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A Review of Satellite Time Transfer Technology – Accomplishments and Future Applications

Robert S. Cooper and Andrew R. Chi

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Goddard Space Flight Center
Greenbelt, Maryland 20771

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ABSTRACT

A brief review of the research accomplishments by NASA in meeting the needs of the space program for precise time in satellite tracking will be presented. As a major user of precise time signals for clock synchronization of NASA's worldwide satellite tracking networks, the agency provided much of the necessary impetus for the development of stable frequency sources and time synchronization technology. The precision time required for both satellite tracking and space science experiments has increased at a rate of about one order of magnitude per decade from 1 millisecond in the 1950's to 100 microseconds during the Apollo era in the 1960's to 10 microseconds in the 1970's. As we enter into the 1980's, when the Tracking and Data Relay Satellite System (TDRSS) comes into operation, satellite timing requirements will be extended to 1 microsecond and below. These requirements are needed for spacecraft autonomy and data packeting which are now in active planning stages.

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INTRODUCTION

Since the successful development of various atomic resonance devices, [Ramsey 1957, Essen et al. 1957, Markowitz et al. 1958, Goldenberg et al. 1960, Ramsey 1962] we have witnessed a dramatic improvement in the generation, measurement, and dissemination of frequency and time. In the 1950's we could achieve at best an accuracy of time dissemination of 1 millisecond on a worldwide basis. Now we are developing concepts capable of nanoseconds and even picoseconds in the future. What is the impetus? That is, what are the requirements and what technologies are available to us? The answers to these questions are of interest to many of us.

In the late 1950's terrestrial transmitted time signals were limited, then as today, by our inability to predict the propagation time delay through the atmosphere and the ionosphere [Lawrence et al. 1964]. Various techniques and carrier frequencies were tried. Among them was the pulse rate technique modulated on carrier frequencies in HF and VLF bands. The received signal phase of a VLF signal was found to be very stable [Pierce 1953] and offered the best potential for time dissemination over long distances. Although there is a diurnal phase change from nighttime to daytime paths, this deficiency was overcome in the 1960's by the use of two coherent VLF signals whose frequency separation was very small (in the order of 1 to 2 percent of the nominal carrier frequencies). Through the cooperation between the National Bureau of Standards (NBS) and the National Aeronautics and Space Administration (NASA), and later between the Department of the Navy and NASA, this technique was developed and offered an accuracy at the microsecond level for time transfer over continental distances [Chi and Witt 1965]. While the dual VLF time transfer technique was developed in the 1960's, two factors affected its eventual application as an operational system. One, of course, was the urgent need for clock synchronization by the Manned Space Flight Network (MSFN) to support the Apollo program. The other was the successful demonstration experiments using satellites to transfer time. As we shall see later in this paper, both these factors, requirements and technology, played a strong role in influencing the outcome of frequency and time transfer technology.

As most people working in the field of time dissemination know, dedicated time transmission systems are expensive to build and often cannot be justified if the number of users is small (see table 1). For this reason, most resourceful managers plan their programs by an add-on approach or piggyback, as a hitchhiker on a system used for some other purpose. The time transmission on such navigation systems as LORAN-C [Davies and Doherty 1960] and the OMEGA [Chi et al. 1972, 1973] are good examples. When NASA had to synchronize its MSFN station clocks to an accuracy of 100 microseconds, the only techniques available then were the portable clocks supplemented by a hybird of HF and VLF techniques. It was quite fortuitous that the signal phase of the emissions from the Mediterranean Sea Chain of LORAN-C was just then being synchronized to the master clock of the United States Naval Observatory (USNO). With the cooperation of the USNO and the United States Coast Guard, LORAN-C supported the clock synchronization of our tracking station in Madrid, Spain. As more LORAN-C chains were synchronized, this navigation system played a vital role in the advancement of clock maintenance, in particular in the clock comparison among the standard laboratories.

