A SPACE SYSTEM FOR HIGH-ACCURACY GLOBAL TIME AND FREQUENCY COMPARISON OF CLOCKS

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ABSTRACT

NASA is planning a Space Shuttle experiment to demonstrate high-accuracy global time and frequency transfer. A hydrogen maser clock on board the Space Shuttle will be compared with clocks on the ground using two-way microwave and short-pulse laser signals. The accuracy goal for the experiment is 1 nsec or better for the time transfer and 10^{-14} for the frequency comparison. A direct frequency comparison of primary standards at the 10^{-14} accuracy level is a unique feature of the proposed system. Both time and frequency transfer will be accomplished by microwave transmission, while the laser signals provide calibration of the system as well as sub-nanosecond time transfer. Following the demonstration with the Space Shuttle, an operational system could be implemented in a free-flying satellite to provide permanent global time and frequency transfer.

Introduction

Plans for a spaceborne system to meet the needs for global, high-accuracy time and frequency transfer are being studied by NASA's Office of Space and Terrestrial Applications, Geodynamics Branch. The system uses a hydrogen maser clock on board a space vehicle which will be compared with clocks on the ground by one-way and two-way transmission of CW and time-code modulated microwave signals. In addition, short-pulse laser signals will be transmitted simultaneously with the microwave signals for calibration of the system and for time transfer. The unique feature of the proposed system is its capability to make direct frequency comparison of primary standards at the 10^{-14} accuracy level. No other technique or experiment in existence or planned has this capability with coverage over most of the inhabited globe. In addition, the proposed system is expected to provide time transfer with an accuracy of 1 nsec or better.

The techniques to be employed have been used successfully in earlier experiments. The microwave portion of the system is similar to a system used with the Gravitational Redshift Probe (GP-A) flown in 1976 [1]. The short-pulse laser technique was successfully used in airborne clock experiments in 1975 which measured general relativistic effects on time [2]. Because of this experience with previous experiments, basic new technology development is not required for the Shuttle experiment.

The first step of the proposed program will be a demonstration experiment using the Space Shuttle. Following a successful demonstration, the system could be implemented with a free-flying satellite or on a space platform to provide permanent, global high-accuracy time and frequency transfer. The following discussion deals primarily with the concept of the Shuttle demonstration experiment which is the subject of a definition study in progress at Marshall Space Flight Center. The first flight is planned for 1985, pending approval of the project. Ideas similar to the concept discussed in this paper have been proposed earlier [3].

Overall Objectives

The purpose of the Shuttle experiment is to demonstrate and evaluate the techniques for a later operational global system. A variety of users would benefit from an operational system providing time transfer with accuracies of 1 nsec or better and frequency comparison with an accuracy of 10^{-14}. Potential user groups include primary standard laboratories, high-accuracy timing operations such as the computation of TAI and coordination of major BIH contributors, NASA's Deep Space Network (DSN), and various other users of precision time, e.g., radio astronomy and geodynamics research.

The stability and accuracy of precision clocks and primary frequency standards have improved far beyond present capabilities to transfer time and frequency information between widely separated standards. Further improvements in the stability and accuracy of primary standards can be expected in coming years which will result in increased requirements for high-accuracy time and frequency transfer. The most accurate time transfer method now in use is the transportable clock. This method has many logistic problems and is very expensive if high accuracies are required. The latter problem is illustrated by Figure 1, which shows estimated yearly cost for synchronization of one remote station as a function of accuracy. The operational cost becomes prohibitive if high accuracy is required. The proposed space system using an orbiting hydrogen maser clock can be viewed as an extension of the transportable clock method, providing accurate time and frequency transfer at frequent intervals with worldwide coverage and at a much lower cost for the individual user.

