# THE ROLE OF A LOW EARTH ORBITER IN INTERCONTINENTAL TIME SYNCHRONIZATION VIA GPS SATELLITES*

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## ABSTRACT

Time synchronization between two sites using differential GPS has been investigated by a number of researchers. When the two sites are widely separated, the common view period of any GPS satellite becomes shorter; low elevation observations are inevitable. This increases the corrupting effects of the atmospheric delay and, at the same time, narrows the window for such time synchronization. This difficulty can be alleviated by using a transit site located midway between the two main sites. The main sites can now look at different GPS satellites which are also in view at the transit site. However, a ground transit site may not always be conveniently available, especially across the Pacific Ocean; also, the inclusion of a ground transit site introduces additional errors due to its location error and local atmospheric delay. An alternative is to use a low earth orbiter (LEO) as the transit site. A LEO is superior to a ground transit site in three ways: (1) It covers a large part of the earth in a short period of time and, hence, a single LEO provides worldwide transit services; (2) it is above the troposphere and thus its inclusion does not introduce additional tropospheric delay error; and (3) it provides strong dynamics needed to improve GPS satellite positions which are of importance to ultra-precise time synchronization.

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This paper investigates the use of a LEO, at 1300-km altitude, as a transit site for intercontinental time synchronization via GPS. Results of analysis indicate the capability of time synchronization over intercontinental baselines (~10,000km) to 1-2 nanoseconds.

## INTRODUCTION

By the end of this decade, the operational phase of the Global Positioning System (GPS) will be completed. A constellation of 18 satellites in six orbit planes (Ref. 1) will be dedicated to time keeping, positioning and navigation. The concept of differential GPS for time synchronization between two remote sites was introduced in the early stage of GPS development and has been investigated by several groups of researchers (Refs. 2-4). Time synchronization accurate to about 10 nanoseconds across a 3000-km baseline has been demonstrated using differential GPS (Ref. 4).

The concept of differential GPS is analogous to that of Very Long Baseline Interferometry (VLBI) (Refs. 5,6). That is, the same signal emitted from a distant radio source is simultaneously received at two widely separated sites and later brought together and compared. The difference in arrival times of this signal at the two sites contains information of time offset between the sites as well as the geometrical group delay, propagation delays and instrument delays. Precision time synchronization can be performed provided the positions of the two sites and the distant radio source are accurately known and the propagation and instrument delays properly calibrated. In the case of VLBI the distant radio source is an extragalactic source such as a quasar. To perceive the faint signal of a quasar, large antennas and ultra-low-noise receivers are required. Also, to extract time delay information from the random signal emitted by a quasar, cross-correlation between the signals received at the two sites is essential. This calls for high data rate to maintain a certain usable signal-to-noise ratio. On the other hand, a GPS satellite transmits a much stronger, coded signal. The strong signal allows the use of compact antennas and receivers; the coded signal structure eliminates the need for a cross-correlation process, and a much lower data rate can be used. Hence, differential GPS provides a low-cost vehicle for time synchronization between remote sites and is highly preferred over VLBI approach.

Differential GPS relies on common view of a satellite at the two sites simultaneously. When the two sites are separated by a large distance around the earth, a simultaneous common view of a GPS satellite may not always be available. For instance, with the full constellation of

18 GPS satellites in orbit, a common view between two of the NASA Deep Space sites at Goldstone, California and Canberra, Australia is not available two thirds of the time, as shown in Fig. 1(a). In the remaining one third there is only one satellite in common view and the viewing elevation angles are conceivably low. When the two sites are both at high latitudes (north or south) the situation is not as bad, as shown in Fig. 1(b) for a baseline between Goldstone and another NASA Deep Space site at Madrid, Spain.

The problem of lacking a common view can be alleviated if a trasit site located midway between the two main sites is used. Better still, a low earth orbiter (LEO) can be used as a transit. This paper investigates the use of a ground transit and of a LEO transit in intercontinental time synchronization. The results of a covariance analysis are presented comparing the estimated time synchronization accuracies using the two approaches.

## TIME SYNCHRONIZATION VIA A GROUND-TRANSIT SITE

Fig. 2 describes schematically the use of a ground transit site in intercontinental time synchronization. This transit site is selected to be somewhere midway between the two main sites between which time synchronization is to be performed. Differential GPS pseudo-range measurement is made between this transit site and each of the main sites. A second difference is then taken between these differential GPS measurements. This second difference completely removes whatever clock error at the transit site, thus a precision clock is not needed there. Now there is no need for the two main sites to have a common view of any GPS satellite. These main sites can look at different satellites, as long as these satellites are also in view simultaneously at the transit site. Therefore more satellites can be in view at higher elevation angles. Fig. 3 shows, in chronological order, the number of GPS satellites in common view between a transit site at Johnston Island in central Pacific and either of the two main sites at Goldstone and Canberra. There are 4 to 5 satellites in common view for nearly all the time, as opposed to only one satellite in common view between the two main sites which happens only about one third of the time (cf. Fig. 1(a)). Therefore, a transit site increases the opportunity for intercontinental time synchronization with differential GPS.

However, a ground transit site may not always be conveniently available, especially across the Pacific Ocean. Also, the use of a ground transit site introduces additional station location and tropospheric delay errors. These concerns lead to the concept of using a LEO in place of a ground transit site.