Table 1

Capability and Cost Comparisons of Terrestrial Time Transfer Systems

SYSTEM	PRIMARY FUNCTION	SYSTEM COVERAGE	FREQUENCY	RADIATED POWER (KW)	SYSTEM ACCURACY	ESTIMATED COST IN MILLIONS
LORAN-C	NAVIGATION	REGIONAL	100 kHz	100	0.15 μS (GROUND WAVE) 25-50 μS (SKY WAVE)	\$20 M PER CHAIN \$6 M PER STATION
OMEGA	NAVIGATION	WORLDWIDE	10-14 kHz	10	1-10 μS CAPABILITY	\$8-12 M PER STATION
NAVY VLF	COMMUNICATION	WORLDWIDE	10-20 kHz	500-1000	1×10^{-12} PER 10 DAYS	\$30-40 M PER STATION
WWVB	FREQUENCY	NEARLY WORLDWIDE	60 kHz	10	1×10^{-12} PER 10 DAYS	\$4-8 M PER STATION
WWV/WWVH	TIME	WORLDWIDE	2.5-25 kHz	10	1 ms	\$2 M PER STATION
PORTABLE CLOCK	TIME & FREQUENCY	WORLDWIDE			0.05-5 μS	DEPENDS ON DISTANCE AND NO. OF TRIPS

Unfortunately, all good systems have their limitations. In the case of LORAN-C, this limitation is in the range of coverage of the ground wave propagated signals. This range is in the order of 2000km.

Preceding the advancement of frequency and time technology were many successes in the basic research and development programs in related fields. They served as the essential precursors. Although they are too numerous to cite, several activities come immediately to mind. They are: ultrastable crystal oscillator development in the 1940's and 50's [Gerber and Sykes 1966], atomic frequency standards development of cesium beam tube [Holloway and Woodward 1964, Bagley and Cutler 1964], rubidium gas cell [Bender et al. 1958] and hydrogen masers in the 1950's and 60's [Vessot and Peters 1962, Vessot et al. 1966], the defining of the second in terms of the cesium atomic resonance frequency in the mid-1960's [General Conference on Weights and Measures 1967], the improved accuracy in the measurement of velocity of light in the 1960's [Stevenson et al. 1972], and so on. NASA, as a new agency in the late 1950's, provided many of the requirements and applications. NASA also provided the opportunities to conduct experiments and to test the new ideas. As the Director of Goddard Space Flight Center, I am glad to say that NASA participated actively in and supported many of these programs.

REVIEW OF HISTORY OF EARLY SATELLITE PROGRAMS

During the early days of the space agency, when space science was still in its infancy, space scientists had many golden opportunities to conduct experiments in virgin territories. There were many firsts to be sure, nobly achieved and properly recorded. Not all planners and experimenters were, however, scientifically minded in the true sense of the word. That is to say there were many realists and practical-minded engineers who thought in terms of applications. Such projects as Tiros, Echo, Telstar, Relay, and later the series of the Applications Technology Satellites (ATS) are examples.

Project Echo was, in fact, the first host satellite which paved the way for a series of successive satellite time transfer experiments. It was a passive communication satellite using an inflatable sphere of aluminized mylar, 100 feet in diameter. The balloon was designed as a reflector to demonstrate long distance two-way communications [Jakes 1961] between the two coasts of the United States. The stated objectives of these experiments were: (1) To demonstrate two-way voice communication between the east and west coasts, (2) To study the propagation properties of the medium, including the effects of the atmosphere, the ionosphere, and the balloon, (3) To determine the usefulness of various kinds of satellite tracking procedures, and (4) To determine the usefulness of a passive communications satellite of the Echo-I type. It was launched into a circular orbit on August 12, 1969. It had an inclination of 47.3° and an altitude of 1000 miles. The tracking configuration for this satellite is shown in figure 1.

It is interesting to note that prior to the launch of the Echo balloon, the system test and system calibration of the tracking station equipment was made in November 1959 via the moon, the earth's natural satellite. The successful receiving of the signals bounced off by the moon's surface led the Jet Propulsion Laboratory (JPL) later to use the "moon bounce technique" to transfer time among the Deep Space Network (DSN) stations.