The current operational mode to compare primary standards in the U.S. (NBS), Canada (NRC), and West Germany (PTB) utilizes Loran C, which suffers from limited global coverage and fluctuations of the ground wave propagation delay, making the system practically incompatible with requirements of high-precision standard laboratories and time services. Other laboratories are interested in the accuracy capabilities of primary frequency standards, either directly or indirectly, but adequate means for international frequency comparison do not exist at the state-of-the-art accuracy. Other techniques of accurate time transfer have been tested experimentally or are planned for implementation in the future. A performance comparison of available and planned methods, including the proposed Shuttle experiment (Shuttle Time and Frequency Transfer Experiment, STIFT) is shown in Table 1. The following definitions apply to the table. Inaccuracy is expressed relative to a perfect portable clock. Stability is the measure of time variations over the course of the measurement (i.e., related to the phase stability of the measurement system with sampling intervals and length of data determined by the method). Cost-effectiveness is the product of inaccuracy and user cost dollars (in mega dollars), the smaller the number the better. The 24-hour frequency accuracy is derived from time stability over 24 hours which determines the accuracy of absolute remote frequency comparison. Though many of the numbers represent anticipated performance, it is believed they are within a factor of two of what will be accomplished. (Where applicable the figures in the table are rms values.) As can be seen, the STIFT experiment looks extremely attractive when compared with other techniques.

Concept of the Shuttle Experiment

The idea of the Shuttle demonstration experiment is illustrated in Figure 2. The experiment package which is mounted on a pallet in the Shuttle bay contains the hydrogen maser clock, a microwave transponder with antenna, a corner reflector array, a photodetector, an event timer, and some associated electronics. Three microwave links are transmitted between a space vehicle and a ground terminal which permits cancellation of the first-order Doppler effect and correction for ionospheric delay. Frequency comparison is accomplished by using the CW carrier frequencies. A time code modulation is applied for the time transfer function. An important feature of the proposed experiment is that the microwave system provides time and frequency transfer independent of weather conditions and that a laser system is used for calibration, providing information about time delays in the propagation path and instrumentation. In addition, the laser portion of the experiment is available for time transfer with sub-nanosecond accuracy. Short laser pulses are transmitted from the ground station to the Shuttle and returned by the corner reflector. The arrival time of the laser pulse at the Shuttle is measured by the photodetector and event timer and is recorded in the time frame defined by the on-board hydrogen maser clock. The simultaneous transmission of laser and microwave signals should yield valuable and interesting high-accuracy data about wave propagation and related effects.

Planned Shuttle orbits have a rather low altitude (~200 n mi) which limits the time available for clock comparison during a pass over a ground station to several minutes. Otherwise, the Shuttle is rather ideal for a demonstration experiment because it provides very generous volume, weight, and power limits for the experiment package as well as return of the flight hardware with the option of reflight at minimum cost. High-inclination orbits up to 57^o are planned for several Shuttle missions which give sufficient global coverage for the demonstration experiment, including all of the primary standard laboratories and many other important stations. While the Shuttle orbits are adequate to demonstrate the performance of the system, a higher orbit would be adopted for an operational time and frequency transfer satellite.

Microwave System

The key to the direct frequency comparison technique is elimination of the first-order Doppler shift. This method was successfully used with the Gravitational Probe A (GP-A) in 1976, a joint project of Smithsonian Astrophysical Observatory and Marshall Space Flight Center [1]. During this mission the frequencies of two hydrogen masers, one on the ground and one in the space probe, were compared to measure the gravitational redshift effect. For 100 sec averaging intervals, the frequency comparison was accurate to 1×10^{-14}, which was at the stability limit of the space probe maser. This mission demonstrated the capability to eliminate first-order Doppler shifts and ionospheric propagation fluctuations to achieve direct frequency comparison with an accuracy of 1×10^{-14}. Since 1976, further improvements of the hydrogen maser stability have been achieved which make 10^{-14} a safe accuracy goal for the Shuttle experiment [4].