## TIME SYNCHRONIZATION VIA A LOW EARTH ORBITER

Fig. 4 provides a conceptual view of using a LEO in intercontinental time synchronization with differential GPS. Here, the differential GPS pseudo-range measurement between a main site and the LEO is differenced with that between another main site and the same LEO. Hence the LEO plays the same role as a ground transit site as before. However, a LEO is superior to a ground transit site in three ways:

(1) The ground track of a LEO covers a large part of the earth in a short time. Hence, a LEO is capable of providing transit for time synchronization for a world-wide community.

(2) A LEO is above the earth's troposphere and, hence, its inclusion does not introduce additional tropospheric delay error.

(3) The rapidly changing geometry of a LEO provides strong dynamics needed to improve the GPS satellite positions which will in turn improve time synchronization accuracy.

## GEOMETRY AND ERROR MODELS

To predict the accuracy with which times between intercontinental sites can be synchronized using differential GPS, a covariance analysis was performed. For this purpose, the three NASA Deep Space sites were selected as the main sites between which time synchornization was to be performed. A 1300-km LEO at an inclination of 65 degrees was used as a transit. For comparison, the case using a ground transit site was also studied. The ground transit site between Goldstone and Canberra was selected to be at Johnston Island in central Pacific; and that between Goldstone and Madrid was selected to be at the site of Haystack Observatory in Massachusetts. The ground track of the LEO over a period of two hours is shown in Fig. 5 together with the geographical locations of the ground sites. The full constellation of 18 GPS satellites was assumed. The key orbit parameters of these GPS satellites can be found in Reference 1.

Table I summarizes the error models used in the analysis. A data noise of 10 cm was assumed for the GPS pseudo-range measurement. This implies a 14-cm differential GPS (for time synchronization without a transit) and a 20-cm double differential GPS (for time synchronization via a transit). Two sets of errors, optimistic and conservative, for the transit station location, the LEO position and the GPS satellite positions are shown in Table I. When the optimistic errors were used, they were modeled into time synchronization error; when the conservative errors were used, these parameters were adjusted simultaneously with the time synchronization solution.

## RESULTS OF COVARIANCE ANALYSIS

When optimistic GPS satellite position errors are assumed, time synchronization using only instantaneous measurements is possible. Fig. 6 compares the estimated errors of such instantaneous time synchronization using a LEO as transit with those using a ground transit. The instantaneous measurements were taken at a time when the LEO was nearly midway between the two main sites. For the baseline between Goldstone and Canberra, it was at the beginning of the 2-hour arc; for the baseline between Goldstone and Madrid, it was at 25 minutes later. Both optimistic and conservative errors for the LEO and the ground transit positions were studied. In all cases, the errors are lower when a LEO is used in place of a ground transit site.

In practice, the optimistic sub-meter GPS positions are very hard to maintain. The conservative errors of 10 meters may be more realistic. When such conservative GPS satellite position errors are used, time synchronization to a few nanoseconds can be achieved only when these GPS satellite positions are adjusted simultaneously with time synchronization using measurements over a period of time. The results using differentianl GPS over a 2-hour arc are shown in Fig. 7. Also included is the case when no transit was used. While a suitably located ground transit improves time synchronization using differential GPS by 30-40%, a LEO provides an improvement by a factor of 5 to 6. Such vast improvement is a result of the strong dynamics of the LEO which can better determine the GPS satellite positions. With such a LEO, time synchronization is accurate to about 1.5 nsec between intercontinental sites.

A breakdown of the 1.5-nsec time synchronization error into its component contributions from individual error sources is shown in Fig. 8. Because the GPS and LEO positions were adjusted, the effects of their a priori errors were buried in the data noise effects. To separate them from one another, the covariance analysis was repeated with perfect GPS and/or LEO a priori positions.

The major error sources are seen to be the 10-cm tropospheric delay error and the 10-m a priori errors of the GPS satellite positions. Sub-nanosecond time synchronization is possible if these errors are reduced by a factor of 2 to 3. It should be pointed out that an increase in the data noise will also increase the effects of satellite position errors because these satellite positions, being adjusted using the same data set, will be worse determined.

The larger effects of the earth's mass and geopotential errors on time synchronization over one of the two baselines can be explained as follows: The information for time synchronization is strongest when the ground track of the LEO falls between the two ends of the baseline. Referring to Fig. 5, we observe that the information over the baseline between Goldstone and Canberra concentrates mainly at two separate segments near the two ends of the 2-hour data arc. However, it is well known that the effects of unmodeled force parameters on the orbit determination of a LEO are also largest at the two ends of a data arc. This larger LEO orbit error in turn results in larger time synchronization error. For the baseline between Goldstone and Madrid, the information concentrates mainly in a single short segment within the 2-hour data arc and the effects of these unmodeled force parameters are expected to be much smaller. Therefore, the effects of these unmodeled force paremeters can be kept small by selecting the proper data arc. The larger errors on the baseline between Goldstone and Canberra is simply an artifact.

## REMARKS

A LEO at an altitude of 1000-1500 km is capable of improving intercontinental time synchronization using differential GPS to 1-2 nsec. Time synchronization using an earth orbiter much lower than these altitudes will suffer from larger geopotential and atmospheric drag errors. On the other hand, time synchronization using a much higher earth orbiter will be more sensitive to GPS satellite position errors. Using a LEO as transit, sub-nanosecond time synchronization between intercontinental sites is possible provided that 3-cm zenith tropospheric delay calibration and 5-m GPS satellite positions are available.

Due to a complete cancellation of its effects, the clock on board the LEO need not be of high precision. Also, because no GPS clock information is used in differential GPS, a simple SERIES receiver (Ref. 7) can be used at all sites including the LEO. Such a receiver extracts GPS pseudo-range without having to know the GPS transmitted codes. However, an independent knowledge of time synchronization better than half a microsecond is required to resolve the cycle ambiguity corresponding to the 1-MHz chip rate of the C/A code modulating the GPS transmitted signal.

