than r/c, where r is the range distance, and c is the velocity of light. Therefore t is of the order of milliseconds for GPS satellites, and the corrections apply to the time intervals shown in Figure 2.

The effectiveness of a real-time correction of frequency fluctuations from ionospheric and tropospheric effects is shown in Figure 2 in the dotted curve (b), which represents comparison data between Earth and space masers during a 2-hour flight going to 10,000 km altitude (Vessot et al. 1980). The solid line (b) represents concurrent data made between two 1976 model hydrogen masers in the same room. Little or no residual effect of propagation is seen at the level of stability of these masers in this experiment.

Because the ionosphere's columnar electron density affects the speed of light in a well understood way that depends on frequency, one can measure the density by simultaneously receiving signals transmitted at different frequencies, phase coherently generated from a common oscillator. The phase differences between the carriers of the received signals convey information that can be used to infer the electron density, hence the time delay. While a two-frequency version of this technique is routinely used to make ionospheric corrections, it accounts only for the leading term in the ionospheric dispersion, and more sophisticated methods may be needed to compensate for smaller effects. Going to generally higher radio frequencies would also help reduce ionospheric effects.

By contrast, high accuracy correction for the troposphere is far less easily made. Compensation for tropospheric effects can be made using barometric pressure and humidity data taken at the Earth station. Further corrections can be made using water vapor radiometer data taken in the line of sight to the spacecraft. This is currently an active area of research and future progress is expected. Thus far the best technique for subnanosecond time transfer, or for frequency comparisons at or below the 10^{14} level, is to measure the round-trip path delay, divide the result by two, and use this value to correct the data from the spaceborne clock.

This two-way process has drawbacks in that it complicates the system and requires the user of ground-based GPS equipment to transmit and thus possibly reveal his position. Use of laser signals, or other very highly directed signals, and installation of on-board safeguards such as shutters, can reduce the vulnerability of this technique to "spoofing" by undesired operators.

6.3 Performance and Reliability of Frequency Standards

Many frequency and time standards have been used for precision timing in space since the early 1960s. Most of these devices were quartz oscillators. With one exception these units all have been associated with the GPS constellation and its antecedent programs, Timation 1 and 2, and the Navigation Technology Satellites (NTS 1 and 2). These satellites have carried quartz, rubidium, and cesium standards. The exception was a suborbital rocket flight that carried a hydrogen maser. The successful maser experiment, carried out in 1976 (Vessot et al. 1980), measured the change in maser frequency of the unit brought to 1.5 Earth radii above the Earth's surface, caused in part by the change in gravitational potential.

Timation 1 and 2 were launched in 1967 and 1969, respectively, and both carried quartz oscillators. NTS 1, launched in 1974, carried two quartz units and two rubidium standards, modified for use by NRL. NTS 2 carried two cesium standards. The GPS program has launched successfully 9 satellites carrying 5 cesium and 27 rubidium clocks.

The early rubidium clocks had major technical difficulties, but these are now understood and have been corrected. There have been instances using both cesium and rubidium where better and longer test procedures might have avoided clock failures in orbit. Moreover, better controlled production runs combined with field experience are indispensable to obtain higher reliability. Thus the qualification program should be concerned with the "low-tech" components of clocks (such as power supplies) as well as with the physics package.

We recommend that there be closer coordination within the Air Force among programs that require precise time. A recently issued DoD directive, 5160.51, of June 14, 1985, has designated a central organization for the coordination of timing needs (Appendix D). The Air Force should issue a directive to its acquisition divisions to solicit the assistance of this organization in making decisions on timing hardware. This directive also should extend to System Program Office contractors since the SPO is not always involved in requisitioning components such as clocks. The interest of the timing needs center will be not to control what users purchase, but rather to assist users in making an intelligent choice. Users would benefit from a current source of information as to what choices are available and from the opportunity to discuss requirements with other users reachable through the timing needs channel.

As an example of such coordination activity, Rome Air Development Center is currently conducting a standardization program to develop a small family of clocks and frequency standards for general Air Force application. The Multiple Use Frequency Standard (MUFS) activity should be finished in FY87 or FY88 and will encompass cesium, rubidium, and quartz technologies. In time these clocks will be space-qualified and hardened. Headquarters of the Air Force Systems Command is prepared to direct SPOs and contractors to acquire timing hardware from the MUFS family by the end of the decade.

Finally, extensive operation of production clocks on a continual basis before launch is the only way to find out if there are any early-life failure modes. Such problems are detectable under burn-in operation long before they become painfully obvious in orbit. The life of the clock should be specified to include both the anticipated mission lifetime requirement plus an appropriate long-term pre-mission operating and testing period.

6.4 Tightening of Requirements as Technology Permits

In the future, scientific and technological progress in atomic clocks, spacecraft tracking, or the understanding of signal propagation effects, may make it possible to improve significantly the accuracy of time transfer systems such as GPS. Yet such improvements might not be made because the stated requirements at the time may not be tight enough to make them obligatory. This might occur, for instance, if no clear military need for such improvements had yet been identified. In the absence of tighter requirements the system would continue to operate at its current level despite the possibility for improvement. We think this would be a mistake. We recommend that the possibilities for improvement in time transfer accuracy afforded by technological advances be reviewed periodically, and that the accuracy requirements be systematically tightened accordingly. Achieving the goals set by such tighter requirements will lead to a more accurate time transfer and navigational system, will further enhance its capability for autonomous operation, and may lead to additional technological advances of unforeseen benefit.

CHAPTER VII. TIME TRANSFER: AN OPPORTUNITY TO STUDY RELATIVISTIC EFFECTS

The dominant relativistic effects--time dilation, gravitational redshift, and the Sagnac effect--are well understood and are taken into account routinely in GPS and other time transfer systems. Assuming the validity of special and general relativity, the next class of relativistic effects are well below the 2 ns level and are not currently relevant to the operation of time transfer systems. Developing improved accuracy will provide opportunities to detect or test for relativistic effects using precise timing. In addition to advancing fundamental knowledge, this will provide a foundation for future technological advances.

7.1 Relativistic Effects at the Sub Nanosecond Level

The dominant factor that regulates the size of relativistic effects in time transfer problems is the dimensionless gravitational potential of the Earth at the altitude of a GPS satellite, which is the usual gravitational potential divided by c^2, and is of order 2×10^{-10}. This is also comparable to the square of the satellite's orbital velocity in units of the speed of light. These factors, acting on clock rates, give the rate difference of microseconds per day between GPS satellite and ground clocks.

In addition to affecting clock rates, general relativity also predicts perturbations of the orbits, with a comparable fractional size (2×10^{-10}) corresponding to centimeters in distance, or 0.1 ns in signal travel time. The largest effect of this kind is the precession of the perigee of the orbit, amounting to about 8 cm/orbit (regardless of the radius of the orbit), or 60 m/yr for GPS altitudes. However, this effect will be difficult to detect even under optimal conditions because GPS orbits are highly circular. General relativity also affects the propagation of signals between Earth and satellites, producing a delay in signal reception known as the Shapiro Time Delay. Its size is also given roughly by the above dimensionless fraction of a characteristic light travel time, corresponding to 0.6 cm in range or 0.02 ns in time. Both these effects have been measured with high precision using planetary and spacecraft radar ranging.

One important relativistic effect that has not been detected to date is the "Dragging of Inertial Frames." The rotating mass of the Earth attempts to "drag" the space near it into rotation. The effect of this on a satellite in a non-equatorial orbit is to drag the plane of the orbit slowly around an axis aligned with the rotational axis of the Earth. For a satellite at GPS altitude, the dragging of the plane of the orbit amounts to around 10^{-8} radians/yr, corresponding to about 40 cm/yr, or 1 ns. This effect is one of the most important unmeasured effects in observational relativity, and several experiments are proposed to try to detect it, including Gravity Probe B, the orbiting gyroscope experiment in preparation at Stanford University with the cooperation of NASA and Marshall Space Flight Center. Other possible relativistic effects are much smaller and are not likely to be detectable in the foreseeable future. Appendix E provides estimates of these and other relativistic effects.