A stability comparison of various techniques and standards including the 1976 system and the new hydrogen maser (1979) is given in Figure 3. To achieve the desired accuracy requires corrections for relativistic effects, including the second-order

Doppler shift and the gravitational redshift effect. These corrections will be calculated from orbital data of the space vehicle. Figure 3 also illustrates the relationship of time transfer accuracy and frequency stability for measurements spaced by τ seconds. The two dotted lines represent a microwave pulse system (0.6 nsec precision) and a laser pulse system (0.1 nsec precision). If time comparisons are made at 24-hour intervals (10^5 sec), a time transfer accuracy of 0.6 nsec or better is needed to compare frequencies at the 10^{-14} level.

A functional diagram of the microwave system is shown in Figure 4. Three S-band microwave frequencies are transmitted, providing one-way and two-way Doppler information in the ground station. The first-order Doppler effect is cancelled by subtracting one-half of the two-way shift from the clock down-link signal. This process also eliminates propagation effects in the ionosphere for temporal variations longer than the propagation time. The three frequencies have to be selected carefully to compensate for ionospheric dispersion. (Frequencies shown in the diagram are those used with GP-A.) A single antenna is used on the spacecraft and in the ground station to handle the three frequencies. The frequency comparison information generated in the ground terminal is contained in the beat signal of the two clock frequencies which is obtained after removal of the Doppler shift.

The frequency comparison method utilizes the phase information of the CW phase coherent carrier signals. To accomplish time transfer a PRN phase modulation is applied. The round-trip propagation delay (2R/c) is determined by a correlation technique applied to the two-way signals (Figure 5). The time shift between space clock and ground clock is determined from the displacement of the two corresponding time codes. The space clock time code is modulated on the clock down-link carrier. The correction for the one-way propagation delay is obtained from the two-way signal correlation process. One important objective of the proposed program is the development of a low-cost microwave ground terminal which can be afforded by a large number of users of a later operational system. The Shuttle experiment will use S-band frequencies. (The optimum frequency for an operational system is the subject of further studies.) Participation in the STIFT experiment requires a microwave ground terminal. It is anticipated that several ground terminals will be in operation for the demonstration flight(s). Most of these terminals should be located at the site of primary standard laboratories and time service operations.

Laser System

The short-pulse technique is presently the most accurate method of time transfer. This technique has been used by the University of Maryland with support from the U. S. Navy in comparing airborne clocks with clocks on the ground to measure general relativity effects with sub-nanosecond accuracy [2]. The uncertainty in the clock comparison was only a few tenths of nanoseconds. A disadvantage of the laser technique for an operational system is its dependence on weather. In the proposed time and frequency transfer system the short-pulse laser method is used primarily for calibration and performance comparison. However, the laser portion of the experiment can be used independently for time transfer experiments. Any laser ground station equipped with a stable clock and means to record epochs (event timer) can perform time transfer experiments. The Shuttle experiment will utilize existing laser ground stations.

A block diagram of the laser system, including on-board and ground station systems, is shown in Figure 6. A corner reflector array is used to return the laser signal to the ground station. Simultaneously the laser pulse is received by a fast photodetector in the Space Shuttle. The event timer measures the arrival time t_2 of the laser pulse in the time scale established by the on-board hydrogen maser clock. This information is sent by telemetry to the ground station for comparison of the space and ground clock epochs. The epochs of transmission and return of the laser pulse, t_1 and t_3, respectively, are recorded at the ground station. Clock synchronization is accomplished by comparing t_2 (measured at the space vehicle) with the midpoint between t_1 and t_3, including a small correction for earth rotation. Figure 7 shows the result of the 1976 short pulse laser experiments. The uncertainties of individual clock comparisons are only a few tenths of nsec. Neither the relative velocity between space vehicle and ground station nor the distance separating them enters into the comparison.

Conclusion

The proposed concept using a hydrogen maser in a space vehicle is expected to meet the future need for global high-accuracy time and frequency transfer. It has a number of advantages compared to other techniques, including high accuracy, direct frequency comparison, weather independence, global coverage (for operational system), and comparatively low cost for the user. Only a single station is needed to accomplish time and frequency transfer, namely the station which wants to synchronize its clock or compare its frequency standard. The microwave ground terminal can be located in close proximity to the standard. In addition, the laser portion of the experiment makes time transfer available with accuracies in the sub-nanosecond region.