The proposed Ocean Topography Experiment (TOPEX), if approved and funded which is very likely, will begin its mission in the later part of this decade. A LEO will be put in a circular orbit at an altitude of 1300 km. An experimental GPS receiver will be placed on board this LEO for testing out a newly developed radio metric tracking technology (Ref. 8). This will provide an opportunity for experimenting the time synchronization system proposed in this paper. The differential GPS data needed for time synchronization can be derived from the tracking data of TOPEX satellite. As a matter of fact, the 1300-km LEO used in the above analysis has been adopted from TOPEX with its possible capability of providing precision global time synchronization in mind.

References:

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TABLE I. Error Models

| | |
|---|---|
| Data Noise: | 10 cm GPS pseudo-range |
| Main Site Locations: | 10 cm |
| Ground Transit Location: | 50 cm --- optimistic |
| | 5 m --- conservative |
| GPS Satellite Positions*: | (0.4m, 0.4m, 0.8m) optimistic |
| | (3m, 10m, 10m) conservative |
| LEO Position*: | (10cm, 15cm, 30cm) optimistic |
| | (5m, 5m, 5m) conservative |
| Zenith Tropospheric Delay: | 10 cm |
| Mass of Earth: | 1 part in $10^7$ |
| Geopotential (on LEO only): | 10% of GEM 6 - APL 5.0 |

* The three components of satellite position errors are in altitude, cross-track and in-track directions, respectively.