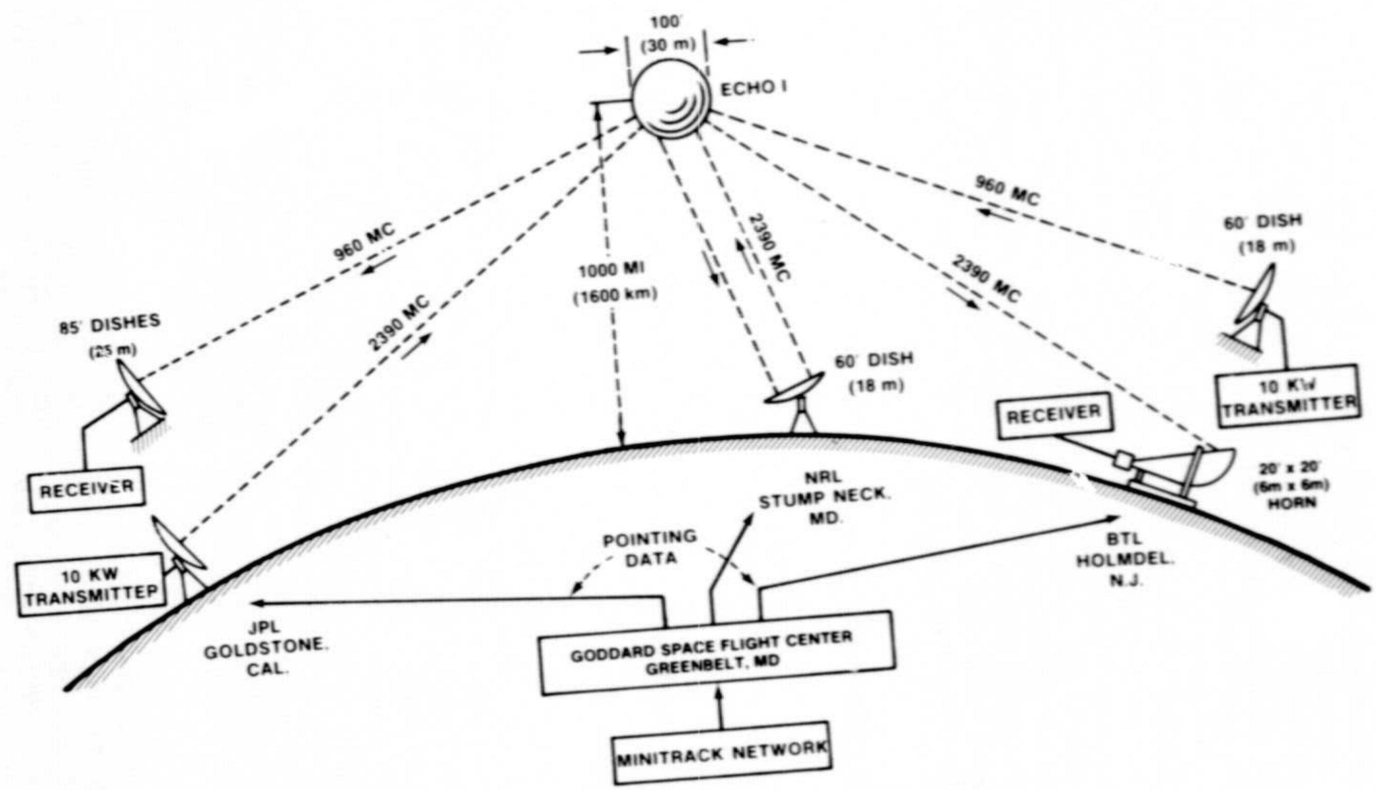

Figure 1. General Features of the Project Echo Experiment
(After William C. Jakes, Jr.)