References

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3. TEMPUS, A proposal for an international time transfer and precision tracking satellite, D. C. Holmes, Proceedings of the Tenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, November 1978, Goddard Space Flight Center.

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TABLE 1. INTERNATIONAL TIME TRANSFER COMPARISON (<< 1 μs)

Method	Inaccuracy	Stability	Cost-Effectiveness (M$·ns)	24-Hour Frequency Accuracy	Coverage	When Available
GPS (Common-view)	10 ns	1 ns	0.25	$\lesssim 10^{-13}$	Global	1981
Shuttle (STIFT)	1 ns	0.001 ns*	0.25	$\lesssim 10^{-14}$	To ± 57° Latitude	1985
TDRSS	10 ns	1 ns	1.0	$< 10^{-13}$	All but India Longtudes	1982
LASSO	1 ns	0.1 ns	1.0	$\sim 10^{-14}$	All but near the poles	1981
GPS	40 ns**	10 ns	2.0	$\sim 3\text{x}10^{-13}$	Global	1980
2-Way (Communication Satellite)	50 ns	$\lesssim$ 1 ns	5.0***	$\sim 10^{-13}$	All but near the poles	1980
Portable Clock	100 ns	N/A	6.0	$\lesssim 10^{-12}$	Global (Best accuracy within reasonable driving vicinity of Air Ports)	1980
Loran-C	500 ns	$\lesssim$ 40 ns	3.0	$\lesssim 10^{-12}$	Excludes Most of Asia and Southern Hemisphere	1980

*This figure represents the time stability of the microwave Doppler cancellation system (1).

**This inaccuracy may incrase if the GPS C/A code is deteriorated for strategic reasons.

***Cost includes estimate of annual rental.

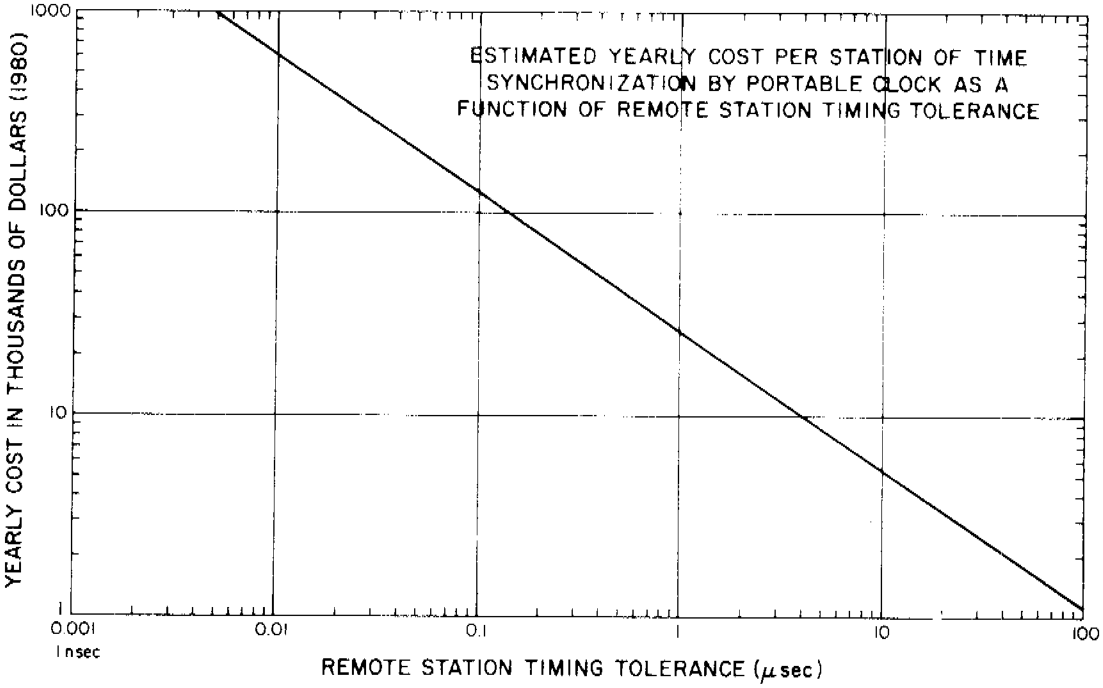

Figure 1. Cost of portable clock method.