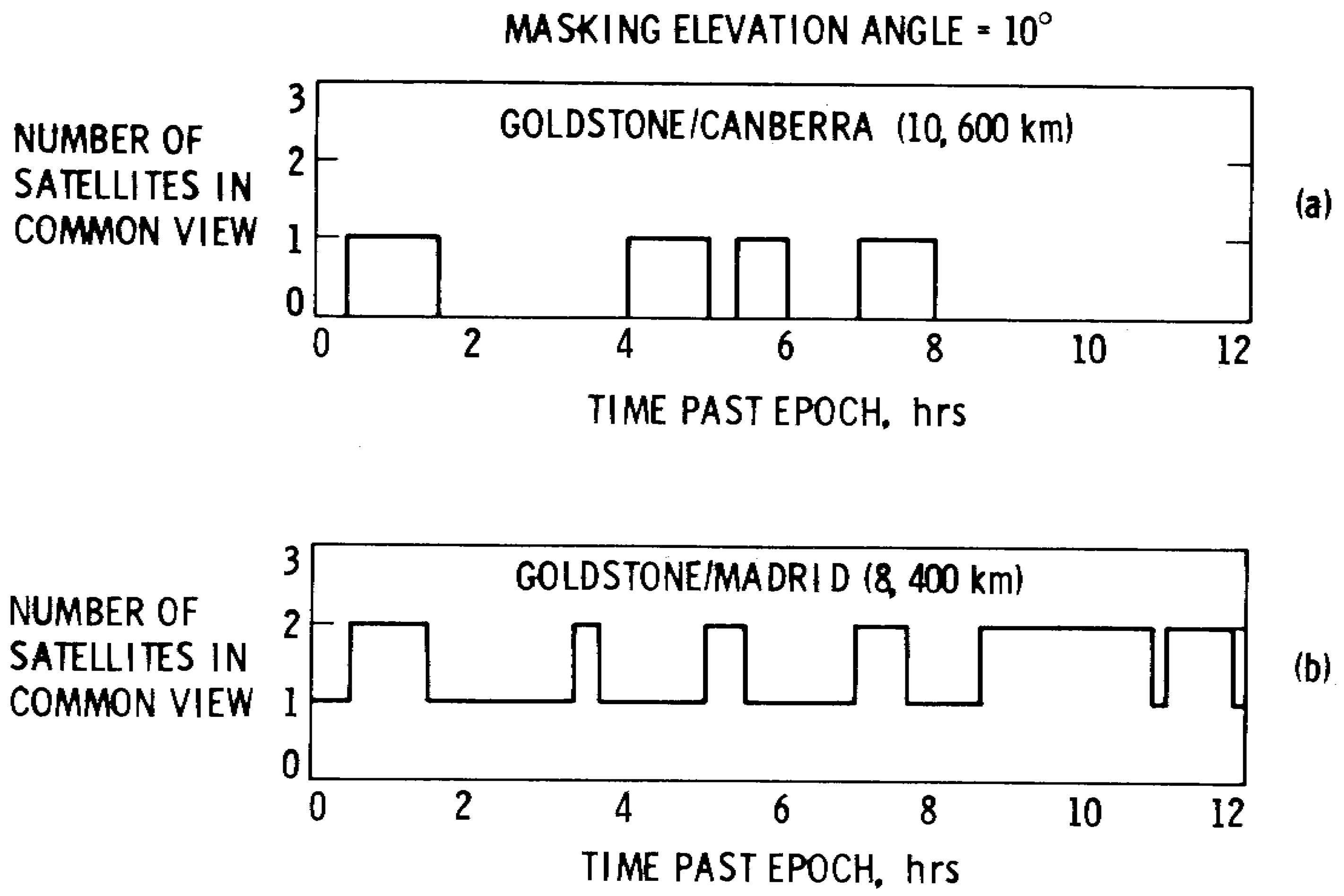

Figure 1. Number of GPS Satellites In Common View Between Remote Sites

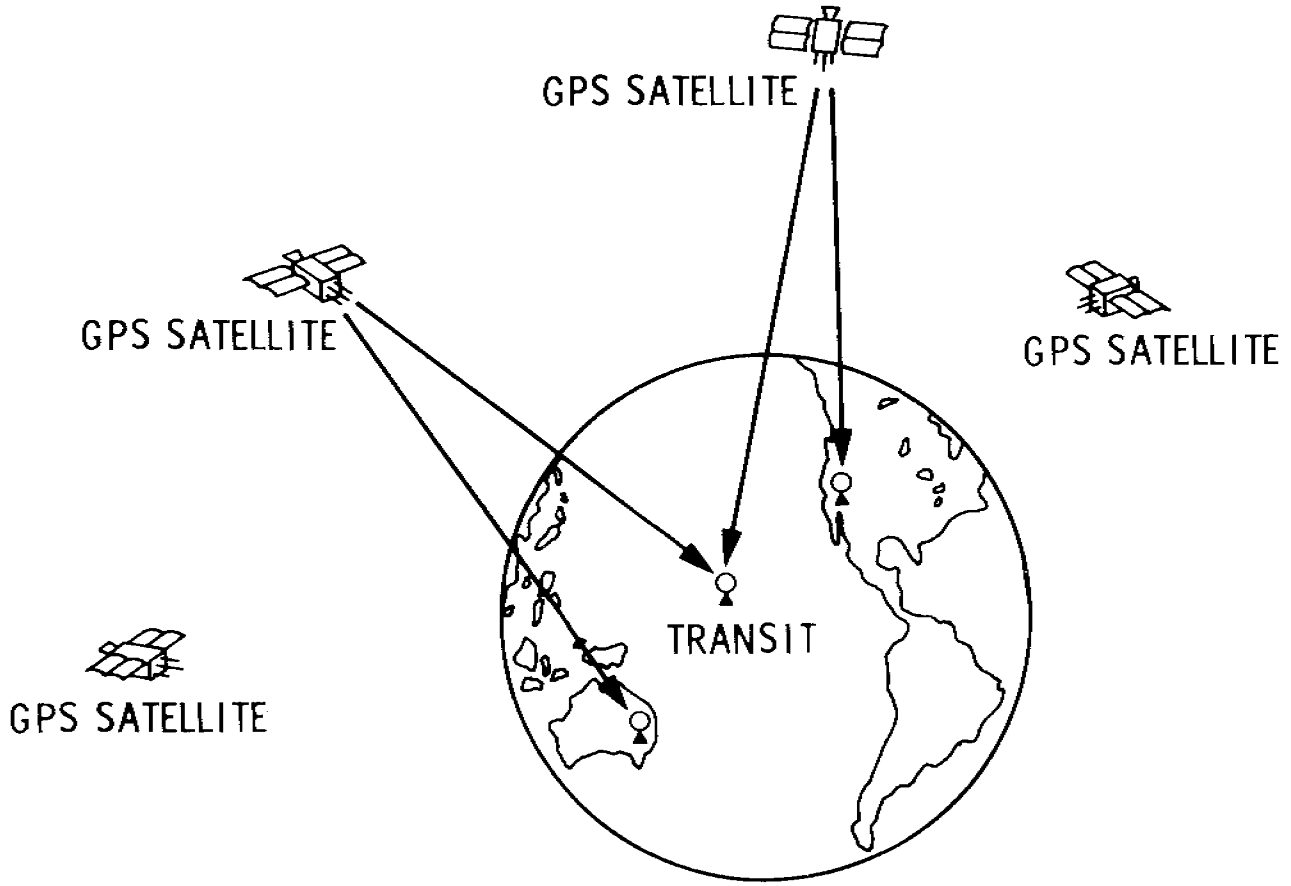

Figure 2. GPS Intercontinental