7.2 Tests of the Postulates of Relativity

The basic postulates of any physical theory should always be subjected to experimental scrutiny, no matter how well accepted the theory might be.

Improved time transfer systems, such as GPS, may provide the means to perform tests of the postulates of special relativity at interesting levels of precision. One postulate of special relativity is the independence of the speed of light of the velocity of the observer or of the direction along which it propagates. This postulate would be violated if the speed of light were to depend on its direction relative to the Earth's direction of motion through the 3K microwave background, or relative to some preferred axis associated with a local anisotropy in the universe. A negative search for the effects of such violations in GPS-type time transfer at nanosecond levels of precision could set limits on fractional variations of the speed of light at the 10^{-8} level.

7.3 Rigorous Relativistic Analysis of Time Transfer

The committee concludes that one factor responsible for the spurious criticisms of the handling of relativistic effects in GPS is a failure in communication between scientists who speak rather different languages. The time transfer community uses the language of Cartesian three-dimensional vector calculus to analyze time, signal propagation, satellite orbits, and the inclusion of relativistic effects. There is no evidence that this procedure produces incorrect results, providing the calculations are done with care, and we are convinced that they have been done with the appropriate care. However, the relativity community uses the language of four-dimensional spacetime and the calculus of differential geometry; and the transformation between the two languages is not always transparent. We recommend as a useful pedagogical exercise an analysis of time transfer beginning from relativistically rigorous first principles, and demonstrating the proper translation to the operationally more useful Cartesian language. We reiterate that such an analysis will not produce any disagreement with existing results, but will provide a useful bridge between relativists and time transfer experts.

Appendix A

BACKGROUND TO CATTISS: A CHRONOLOGY

The following is a chronological list of events and correspondence that led to the formation of the Committee on Accuracy of Time Transfer in Satellite Systems.

26 December 1977	*Physical Review Letters* paper on "New Test of the Synchronization Procedure in Noninertial Systems" by Jeffrey M. Cohen (University of Pennsylvania) and Harry E. Moses (University of Lowell).
24 October 1983	*Physical Review Letters* paper on "Clock Transport Synchronization in Noninertial Frames and Gravitational Fields" by Cohen, Moses, and Arnold Rosenblum (Temple University).
December 1983	Proposal for Synchronization of a Global Satellite Network, by Cohen and Angelo J. Skalafuris (AJS) (Naval Research Laboratory)
2 December 1983	Letter, AJS to Lt. Col. J. Sheerer,SD/GPS (AFSC).
3 January 1984	Letter, AJS to Sheerer
February 1984	Draft Paper on "Current Theoretical Attempts Toward Synchronization of a Global Satellite Network" by A. J. Skalafuris (submitted to *Radio Science*, published in November 1985)
3 February 1984	Letter, AJS to N. Yannoni, RADC (AFSC)
3 February 1984	Letter, AJS to DARPA
6 February 1984	Letter, Sheerer to AJS
6 February 1984	Letter, Documentation, AJS to Yannoni
10 February 1984	Letter, Yannoni to B. Kulp, HQ AFSC (AJS materials forwarded)
22 February 1984	Letter, AJS to Sheerer
1 March 1984	Letter, AJS to Yannoni
6 March 1984	Letter, Yannoni to Kulp (more AJS materials forwarded)
23 March 1984	Letter, Brig. Gen. P. Bouchard to J. Davidson, AFSB
10 April 1984	Letter, Yannoni to Kulp (more AJS materials forwarded)
9 May 1984	Letter, Davidson to C. Will (formation of CATTISS)

Appendix B

COMMITTEE ACTIVITIES

The Committee on Accuracy of Time Transfer in Satellite Systems (CATTISS) was formed during the late spring of 1984, and held meetings in various locations during the academic year 1984-85. A parallel study by the JASON group for DARPA was held in July 1984, led by committee member D. Eardley. The following is a list of meetings and dates:

Study initiated	May 1984
Mitre Corporation, La Jolla (JASON)	July 1984
Hanscom Air Force Base	Sept. 10, 1984
Washington University, St. Louis	Dec. 17, 1984
Stanford University	Feb. 7, 1985
U. S. Naval Observatory	Apr. 10, 1985
National Academy of Sciences	July 2-3, 1985

Appendix C

TROPOSPHERIC AND IONOSPHERIC EFFECTS ON SIGNAL PROPAGATION BETWEEN EARTH AND SPACE

The frequency and time delay of signals transmitted between Earth and space are affected by the Earth's troposphere and ionosphere. In addition to the Doppler effects from range distance variations, there are frequency shifts and path delay variations that result from the temporal and spatial variations of the near-Earth transmission medium and the way the path of propagation seen at the Earth station changes as the satellite moves from horizon to horizon.

An example of the frequency instability introduced by the troposphere alone, given in terms of the Allan variance data obtained from radio interferometry data at 3 mm wavelength (Rogers et al., 1984) is shown in the dashed curve of Figure 2 (page 36). The effects of both tropospheric and ionospheric fluctuations (Smarr et al., 1983) at 18 cm are shown in the dotted curve of Figure 2. We see that the troposphere and ionosphere cause at least two orders of magnitude degradation in space-to-Earth comparisons with high stability oscillators.

This section offers an overview of these effects and discusses some methods for correcting, or compensating for, ionospheric and tropospheric propagation disturbance.

C.1 Tropospheric Effects

The refractive index, $\eta = \frac{\text{velocity of light}}{\text{velocity of light in a medium}}$, for cases where it differs only slightly from 1, is often written in terms of the refractivity $N = (\eta - 1) \times 10^6$. For air, the dependence of N on pressure, p, water vapor partial pressure, e (e and p in millibars), and temperature, T (in Kelvin) is given by (Smith and Weintraub, 1953):

$$N = \frac{77.6p}{T} + 3.73 \times 10^{-5} \frac{e}{T^2}$$

Refractivity also depends on altitude, h approximately as follows: $N(h) = N e^{-h/H}$, where N is the refractivity at the Earth's surface near the station and H is the scale height, typically about 8 km (for a review, see Altschuler 1983).

Microwave absorption bands occur for oxygen at 5 mm and 2.5 mm wavelengths and for water vapor at 1.35 cm and 1.6 mm. Generally, signals at wavelengths greater than 1.35 cm and shorter than 1.6 mm are free from molecular absorption.

A number of atmospheric correction algorithms have been developed to account for path delay as a function of angle from the zenith, Z, surface humidity partial pressure, e, and barometric pressure, p. One such correction (Saastamoinen, 1970) is given in centimeters of path delay as follows:

$$\Delta S = (0.2357p + 0.017e)\sec Z - 0.243(\sec^3 Z - \sec Z).$$

For $Z \approx 90^\circ$ (horizontal) ΔS can be as large as 100 meters.

While the systematic effects are relatively easily accounted for, fluctuations depend very much on local conditions, weather, etc. To some extent the fluctuations have a dependence on signal frequency, especially when the dimensions of inhomogeneities are commensurate with wavelength. The effect of raindrops (Hogg and Chu, 1975) becomes very evident as wavelength decreases as shown in Figure 3. The characterization of atmospheric noise in terms of the Allan variance shown as the dashed curve in Figure 2, made from data at 3 mm wavelength (89 GHz), is consistent with turbulence effects over velocity-time scales consistent with the atmospheric scale height.

Except for wavelengths near the absorption bands of water vapor and oxygen, there is little dispersion (velocity dependence on frequency) in signals propagating through the atmosphere.