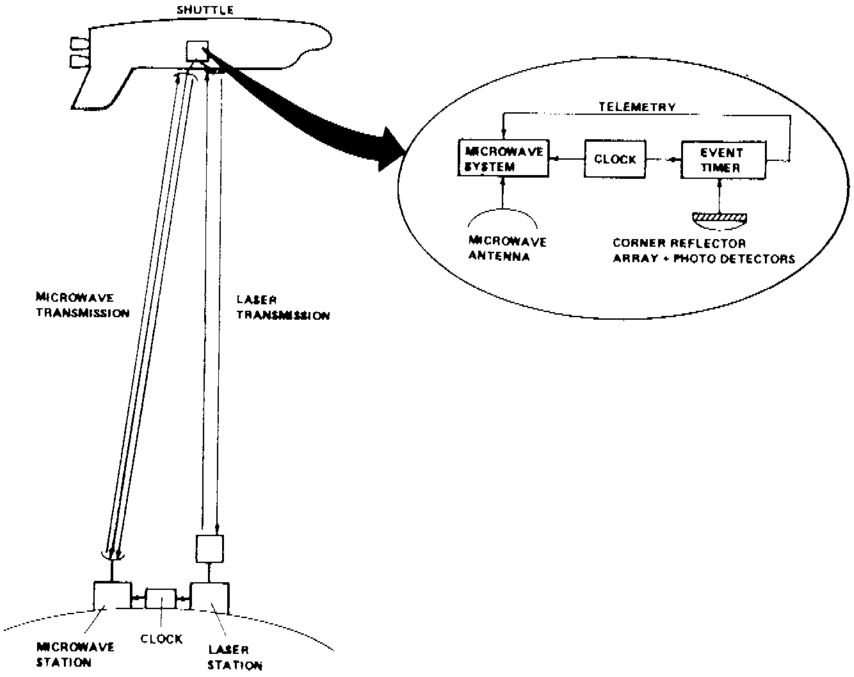

Figure 2. Shuttle time and frequency transfer experiment.