Time Synchronization Via A Transit Station

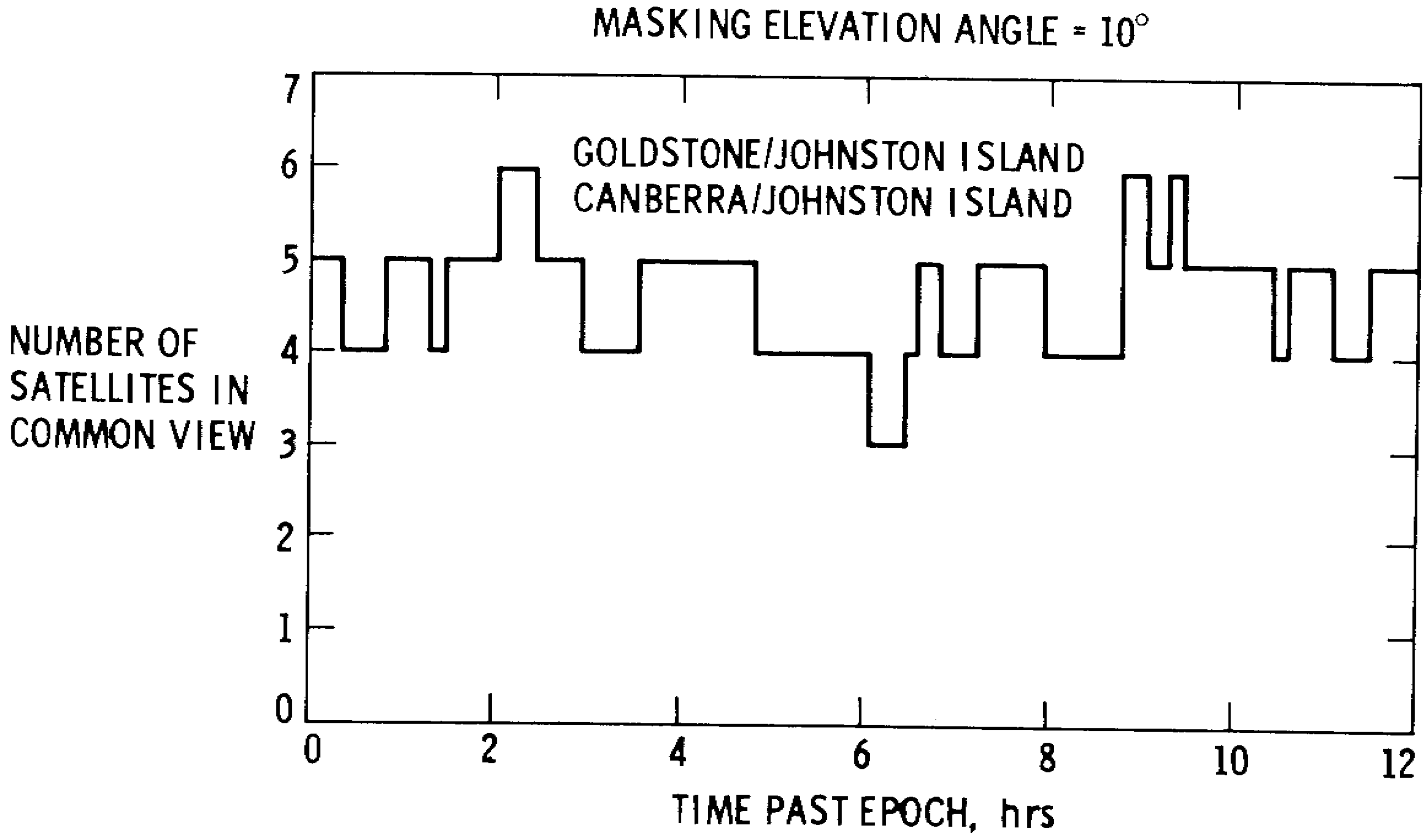

Figure 3. Number of GPS Satellites In Common View Between A Transit Site and One of The Main Sites