C.2 Ionospheric Effects

The refractive index, η, is highly dispersive (i.e., frequency dependent) and depends on the density $\rho(\vec{r})$ at the location $\vec{r}$ through which the ray passes, the signal frequency, f, magnetic field, H, and the angle, α, between the ray direction and the field lines. The refractive index can be described in terms of a series in inverse powers of frequencies f^2, f^3, and f^4 as follows (Tucker and Fannin, 1968; Klobuchar, 1983):

$$\begin{aligned}\eta(\vec{r}) = 1 &- \left(\frac{e^2}{2(2\pi)^2 m\varepsilon_o}\, \rho(\vec{r}) \right) f^{-2} \\ &\pm \left(\frac{|e^3|\mu_o}{2(2\pi)^3 m^2 \varepsilon_o}\, H(\vec{r})\cos\alpha \;\rho(\vec{r}) \right) f^{-3} \\ &- \left(\frac{e^4 \rho^2(\vec{r})}{8(2\pi)^4} + \frac{e^4 \mu_o^4 H^2(\vec{r})\cos^2\alpha}{2(2\pi)^4 m^3 \varepsilon_o}\, \rho(\vec{r}) \right) f^{-4} \qquad (C.1)\end{aligned}$$

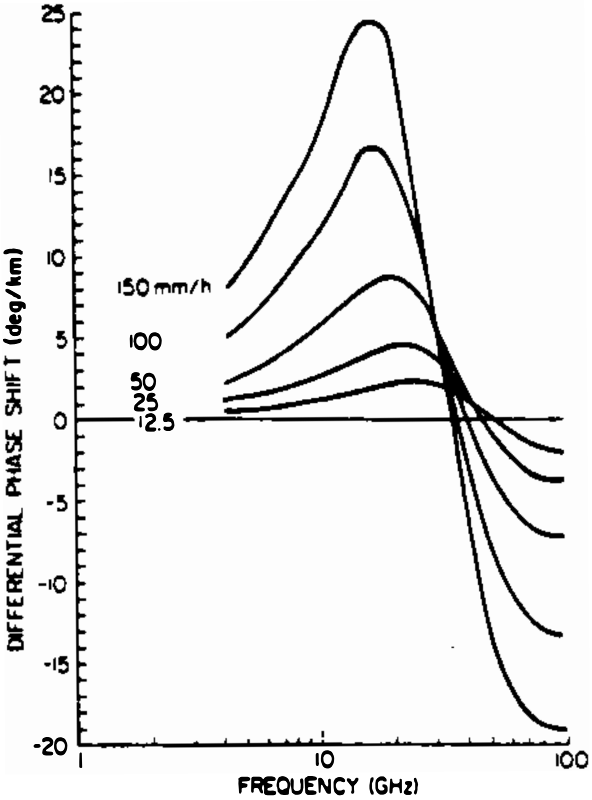


FIGURE 3 RAIN INDUCED DIFFERENTIAL PHASE SHIFT

[From Hogg and Chu, 1975, c 1975 IEEE]

where e and m are the electron's charge and mass, $\rho(\vec{r})$ is the density of electrons at location $\vec{r}$, ε_0 is the permittivity of free space, and μ_0 is the Bohr magneton.

The fractional Doppler effect $\Delta f_D/f$, owing to the rate of change of the ray path, g, between the transmitter and receiver is

$$\frac{\Delta f_D}{f}, = -\frac{\dot{r}}{c} = -\frac{1}{c}\frac{d}{dt}\int_g \eta(\vec{r})ds$$

where g is the ray path.

When we substitute for $\eta(\vec{r})$ the expression in Eq. (C.1), we obtain four contributions to the fractional Doppler shift.

The first term in Δf_D, arising from the factor 1 in Eq. (C.1), is the conventional vacuum term. This term along with the tropospheric refraction term is frequency independent. The second and higher terms are frequency dependent and are referred to as the ionospheric Doppler effect.

The first-order ionospheric Doppler shift is given by:

$$\Delta f_{I,1} = \frac{e^2}{2(2\pi)^2\varepsilon_0 mc}\frac{1}{f}\frac{d}{dt}\int_g \rho(\vec{r})ds$$

At microwave frequencies this is the dominant term and, from its sign, we note that an increase in the columnar electron density, $\int_g \rho(\vec{r})ds$, causes an <u>increase</u> in the frequency of the carrier signal owing to the increase in the <u>phase velocity</u> that results from the minus sign in the f^{-2} term in $\eta(\vec{r})$.

The second-order ionospheric Doppler has plus and minus signs indicating that there is a splitting of a linearly polarized signal into two circularly polarized components, the ordinary ray and the extraordinary ray. Since these have different indices of refraction they will have different ray velocities and ray paths.

The third-order term is more complicated in that it involves contributions resulting from the extra path distance owing to ray bending in addition to the f^{-4} terms in $\eta(r)$.

The Doppler signature from ionospheric effects is further complicated by the fact that the ionosphere electron density profile with altitude changes substantially from night to day and with the level of solar activity. To illustrate this variability, Figure 4 shows electron density vs altitude profiles at about 6:45 a.m. and at 8:30 a.m. Eastern Daylight Time on June 18, 1976 for Cape Canaveral, Florida; this was a quiet period in the 11-year cycle of solar activity.

We see that the effect of the ionosphere on frequency comparisons depends on the rate of change of the colunnar electron density, $\int_{\mathcal{P}} \rho(\vec{r})ds$, in the ray path. The first-order component of the ionospheric Doppler shift (Hertz) is

$$\Delta f_{\mathcal{I},1}(t) = \frac{2.18 \times 10^{-8}}{f} \frac{d}{dt} \int_{\mathcal{P}} \rho(\vec{r})ds$$

where s is in meters, $\rho(\vec{r})$ is in number of electrons per cubic meter.

The first-order effect on time transfer depends on the group velocity of the time pulse and is given by:

$$\Delta t_{\mathcal{I},1}(t) = \frac{1.343 \times 10^{-7}}{f^2} \int_{\mathcal{P}} \rho(\vec{r})ds, \text{ sec.}$$

Spatial and temporal irregularities in the ionosphere and atmosphere cause instabilities in time and frequency measurements. While these can be described as noise processes, in terms of the Allan variance, as shown in Figure 2, they can also be considered as systematic effects and largely eliminated using reflected or transponded signals that traverse the medium and allow a two-way measurement of the propagation anomaly.