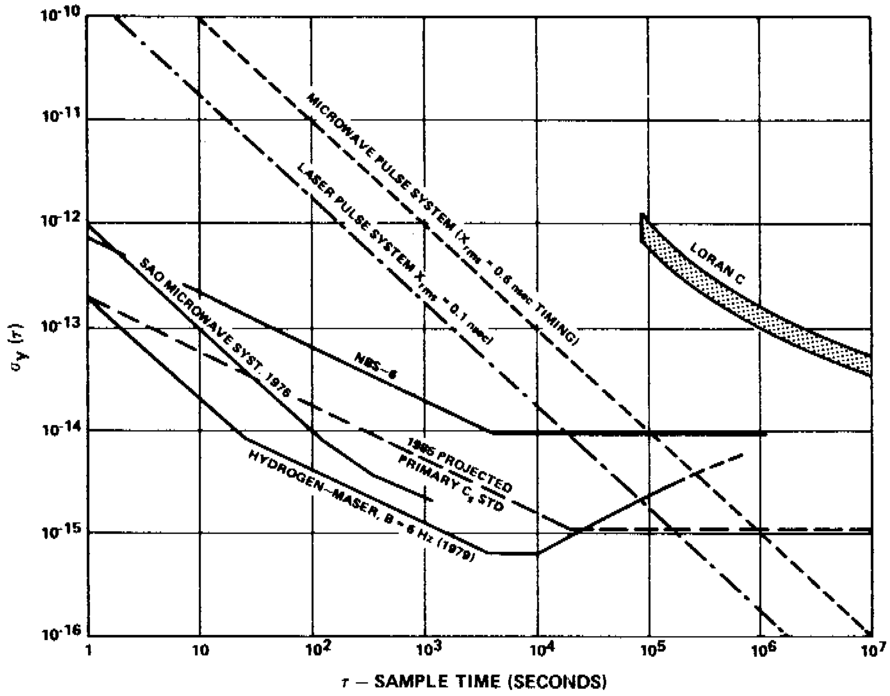

Figure 3. Stability comparison.

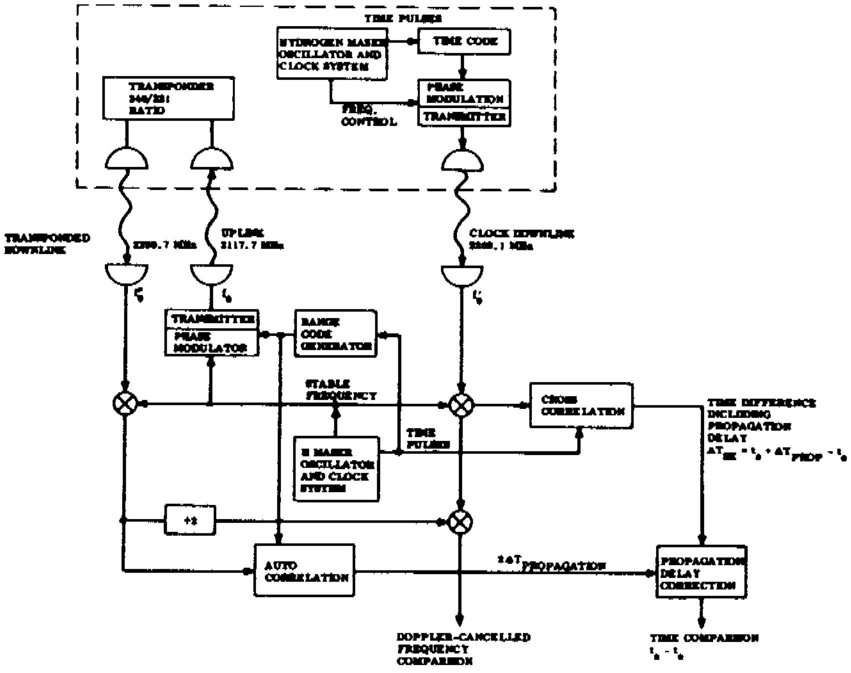

Figure 4. Microwave system block diagram.