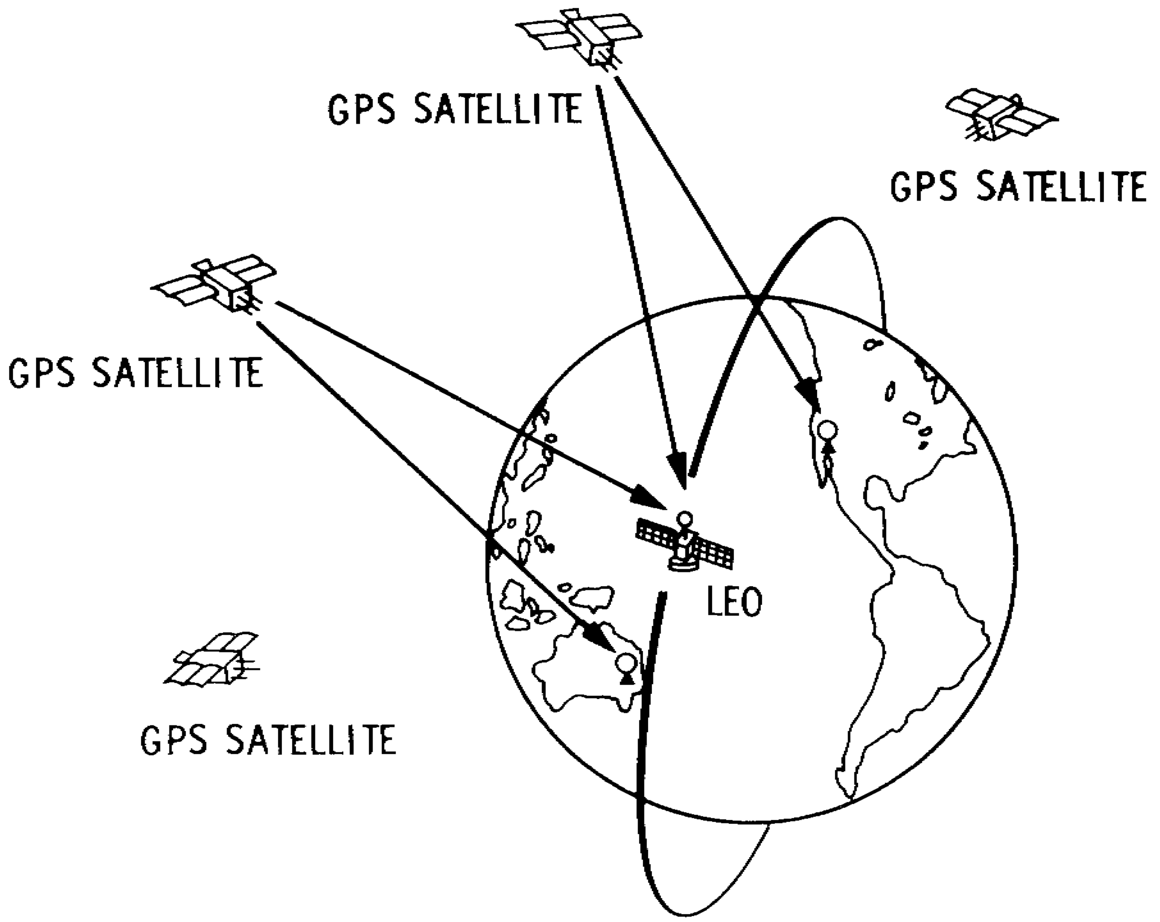

Figure 4. GPS Intercontinental Time Synchronization Via A Low Earth Orbiter

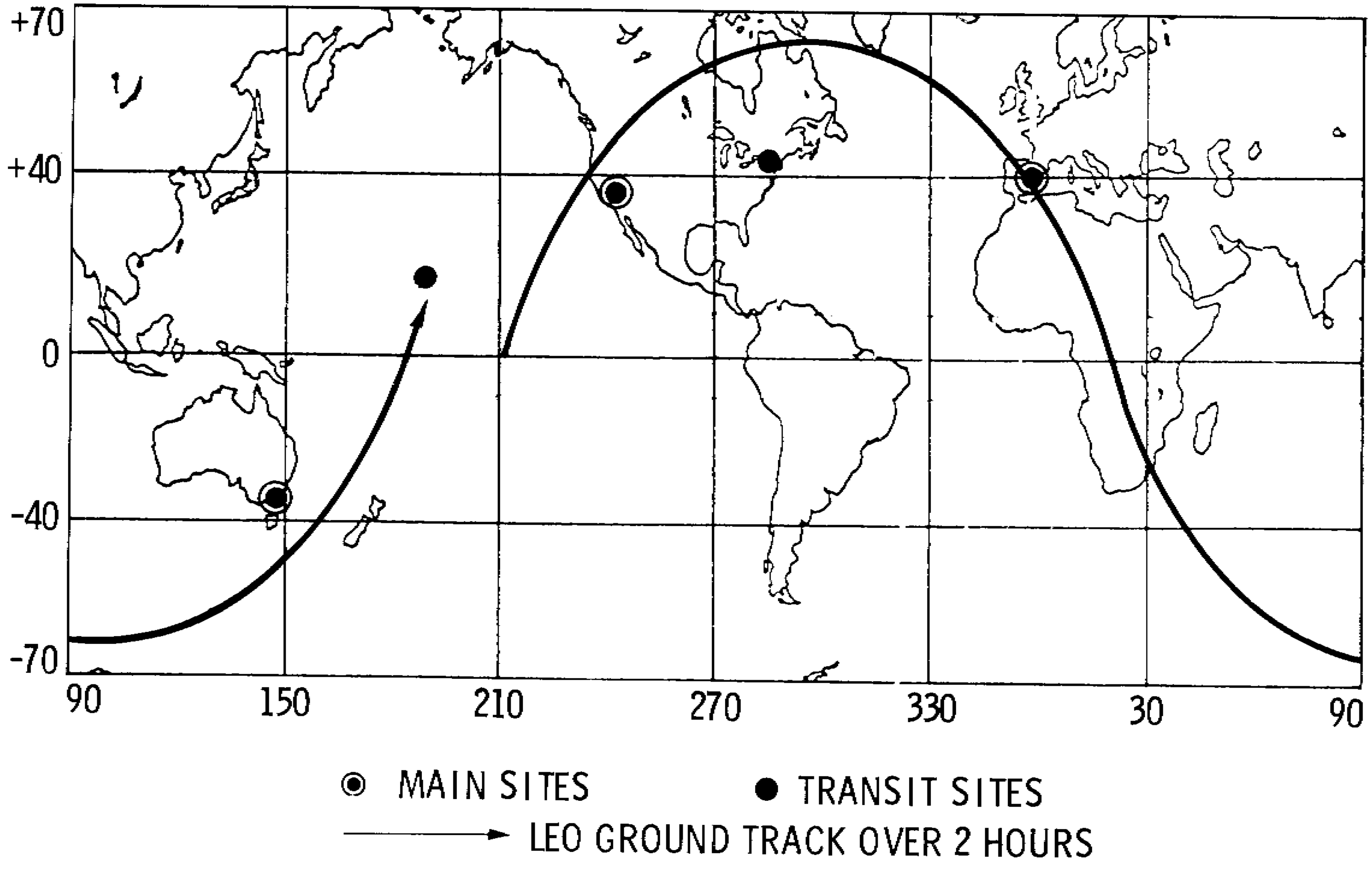