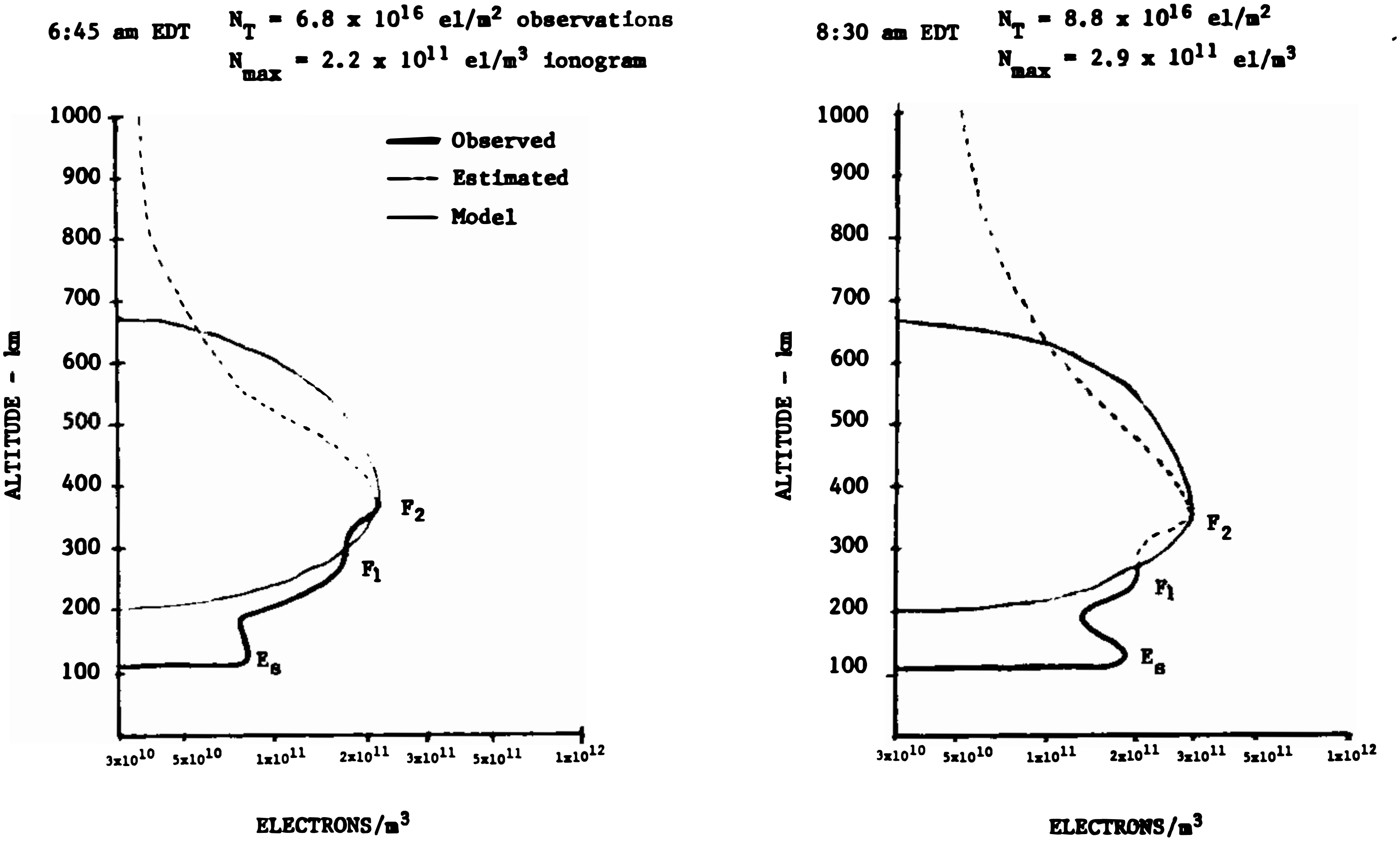


FIGURE 4 ELECTRON DENSITY vs. ALTITUDE PROFILES, 18 JUNE 1976, CAPE CANAVERAL, FLORIDA

Consider the process shown in Figure 5, where range distance is shown plotted versus time. Let a pulsed signal be sent to the spacecraft from Earth at t_1 and received at the spacecraft at time t_2 and simultaneously reflected Earthwards to be received at the Earth station at time t_3.

For time intervals $t_3 - t_1$ we will assume the troposphere and ionosphere have not changed. (For synchronous altitudes this time is approximately 0.2 seconds). Under that assumption, and allowing for the relativistic effects described elsewhere in this document, we can write:

$$t_2 - t_1 = \tfrac{1}{2}(t_3 - t_1).$$

We can thus remove the propagation interval, $t_2 - t_1$, including atmospheric and tropospheric disturbances, and thus transfer time with very high accuracy. This is the system used by Alley and his colleagues in 1975 to make high accuracy time transfer between atomic clocks in a high altitude aircraft and Earth using very short pulsed laser techniques (Alley, 1981). Since these pulses were all at optical frequencies, the dispersive effects of the ionosphere were negligible and sub-nanosecond time comparisons were routinely made. However, if we operate at microwave frequencies our pulse lengths are generally considerably longer than the light time and we must diversify the frequencies in the three links so as to avoid having more than one carrier on the same channel. Under these conditions we must take into account the dispersion effects of the ionosphere. The measurement of two-way path delay includes a first-order ionospheric time delay contribution:

$$\Delta t_{13} = \left(\frac{1}{f_1^2} + \frac{1}{f_2^2} \right| K \int_g \rho(\vec{r}) ds$$

where f_1 and f_2 are the up and down carrier frequencies, and the time comparison link also has an ionospheric delay given by:

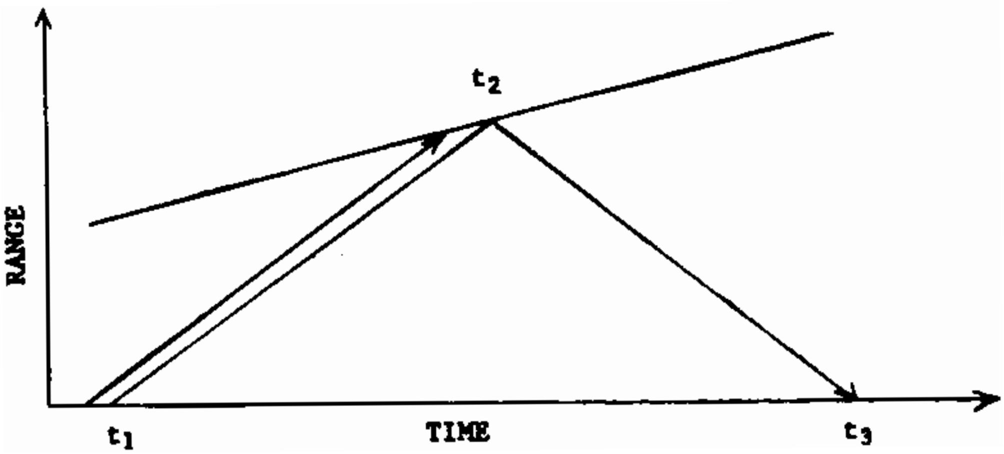


FIGURE 5 RANGE DISTANCE vs. TIME

$$\Delta t_{12} = \frac{K}{f_3^2} \int_{\gamma} \rho(\vec{r}) ds,$$

where f_3 is the time link's carrier frequency. The first-order ionospheric error can be cancelled by choosing the 3 frequencies as follows:

$$\frac{1}{f_3^2} = \frac{1}{2}\left(\frac{1}{f_1^2} + \frac{1}{f_2^2}\right)$$

In the case of continuous microwave frequency comparisons from space to Earth, carrier frequency separation is required and this also leads to problems owing to ionospheric dispersion. Here the variation of all aspects of the propagation path lead to Doppler frequency shifts. These propagation effects can be removed to high accuracy using the phase coherent system shown in Figure 6, which was used in the 1976 joint NASA-Smithsonian Astrophysical Observatory test of relativistic and gravitational effects on time (Vessot et al., 1980). The atomic hydrogen masers in the Earth and spacecraft systems are shown as heavily outlined squares and the ratios of the phase coherent frequency translators are shown in their appropriate blocks. The space-borne phase coherent transponder shown with ratio M/N = 240/221 was from the existing Unified S Band System. The phase coherent system measures the Doppler frequency shift owing to the time variation of all aspects of the propagation path with a two-way (up-down) signal, divides it by two to obtain the one-way Doppler and subtracts the one-way Doppler shift from the "clock" comparison (one-way) downlink.

Because of the frequency separation in the microwave links, the ionospheric dispersion predicted from a typical profile in this application would have caused Doppler shifts of about 5 parts in 10^{10}, if the one-way link frequency had not been chosen to null-out the first-order ionospheric term as shown below.