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The Telstar was designed as an active wideband communication satellite [Dickieson 1963], analogous to a terrestrial microwave repeater located in the sky. Its objectives were: (1) To demonstrate the transmission of multichannel two-way telephony, television, data and facsimile via satellite, (2) To build a very large ground station antenna and find out how to point its extremely sharp (narrow) beam very accurately at the satellite, (3) To gain a firm understanding of the problems of measuring orbital parameters and predicting satellite positions, (4) To gain a better numerical knowledge of the character and intensity of radiation in the Van Allen belt, (5) To face the problems of designing for long life and reliability of electronic equipment for operation in the space environment, and (6) To look for the unexpected. The Telstar system consists of an active communication satellite repeater or transponder. It was launched in 1962. In addition to the stations at Andover, Maine, Holmdel, New Jersey; Washington, DC; and Goldstone, California in the United States, the participating European countries were England with a station at Goonhilly Downs, France with a station at Pleumer-Bodou, and Italy at Fucino. The specific design objectives are: (1) To demonstrate broadband microwave transmission through an active satellite, (2) To test the operation of a ground station capable of transmitting to and receiving from the satellite while tracking it, and (3) To obtain data on the space environment and its effect on the satellite. The spacecraft is shown in figure 2 and the orbit parameters are shown in table 2.

The choice of frequencies for the transponder was more complicated and has a historical interest. Prior study results had shown that the preferred frequencies lay in the range of 1 to 10GHz, more specifically in the bands of 3700 to 4200 and 5925 to 6425MHz. In the United States, and generally in the rest of the world, these frequencies had all been allocated for various terrestrial uses. Satellite communication as a newcomer had to work its way into the establishment. This situation presented a complex international problem which was not

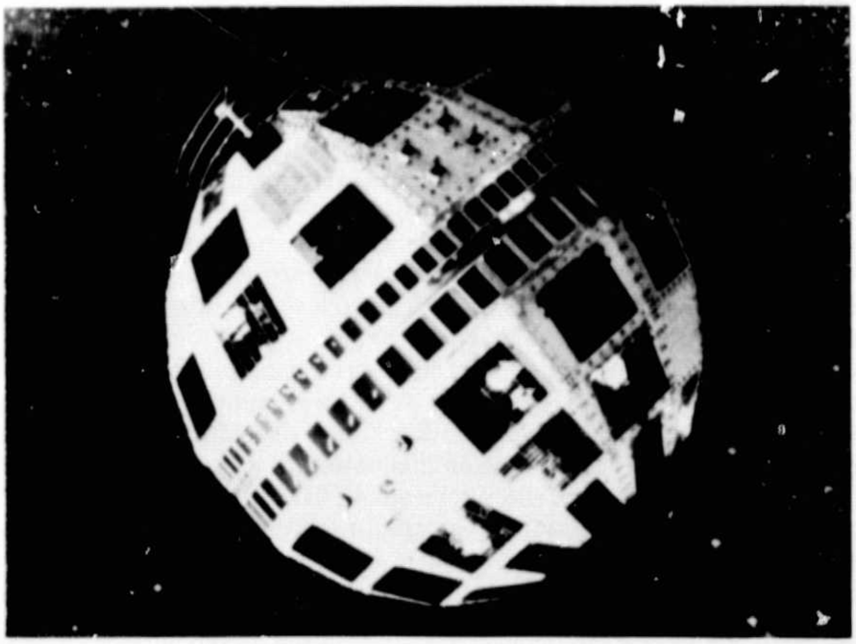

Figure 2. Experimental Communications Satellite, Telstar

Table 2
Orbit of the Telstar Satellite

ORBITAL PARAMETERS	PROPOSED	ACTUAL ORBIT (NASA MINITRACK)
Perigee	500 nm	511.9 nm
Apogee	3000 nm	3043.2 nm
Inclination	45.43°	44.8°
Period	156.47 min.	157.6 min.
Initial Apogee Latitude	8.59°S	11.92°S
Apsidal Advance	2.02°/day	1.98°/day

(After A. C. Dickieson)

resolved until the Extraordinary Administrative Radio Conference for Space Radio Communication met in Geneva in October 1963. The microwave frequencies finally chosen for the Telstar system were 6390 MHz for the ground-to-space transmission and 4170 MHz for the space-to-ground transmission. While the final choice of these frequencies fell short of the ideal, it was nevertheless a good compromise and conformed with the recommendations of the International Radio Consultative Committee (CCIR) of 1959. I am bringing out this history to reflect the frequency allocation experience we had in the early days of the space programs and point out the need for continued international coordination and cooperation.