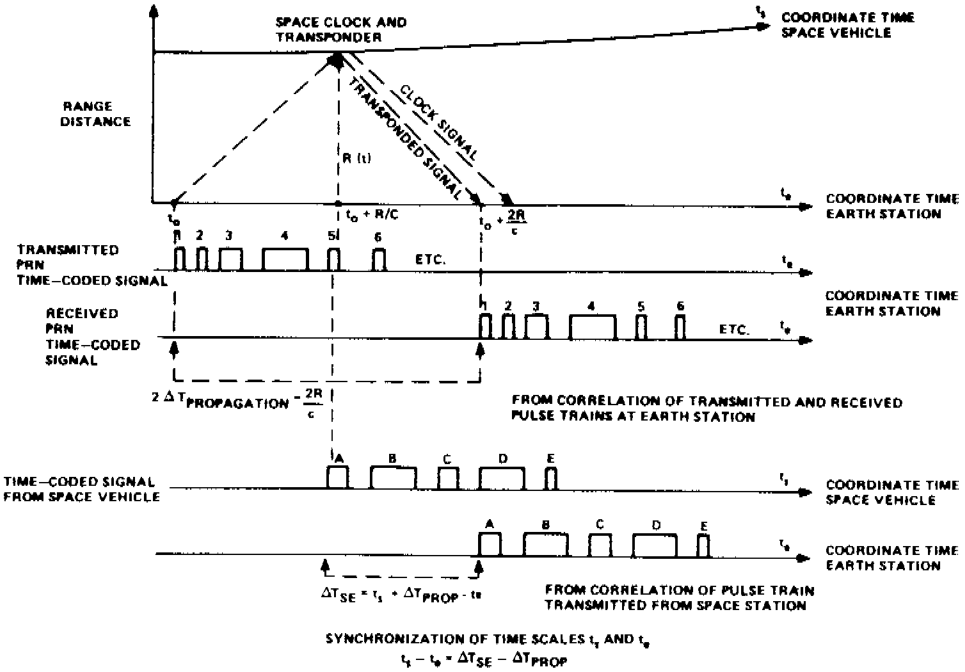

Figure 5. Microwave time transfer scheme.

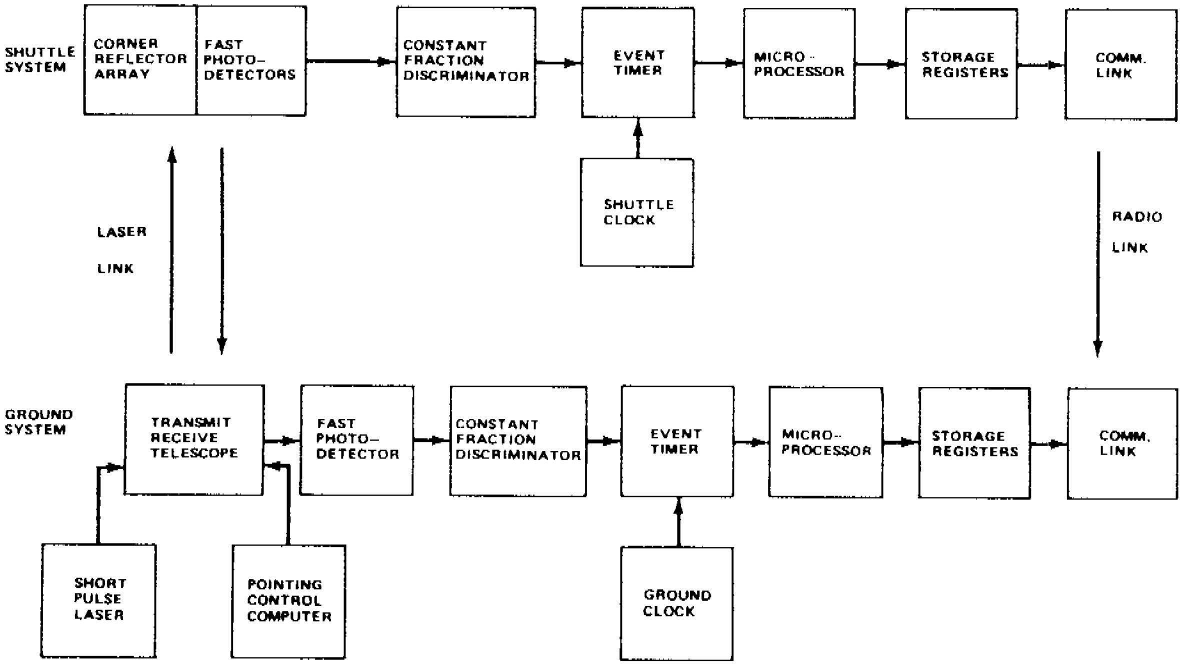

Figure 6. Laser system block diagram.