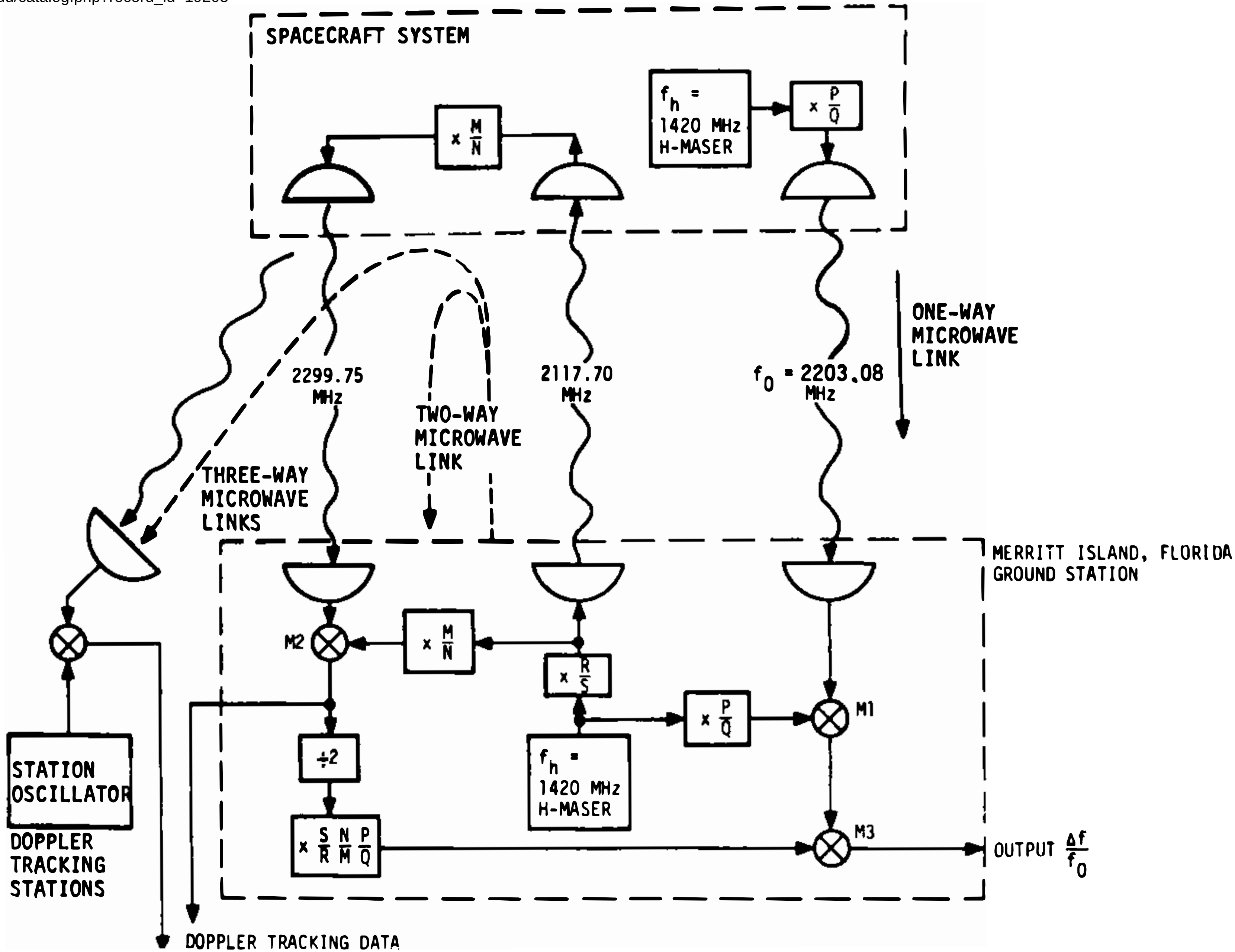


FIGURE 6 PHASE COHERENT SYSTEM USED IN 1976 ROCKET TEST OF TIME DILATION AND GRAVITATIONAL REDSHIFT

The ionospheric Doppler in the two-way link observed at mixer, M_3 is:

$$\Delta f_{I,2} = K \frac{1}{f_h} \left(\frac{M}{N} + \frac{N}{M} \right) \frac{S^2}{R^2} \frac{P}{Q} \frac{N}{M} \frac{1}{2} \frac{d}{dt} \int_{g} \rho(\vec{r}) ds.$$

The one-way link has ionospheric Doppler, which appears at mixer M_3 as:

$$\Delta f_{I,1} = K \frac{1}{f_h} \frac{Q}{P} \frac{d}{dt} \int_{g} \rho(\vec{r}) ds.$$

These cancel when

$$\frac{P}{Q} = \sqrt{2} \frac{R}{S} \left(1 + \frac{N^2}{M^2} \right)^{-\frac{1}{2}}$$

It was estimated that all Doppler effects were cancelled at a level below 2.5×10^{-15} in $\Delta f/f$ in the 1976 GPA experiment with a nearly vertical suborbital trajectory reaching an altitude of 10^4 km. Doppler shifts were as high as 2×10^{-5} in $\Delta f/f$. The resulting comparison between Earth and space masers after removal of predicted relativistic effects from the output from mixer M_3 is shown in Figure 2, as the dotted points on curve (b).

APPENDIX D

Department of Defense
DIRECTIVE

June 14, 1985
NUMBER 5160.51

ASD(C3I)

SUBJECT: Precise Time and Time Interval (PTTI) - Planning, Coordination and Control

References: (a) DoD Directive 5160.51, "Precise Time and Time Interval (PM) Standards and Calibration Facilities for Use by Department of Defense Components," August 31, 1971 (hereby canceled)
(b) DoD Directive 4000.19, "Interservice, Interdepartmental, and Interagency Support," October 14, 1980)

A. REISSUANCE AND PURPOSE

This Directive:

1. Reissues reference (a). Revisions occasioned by organizational and administrative changes also are included.

2. Updates policy and assigns responsibility to a single DoD Component for coordinating PTTI requirements and maintaining a PTTI reference standard (astronomical and atomic) for use by all DoD Components, other agencies of the Federal Government, DoD contractors, and related scientific laboratories. This responsibility includes that of programing the necessary resources to maintain the reference standard and to disseminate precise time to DoD users.

B. APPLICABILITY

This Directive applies to the Office of the Secretary of Defense, the Military Departments, the Organization of the Joint Chiefs of Staff, the Unified and Specified Commands, and the Defense Agencies (hereafter referred to collectively as "DoD Components").

C. DEFINITIONS

The terms used in this Directive are defined in enclosure 1.

D. POLICY

It is DoD policy that:

1. Coordination of the DoD PTTI program will be implemented through a central DoD PTTI manager acting jointly with a PTTI coordinator in each Military Department and user agency.

2. The DoD reference standard for PTTI is that which is established by the Department of the Navy at the U.S. Naval Observatory. All systems that use precise time or precise frequency shall use this reference standard.

3. The maximum practicable interchange of PTTI information shall be effected throughout the Department of Defense. In this regard, it is incumbent upon PTTI users to submit their requirements to the DoD PTTI manager as soon as the requirements are identified and formulated.

4. Maximum practical use of interservice support will be achieved as prescribed in reference (b).

5. The PTTI planning and coordination will be supplemental to, and operate within the current Planning, Programing, and Budgeting System.

E. RESPONSIBILITIES

1. The Department of the Navy is the DoD PTTI manager in carrying out the responsibilities of the DoD PTTI manager, the Department of the Navy shall:

a. Ensure uniformity in precise time and time interval operations.

b. Derive and maintain standards of time and time interval, both astronomical and atomic.

c. Provide coordination of such standards with recognized national and international standards to ensure worldwide continuity of precision.

d. Issue detailed information concerning DoD reference standards for PTTI and distribute these standards by the most efficient, practical methods.

e. Maintain a repository of PTTI information including, but not limited to, such elements as dissemination systems and their characteristics, equipment required to access various dissemination systems, equipment cost, training required, and maintenance support data. Ensure that the availability of such data is publicized widely.

f. Annually, in coordination with the DoD Component and agency PTTI coordinators, develop a summary of PTTI requirements. (A copy of the summary shall be provided to the Assistant Secretary of Defense (Command, Control, Communications, and Intelligence (ASD (C^3I))).

g. In coordination with the Office of the Under Secretary of Defense for Research and Engineering and DoD Component/user agency PTTI managers, monitor DoD research programs concerning PTTI.

h. Participate in PTTI policy negotiations between the Department of Defense and other Federal Government agencies and international organizations.

i. Coordinate all DoD-sponsored portable clock travel. Each DoD Component/user agency will cooperate in combining trips and/or schedules in order to minimize total DoD costs. The Department of the Navy shall serve as the focal point for coordination of all portable clock travel. Costs of portable clock travel will be borne by the Component/agency sponsoring the particula: trip.

j. Within 45 days following receipt of this Directive, inform the Office of the Secretary of Defense and other DoD Component/user agencies of the staff agency and office code of the DoD PTTI Manager.