Figure 5. Geometry of The Problem

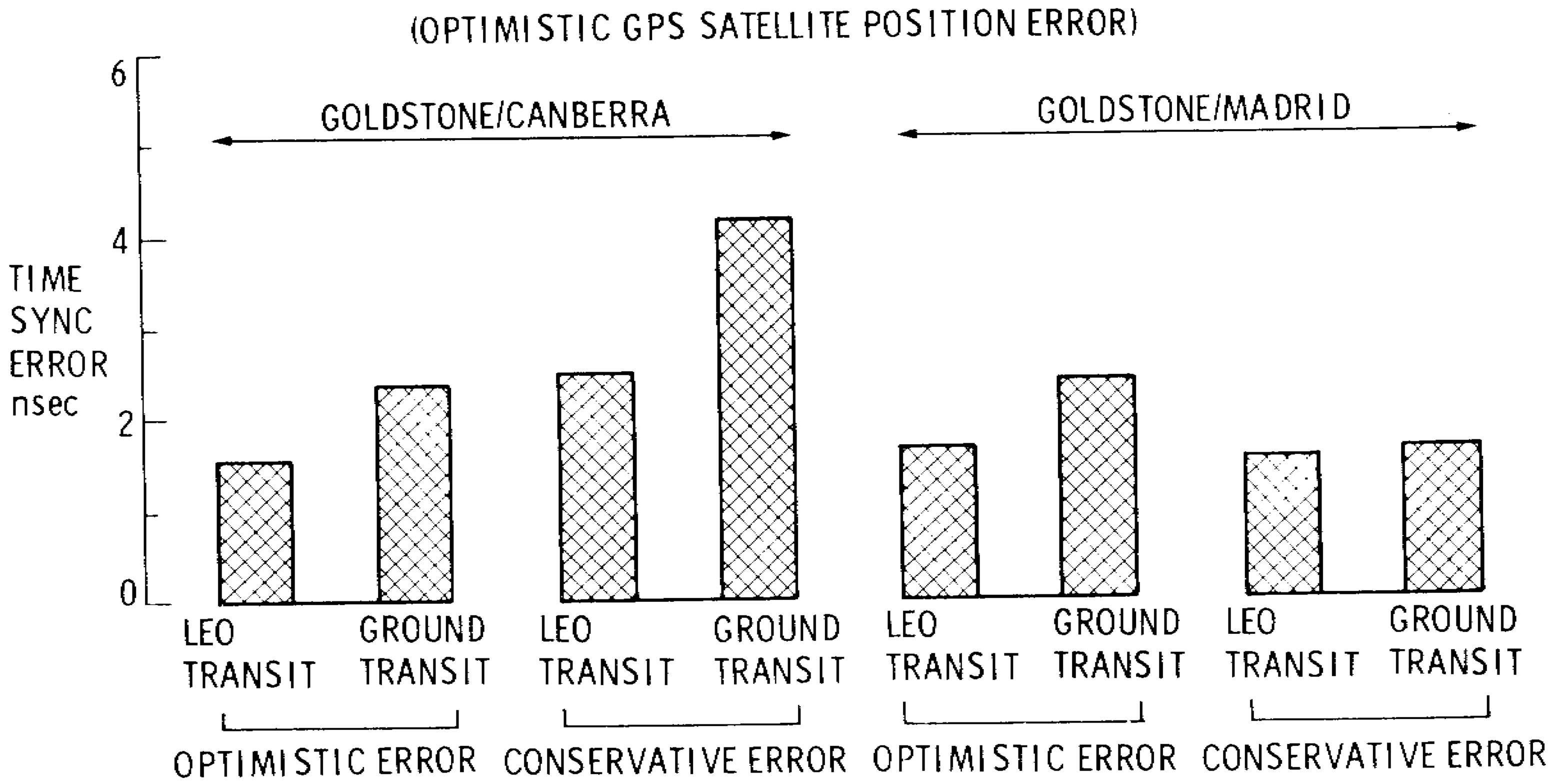

Figure 6. Estimated Time Synchronization Error Using Instantaneous Differential GPS Pseudo-Range