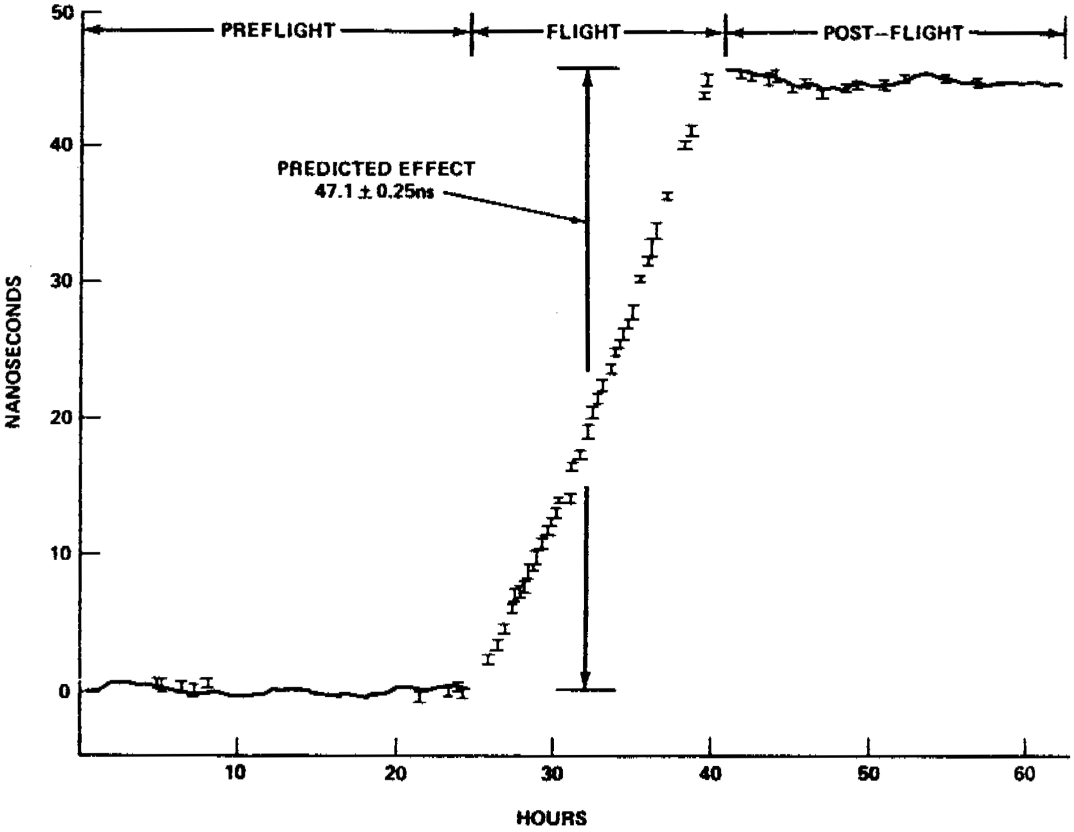

Figure 7. Results of airborne clock comparison experiments.

QUESTIONS AND ANSWERS

CAPTAIN VOHDEN:

I would like to know what the time line would be for this system becoming operational. You say the first flight would be 1985. How long after that would you envision the system being available for general usage?

DR. DECHER:

That is very difficult to answer at the present time. I think we will have several shuttle flights and then a normal lead time of such a program probably is at least two to three years.

MR. BANERJEE:

Does this experiment you have mentioned that you are expecting to do at the Maryland University provide the first calibration of the instrument that will be the elimination of the delay of that order?

DR. DECHER:

You question the accuracy of the system? Is this what you are saying?

MR. BANERJEE:

Yes.

DR. DECHER:

Well, both techniques, the laser and the microwave systems, have been demonstrated in those early experiments, and so I think we are also safe to propose this type of accuracy.

DR. ALLEY:

I would just add the comment that the limiting uncertainty of the early proposed low-altitude flight may be in the ability to measure the velocity of the spacecraft sufficiently well to include the relativistic corrections adequately.

DR. DECHER:

Yes, that is true if you want to achieve the accuracy of 10^{-14}, you have to include relativistic affects, the second-order Doppler Effect and the gravitational affect which you have to get out of the trajectory of the space vehicle. This will be no problem for a satellite system, but for the shuttle will need some doing.