2. The Military Departments and all DoD User Agencies shall:

a. Appoint a DoD Component PTTI coordinator who will coordinate his or her respective PTTI program with the DoD PTTI manager.

b. Refer time and time interval to the standard established by the Department of the Navy at the U.S. Naval Observatory, and maintain specific time scales such that relationship to the established standard is known.

c. Prescribe technical requirements for the coordination of techniques, procedures, and periodic calibration of systems.

d. Prescribe in-house procedures for the development, coordination, and consolidation of the respective DoD Component PTTI requirements.

e. Assist the DoD PTTI manager by providing technical information on current and prospective PTTI requirements in the format prescribed by the DoD PTTI manager.

f. Ensure that PTTI requirements for systems and programs of the DoD Component/user agencies are coordinated with, and approved by, DoD Component PTTI managers.

g. Promote economy by prescribing requirements for precise time that are consistent with operational and research needs for accuracy.

3. The Assistant Secretary of Defense (Command, Control, Communications, and Intelligence) is assigned primary staff responsibility for the DoD PTTI program. In this capacity, the ASD(C^3I) shall provide for overall development, coordination, and promulgation of major DoD policies and plans, and act as the final authority in consolidating the DoD PTTI programs.

F. EFFECTIVE DATE AND IMPLEMENTATION

1. This Directive is effective immediately. It shall be given full distribution by all DoD Components.

2. The Military Departments and DoD user agencies shall provide two copies of their respective implementing documents to the Assistant Secretary of Defense (Command, Control, Communications, and Intelligence) within 90 days of the effective date of this Directive.

3. As soon as practicable, but within 60 days after the effective date of this Directive, each Military Department and DoD user agency shall advise the DoD PTTI manager of the staff agency and office code appointed as its respective PTTI coordinator.

William H. Taft

William H. Taft, IV
Deputy Secretary of Defense

Enclosure - 1
Definitions

DEFINITIONS

1. Precise Frequency. Signifies a frequency (time interval) requirement accurate to within one part in 10^9.

2. Precise Time. Signifies a time requirement accurate to within 10 milliseconds.

3. Standards. Signify the reference values of time and time interval. These standards are determined by astronomical observation and by the operation of atomic clocks. They are disseminated by transport of clocks, by radio transmissions, and by other means.

4. Time. Signifies epoch, that is, the designation of an instant on a selected time scale, astronomical or atomic. It is used in the sense of time of day.

5. Time Interval. Indicates the duration of a segment of time without reference to when the time interval begins or ends. Time interval may be given in seconds of time.

Appendix E

RELATIVISTIC EFFECTS IN EARTH SATELLITE TIMING SYSTEMS

In this appendix, we estimate the size of the "next generation" of relativistic effects in timing and position measurements of satellite systems such as GPS. The important parameters of a typical GPS satellite that concern us are its period, ~12 hours, its orbital radius, ~26.6 km x 10^3 (~$4R_\oplus$), its mean orbital velocity, ~3.9 km/sec ($1.3 \times 10^{-5}c$, where c = speed of light), its eccentricity $e < 0.005$, and the inclination of its orbit, ~63° or ~55°. We shall be concerned with effects that are typically at the sub-nanosecond level.

The dominant points in clock synchronization (Sagnac effect, and rate offsets due to orbital motion and the Earth's gravitational field) are already handled in the GPS system. (These effects are typically 10's to 100's of nanoseconds.) To estimate the size of various effects in the near Earth environment, we will base our estimate on the strength of the appropriate dimensionless potential:

$$\phi \equiv \phi_{\text{Newtonian}}/c^2 \;;$$

for instance (see Table E.1; these estimates have been made only to one or two significant figures):

$$\phi(\text{Earth, at Earth Surface}) \equiv \frac{GM_\oplus}{c^2 R_\oplus} \approx 7 \times 10^{-10}$$

$$\phi(\text{Earth, at GPS Altitude}) \approx 1.8 \times 10^{-10}$$

$$\phi(\text{Sun, at Sun Surface}) \equiv \frac{GM_\odot}{c^2 R_\odot} \approx 2 \times 10^{-6}$$

TABLE E.1

VALUES OF RELEVANT PARAMETERS (See Allen 1976)

G	Newton's constant	$= 6.668 \times 10^{-8}$ dyne cm^2/gm^2
c	speed of light*	= 2.99792458 cm/sec
$M_\oplus$	mass of Earth	$= 5.997 \times 10^{27}$ gm
$M_☾$	mass of Moon	$= 7.379 \times 10^{25}$ gm
$M_\odot$	mass of Sun	$= 1.989 \times 10^{33}$ gm
$R_\oplus$	equatorial radius of Earth	$= 6.378 \times 10^{8}$ cm
$r_\oplus$	semimajor axis of Earth orbit	$= 1.495985 \times 10^{13}$ cm
$R_☾$	radius of Moon	$= 1.7379 \times 10^{8}$ cm
$r_☾$	mean Earth-Moon distance	$= 3.84404 \times 10^{10}$ cm
$R_\odot$	radius of Sun	$= 6.9598 \times 10^{10}$ cm
M_{gal}	mass of galaxy $\simeq 10^{11} M_\odot$	$\simeq 2 \times 10^{44}$ gm
"R_{gal}"	"size of galaxy" $\sim$ 15 kpc	$= 4.5 \times 10^{22}$ cm

*Based on current definition of the meter

$$\phi(\text{Sun, at Earth Orbit}) \equiv \frac{GM_\odot}{c^2 r_\oplus} \approx 10^{-8}$$

$$\phi(\text{Moon, at Moon Surface}) \equiv \frac{GM_{☾}}{c^2 R_{☾}} \approx 3 \times 10^{-11}$$

$$\phi(\text{Moon, at Earth}) \approx 1.4 \times 10^{-13}$$

$$\phi(\text{Galaxy, at Earth}) \equiv \frac{GM_{gal}}{c^2 R_{gal}} \sim 3 \times 10^{-7}$$

For the purposes of this discussion, all our estimates will be made in the context of the theory of general relativity, particularly in estimating orders of magnitude. We will assume that no "large" dimensionless factors arise in the formulas. While there can in principle be theories of gravity in which some dimensionless parameters are large, they have been observationally excluded to the level of accuracy described here. Table E.2 summarizes current observational constraints on alternative gravitation theories.

E.1 Orbital Relativistic Effects

Effects beyond the Newtonian level are typically called second-order effects; they arise from influences that are one power of the dimensionless potential ϕ smaller than the dominant Newtonian terms, which already involve one power of ϕ (see Will, 1981, for further discussion). There are other effects, also, that in the near-Earth environment are comparable in size; these arise from the terms that involve the rotation of the Earth, and are thus linear in the rotation velocity of the Earth. If the Earth were rotating at breakup velocity, then the equatorial

TABLE E.2 SUMMARY OF SOLAR-SYSTEM TESTS OF THEORIES OF GRAVITATION

Measured Effect	Resultant Constraint	Comment
Bound on any non-Newtonian monthly variation in the Earth-moon distance	$4\beta - \gamma - 3 = 0.001 \pm 0.015^{a}$	Test of relative contributions of gravitational binding energy to inertial and to (passive) gravitational mass
Comparison between clock in ballistic trajectory and clock on ground	$\frac{\text{measured change}}{\text{predicted change}} = 1.0000 \pm 0.0001$	Test of metric hypothesis via gravitational redshift and doppler shifts
Deflection of radio waves by gravitational field of sun	$\gamma = 1.01 \pm 0.02$	Test of amount of spatial curvature generated by unit mass
Increase of echo time of radio signals sent from Earth to Mars, due to gravitational field of sun	$\gamma = 1.000 \pm 0.002$	Test of amount of spatial curvature generated by unit mass
Relativistic contribution to advance of perihelion of Mercury's orbit	$(2 + 2\gamma - \beta)/3 = 1.003 \pm 0.005^{a,b}$	Test of combination of amount of spatial curvature generated by unit mass (γ) and nonlinearity in superposition of Newtonian gravitational potentials (β)
Bound on any "anomalous" acceleration of longitude of planetary orbits	$\lvert\dot{G}/G\rvert \leq 1\text{x}\ 10^{-11}\ \text{yr}^{-1}$	Test of constancy of "constant" of gravitation, G

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[a] For simplicity in the presentation of results, we have neglected the implied constraints on PPN parameters concerned with violations of global conservation laws and with preferred frame and location effects. In general relativity, $\delta = \beta = 1$ and $\dot{G} = 0$.