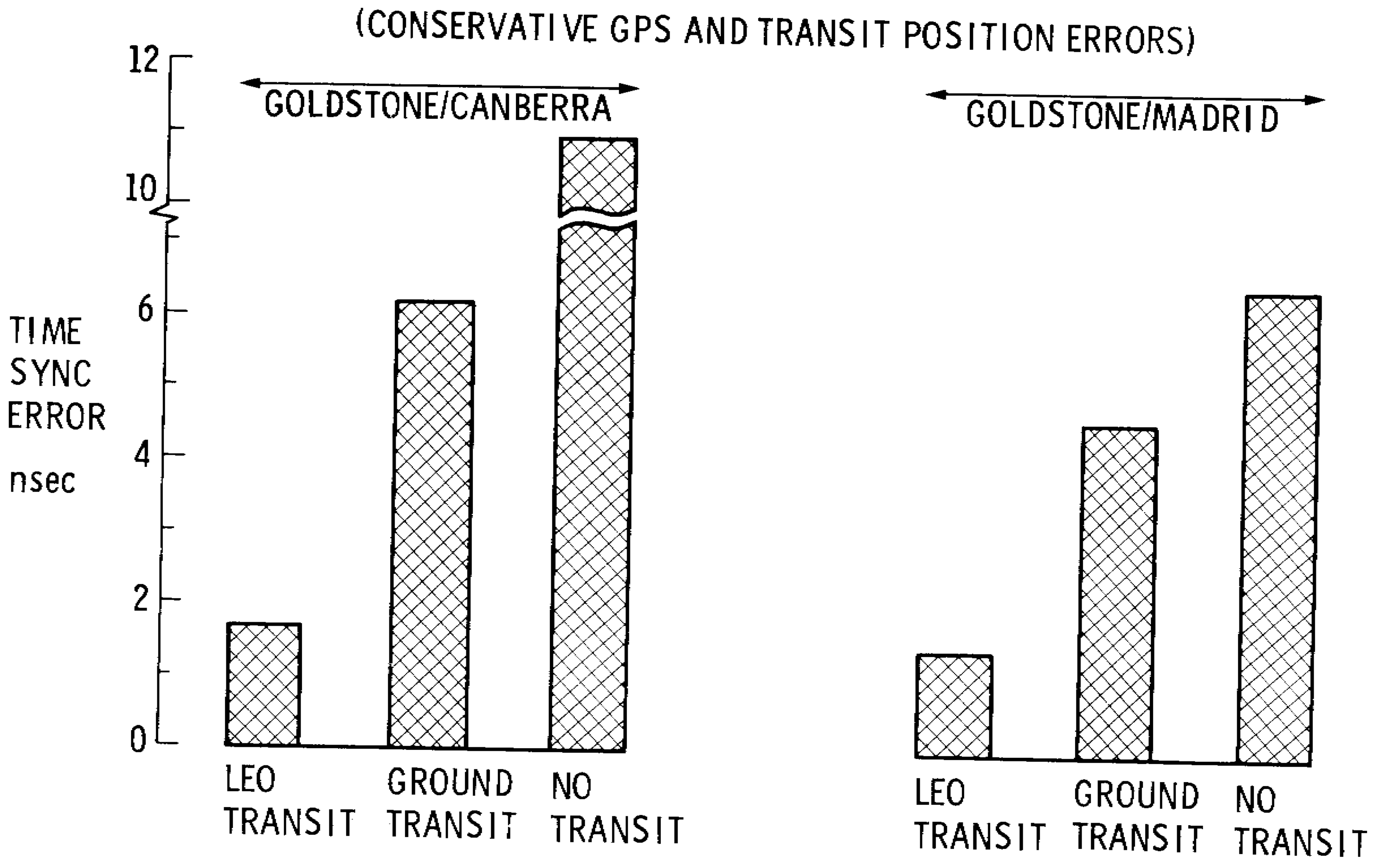

Figure 7. Estimated Time Synchronization Error Using Differential GPS Pseudo-Range Over 2 Hours

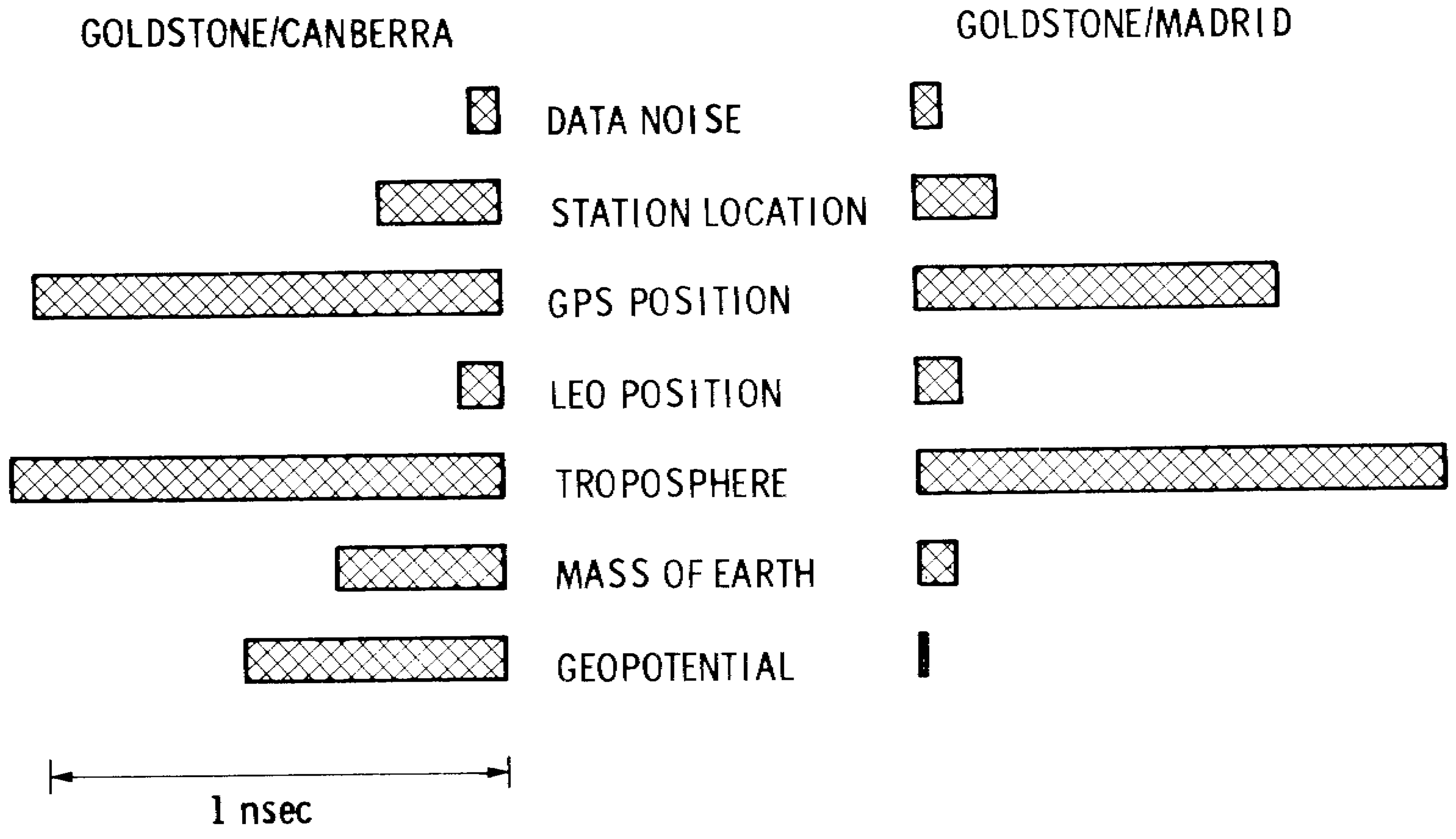

Figure 8. Breakdowns of Time Synchronization Errors

# QUESTIONS AND ANSWERS

DR. VESSOT:

Bob Vessot, Smithsonian. At what level do you need tracking data for the low earth orbiter?

MR. WU:

Would you make it more specific?

DR. VESSOT:

Well, at what level of precision was tracking data needed for the low earth orbiter.

MR. WU:

Oh, for tracking the low earth orbiter it can be either a short arc which is about one centimeter, for the pseudo range, or you can do a long arc solution, which can be twenty centimeters, or you can use integrated doppler.

MR. ALLAN:

When is the low earth orbiter planned to be launched?

MR. WU:

The proposed Topex will be launched in February '89.