[b] A possible contribution by the solar gravitation quadrupole has been assumed to be negligible.

[From Survey of Gravitation, Cosmology and Cosmic Ray Physics, Panel Report for the Physics Survey Committee, National Academy Press, 1985] tangential velocity would equal the orbital velocity at the earth's surface, $v/c \sim (GM/c^2R_\oplus)^{\frac{1}{2}} \sim 10^{-5}$. If this were the case, these $1\frac{1}{2}$ order effects due to rotation would be only 10^{-5} smaller than the Newtonian effects, and would require substantial corrections at the GPS level of accuracy. In fact, the surface velocity at the equator is 20 times smaller than the above velocity. These rotation effects are, nonetheless, the dominant effects in the near Earth orbits, and they dominantly give secular (frame dragging) effects.

We begin with the second order (ϕ^2) effects.

The dimensionless potential is a measure of the deviation from the Newtonian description of gravity. In Newtonian gravity, planets follow orbits that are essentially ellipses, but include deviations due to the higher multipoles of the Earth's gravitational potential - the Earth is not exactly spherical - and due to the influence of other solar system bodies. Further, the non-Newtonian effects come into play at a level whose order is given by the dimensionless potential ϕ; for GPS one would estimate these effects at $\sim 2 \times 10^{-10}$, i.e., effects of order 0.5 cm in the orbital radius $\sim 2.5 \times 10^9$ cm. (A length can be defined from the mass of the Earth: $GM_\oplus/c^2 \simeq 0.5$ cm.) Periodic effects of this size (with period = orbital period) are therefore quite small by current standards, corresponding to 10^{-2} ns effects in the timing accuracy. There are, however, important secular effects whose size can typically be measured by ϕx (number of orbits). After only 200 orbits of a GPS satellite a secular effect $\sim$1 meter ($\sim$3 ns) would build up. The classic effect of this type is the precession of the periapse of the orbit. (The first confirming test of general relativity was this effect for the orbit of Mercury.) The effect is, for small eccentricities,

$\delta\omega$(periapse angular advance per orbit)

$$3\pi \cdot \frac{2GM}{c^2 a} \approx 3.4 \times 10^{-9} \text{ (~8 cm/orbit for Earth satellites)}$$

where a is the semimajor axis of the orbit, and M is the mass of the central gravitating body. The 8 cm/orbit result is comparable to our estimate above of 0.5 cm, but is an order of magnitude larger because of the factor 6π. (Notice also that the amount of perihelion shift down track, per orbit, is a function only of the central mass, and is independent of the orbit itself.) The advance in the periapse of a GPS satellite per year due to this effect is ~60 meters. By Kepler's third law $\tau^2 \propto a^3$, where τ is the orbital period, and so net distance advanced per year decreases with orbital radius:

$$\text{Advance per year} \approx 480 \text{ meter} \times \left(\frac{R_\oplus}{a}\right)^{3/2}$$

The periapse precession is very difficult to measure, particularly for a satellite in near circular orbit, like a GPS satellite. In this regard, we note that the value of the combination of "parametrized post-Newtonian (PPN) parameters" $(2 + 2\gamma - \beta)/3$ can now be estimated from the precession of the periapse of LAGEOS, although not with high accuracy.

The 1½-order ($\phi v \sim \phi\phi^{1/2}$) terms can be explained in the following way. The rotating mass of the Earth attempts to drag the space near it into rotation. This is the Lense-Thirring effect (Misner, Thorne and Wheeler, 1973). The angular rate of dragging near the surface of the Earth is

$$\Omega_{\text{dragging}}(r) = \frac{2GJ_\oplus}{c^2 r^3} \qquad \text{(E.1)}$$

where $J_\oplus$ = the angular momentum of the Earth = $I_\oplus \omega_\oplus$. Now $\omega_\oplus = 2\pi$/day and $I_\oplus = 0.33\, M_\oplus R_\oplus^2$; hence at the surface of the Earth

$$\Omega_{\text{dragging}}(R_\oplus) \approx \frac{2}{3} \frac{GM_\oplus}{c\, R_\oplus} \omega_\oplus$$

This, together with Eq. (E.1) gives

$$\Omega_{\text{dragging}}(r) \approx 4 \times 10^{-10} \omega_\oplus \left(\frac{R_\oplus}{r} \right)^3 \qquad \text{(E.2)}$$

or using Kepler's third law:

$$\Omega_{\text{dragging}}(r) \approx 4 \times 10^{-10} \omega_\oplus \left(\frac{1.5\text{hr}}{\tau} \right)^2$$

The effect of this on a satellite in a non-equatorial orbit is to drag the plane of the orbit slowly around an axis aligned with the angular momentum. For a satellite at GPS altitude, then, the dragging of the plane of the orbit amounts to $\sim 1.4 \times 10^{-8}$ radians/yr. At the GPS satellite orbital radius, ~ 26.6 km $\times 10^3$, this amounts to about 40 cm/yr ≈ 1 ns. The distance dragged scales as r^{-2}. For a satellite with a 90-minute orbit, the dragged distance is ~ 6.5 m/yr.

E.2 Relativistic Effects on Signal Propagation

Light deflection and time delay are phenomena that affect the propagation of signals to and from the timing satellite, rather than affecting the orbit of the satellite. We will dispose of light deflection first.

The direct effect of light deflection is almost irrelevant in the GPS context. This is because the system does not need to know (cannot know) the angular position of the satellite at the level of light deflection due to the Earth $\sim 5 \times 10^{-4}$ arcseconds (about 4 cm when viewing a GPS satellite from Earth). This kind of deflection (4 cm) corresponds to about 10^{-5} seconds of travel time at GPS orbital velocity; a super-accurate transit scheme (whether involving GPS or not) could conceivably find this a troublesome error.

There is a ϕ^2 kind of light deflection correction. Because the photon path is bent, it is slightly longer than a comparison flat space light ray. This effect is $\sim \phi^2$ x length of light ray. For GPS satellites the time of flight is ~ 0.1 seconds, so this amounts to a completely negligible $\sim 10^{-20}$ second correction. (For photon orbits past the sun, this effect is as large as 30 ns.)

A substantially larger effect is called the Shapiro time delay (1964). In this effect, one takes account of the different effective path length when a light ray traverses a gravitational potential, compared to the result in an idealized flat space. This is an effect that is large because it arises from sampling the complete potential difference.

The relativistic equation describing the propagation of photons relates the time differential dt to the distance differential dx:

$$0 = g_{oo} dt^2 + g_{xx} dx^2,$$

$$t = \int \sqrt{g_{xx}/-g_{oo}}\, dx$$

Here $g_{xx} = (1 + 2GM_{\oplus}/c^2 r)$, $g_{oo} = -(1-2GM_{\oplus}/c^2 r)$. Note that g_{oo} is conventionally negative, and we assume that the light path is along the x-direction. Figure 7 gives the geometry of the photon propagation, and

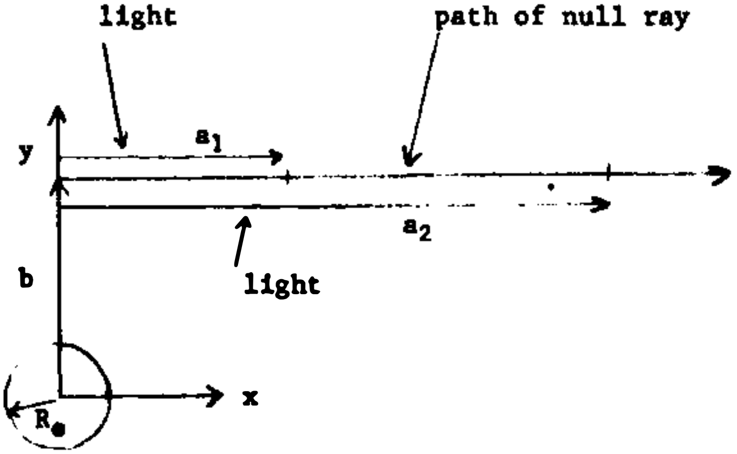

FIGURE 7 GEOMETRY OF LIGHT PROPAGATION PAST THE EARTH

explains the symbols that appear in the approximate result

$$ct_{\text{one way}} = \int_{a_1}^{a_2} \left[1 + \frac{2GM_\oplus}{c^2 \sqrt{x^2+b^2}} \right] dx$$

$$= (a_2 - a_1) + \frac{2GM_\oplus}{c^2} \ln \left| \frac{a_2 + \sqrt{a_2^2 + b^2}}{a_1 + \sqrt{a_1^2 + b^2}} \right| .$$

The round trip time is twice that. These are corrected to proper time for an observer at the transmitter by multiplying by a factor that differs from unity by a term of order (GM/c^2r). The first term is modified by this multiplication, but the second term is so small already that it is not affected.

For application to the GPS problem, we suppose that one station (say a_1) is on the surface of the Earth. We will then compare two configurations:

a) The observed satellite is directly overhead:

$$b = 0, \; a_1 = R_\oplus, \; a_2 = r_{\text{GPS}} \approx 4R_\oplus$$

$$c \times (\text{time delay correction})_{\text{one way}} = \frac{2GM_\oplus}{c^2} \ln(4) \quad .$$

b) The observed satellite is on the horizon:

$$b = R_\oplus, \; a_1 = 0, \; a_2 = R_\oplus \sqrt{15}$$

$$c \times (\text{time delay correction})_{\text{one way}} = \frac{2GM_\oplus}{c^2} \ln(4 + \sqrt{15})$$

This implies a maximum one-way effect of ~ 0.6 cm, $\sim 2 \times 10^{-2}$ ns for the additional offset between the overhead and the horizon clock.

The Shapiro time delays caused by the Sun or Moon are much smaller. For GPS measurements the solar or lunar effect arises because of the difference in potential (tidal potential) across the orbits. We estimate these by computing the tidal potential difference:

$$\Delta\phi_{\odot}\big|_{\text{at Earth}} \approx \frac{GM_{\oplus}}{c^2 r_{\oplus}} \left(\frac{\Delta x}{r_{\oplus}}\right)^2 .$$

with a similar expression for the gradient in the lunar potential. For orbits near the Earth, $\Delta x/r_{\oplus} \approx 10^{-4}$ so that in principle for GPS satellites this could amount to $\sim 10^{-8}\phi_{\odot}\big|_{\text{at Earth}} \simeq 10^{-16}$. For time delay purposes, we simply estimate a shift of this magnitude over the ~ 0.1 second photon paths and obtain a time delay contribution from solar tidal potential $\simeq 10^{-17}$ seconds. The lunar case is similar: $\Delta x/r \simeq 10^{-1}$ is larger by 10^3, but ϕ is smaller by $\simeq 10^5$ to give a time delay contribution from lunar tidal potential $\simeq 10^{-16}$ seconds. In this context tidal gradients due to the galaxy are very small; the potential is $\sim$ 30 times bigger at the Earth than is the Sun's potential, but the scale of variation is very large.

Before leaving the effects of the solar and lunar tidal fields, we should note that over their orbital period the GPS satellites sample potential differences of $\sim 10^{-15}$ to 10^{-16}. Integrated over ~ 6 hours these amount to terms as large as 0.02 ns of periodic variation in clock time, corresponding to ~ 0.6 cm of position uncertainty.

E.3 Cosmology

Cosmological effects appear to be irrelevant at the current level of accuracy. There are few analytical models that deal with the problem of a solar system embedded in a cosmology. One that does is the Einstein-

Strauss model, a "Swiss cheese" model, that we now describe. In a zero pressure expanding universe, take a sphere of matter and squeeze it down to a compact central object. There is vacuum outside this central object, out to the outer spherical boundary where the dust solution begins. The dust is expanding away from the central mass. We can put "test planets" orbiting that central mass and observe the effect of the cosmology on them. There is no effect, a fact that can be demonstrated simply by noting that the spacetime in the vacuum region is the static Schwarzschild spherically symmetric one. Since the spacetime there is static, the orbits are unaffected by what goes on outside the vacuum region. This result is consistent with the Newtonian idea of vanishing field inside a spherical shell of matter.

It does appear that the tidal potential because of the nonsphericity of the surroundings, (i.e., because of the anisotrophy of the cosmology) could have an effect, but our estimates of the tidal effects from the galaxy indicate that such cosmological effects are insignificant.

The gravitational constant G could vary because of cosmological evolution, however, current observations (Table E.2) limit such variations to a part in 10^{11} per year. Relative changes of this magnitude would amount to $\sim 10^{-2}$ cm per year in GPS orbits. This kind of slow, secular change would be removed in orbital modelling, and would be extremely difficult to detect.

The cosmology could affect the orbits of a planetary system by contributing mass to the central attracting body. For instance, if the universe is filled with a uniform fluid of density ρ, then that adds an amount $\Delta M_{\odot} = 4\pi\rho r^3/3$ to the effective mass of the sun when determining a planet's orbit of radius r. But, for instance, suppose the universe were filled with hot neutrinos to a closure density $\sim 10^{-29}$ gm/cm^3 (or had a correspondingly sized cosmological constant). The contribution to the mass inside Earth's orbit is then $\sim 1.5 \times 10^{11}$ gm $\sim 10^{-22}$ $M_\odot$, an extremely small mass. Typical cosmological timescales are the age of the universe, so one could anticipate changes in this quantity, due to the evolution of the cosmology, of ~ 15 gm/yr! We must reluctantly conclude that so far there is no convincing way that cosmology can affect timing accuracy at near-future levels of precision.

E.4 Summary

We have considered several post-Newtonian effects that may be relevant if the level of precision of satellite timing is advanced sufficiently. The largest effect found that directly affects timing measurements is the Shapiro time delay, a differential effect between satellites viewed at different altitudes, that can amount to ~ 0.6 cm (2×10^{-2} ns). Table E.3 summarizes the effects considered, with estimates (in General Relativity) of their sizes. Although the precession and the frame dragging effects are larger over 1 year than is the next larger time delay term, they are the kind of secular term that will most likely be taken out in the fit to the orbital parameters, although they may be explicitly searched for in this fit. The time delay effect, on the other hand, directly enters each observation, and will vary up to its maximum effect within a collection of GPS-like observations.

TABLE E.3

SUMMARY OF RELATIVISTIC EFFECTS

Effect	Magnitude	Relative Magnitude
Periapse Precession	8 cm/orbit, secular $= 480$ m/yr $(R_\bullet/a)^{3/2}$	$\sim 3.4 \times 10^{-9}$
Frame Dragging	6.5 m/yr $(R_\bullet/a)^{2}$	
Time Delay	0.6 cm, 2×10^{-2} ns	$\sim 10^{-9}$
Light Deflection		$\sim 10^{-16}$
Lunar Tidal Forces differential redshifts + time delay	$\sim 10^{-7}$ ns	$\sim 10^{-15}$
Solar Tidal Forces differential redshifts + time delay	$\sim 10^{-8}$ ns	$\sim 10^{-16}$
Tidal Forces, cumulative offset (integration of differential redshift over ½ orbit)	$\sim 2 \times 10^{-2}$ ns	
Cosmology		$\sim 10^{-22}$
		$\sim 10^{-33}$/yr

Appendix F

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