Relay-I and -II which were follow-on programs to Telstar were launched in 1962 and 1964 respectively. They were designed to conduct television and voice communication experiments between the United States, Europe, Brazil, and Japan.

More advanced communications satellite programs were planned for the Syncoms-I and -II and the Series of ATS-I through -VI. The series of ATS projects were to carry out research and development in scientific and technological areas of communication. In addition, each satellite of the ATS series undertook a major area of investigation including satellite stabilization, satellite antenna systems, meteorology, particle evaluation and environmental effects on components and material. The objectives of ATS-I and -III were to demonstrate the feasibility of visual imaging, communications and environmental measurements using spin-stabilized spacecraft at synchronous altitude. ATS-I was launched on December 7, 1966, at 150° west longitude. It remains spin-stabilized and in synchronous orbit today. ATS-III was launched on November 5, 1967 with an inclination of 47° west longitude. The accomplishments of the ATS program are too numerous to list. I mentioned them only to point out that they were used in several important satellite time transfer experiments. However, it should also be emphasized that as we move at an increasingly rapid pace in communication technology toward digital time division multiple access (TDMA) systems, internal time synchronization among ground and space terminals becomes a major system-level problem.

Figure 3 shows the design of Echo, Relay, and ATS types of satellites. Figure 4 shows the first color photograph (reproduced in black and white) of the earth taken at an altitude of 22,3000 miles from ATS-III at 47° west longitude on November 19, 1967.

SATELLITE TIME TRANSFER TECHNIQUES

Several time transfer techniques have been used. They are distinguished by satellite relay and satellite clock techniques. If the satellite does not carry a clock and if the propagation time delay is determined by one-way ranging or by calculation based on a priori knowledge of positions and propagation medium corrections, the technique is called the one-way relay technique. On the other hand if the propagation time delay is determined by two-way ranging measurement, it is called the two-way relay technique. When the satellite carries a clock, the time transfer technique is called the one-way emission. As with most techniques, they can be modified to form a number of hybrid techniques. Historically speaking, the one-way emission technique was developed after the relay technique. This is because the relay technique can be demonstrated easier and cheaper than placing a clock on-board a satellite. For example:

1. The first experiment conducted by Steele, Markowitz, and Lidback [1964] in 1962 using Telstar was to compare clocks between the United States and the United Kingdom via the ground station clocks at Andover, Maine in the United States and Goonhilly Downs in England. They transmitted 10 per second 5 μs pulses from each station to the other at near simultaneous time as shown by figure 5. Each station then measured the arrival time of the received signal relative to its local clock. Based on these data, the difference between the two ground station clocks was measured. In addition, two measurements were made at Goonhilly of its own pulses that were retransmitted from Andover. Thus the total propagation delay was also measured. Although the two-way coherent relay time transfer technique was not used in this experiment, the idea was suggested and paved the way for the Relay experiment.

2. The two-way coherent relay satellite time transfer technique was first used in the experiment conducted by Markowitz, Lidback, Uyeda, and Muramatsu [1966] in 1965 between the United States and Japan using Relay-II as shown in figure 6. The time signal transmitted from Mojave, United States, via Relay-II to Kashima, Japan, was looped back and retransmitted from Kashima to Mojave. This time transfer technique is called the two-way coherent relay time transfer technique in contrast to the two-way noncoherent relay time transfer technique used in the Telstar experiment. To identify the clock pulses from each of the two stations in the Relay-II experiment, longer pulses, 11 μs wide, were used for the transmission from the Mojave to Kashima direction; and shorter pulses, 5 μs wide, were used for transmission from Kashima to Mojave. The pulse rates were 100, 1000, and 10,000 per second. The slower rate of pulses was used to resolve the time ambiguity and the higher rate to increase the resolution.

3. The one-way relay satellite time transfer experiment was first proposed by Martin and Johnson of JPL in 1964. They and their co-workers demonstrated the feasibility via Lunar Orbiter [Martin 1966]. They were also the first to use the pseudo-random noise (PN) ranging code to transfer timing information. At about the same time, Easterling proposed a similar experiment using the moon as the reflector [Baumgartner

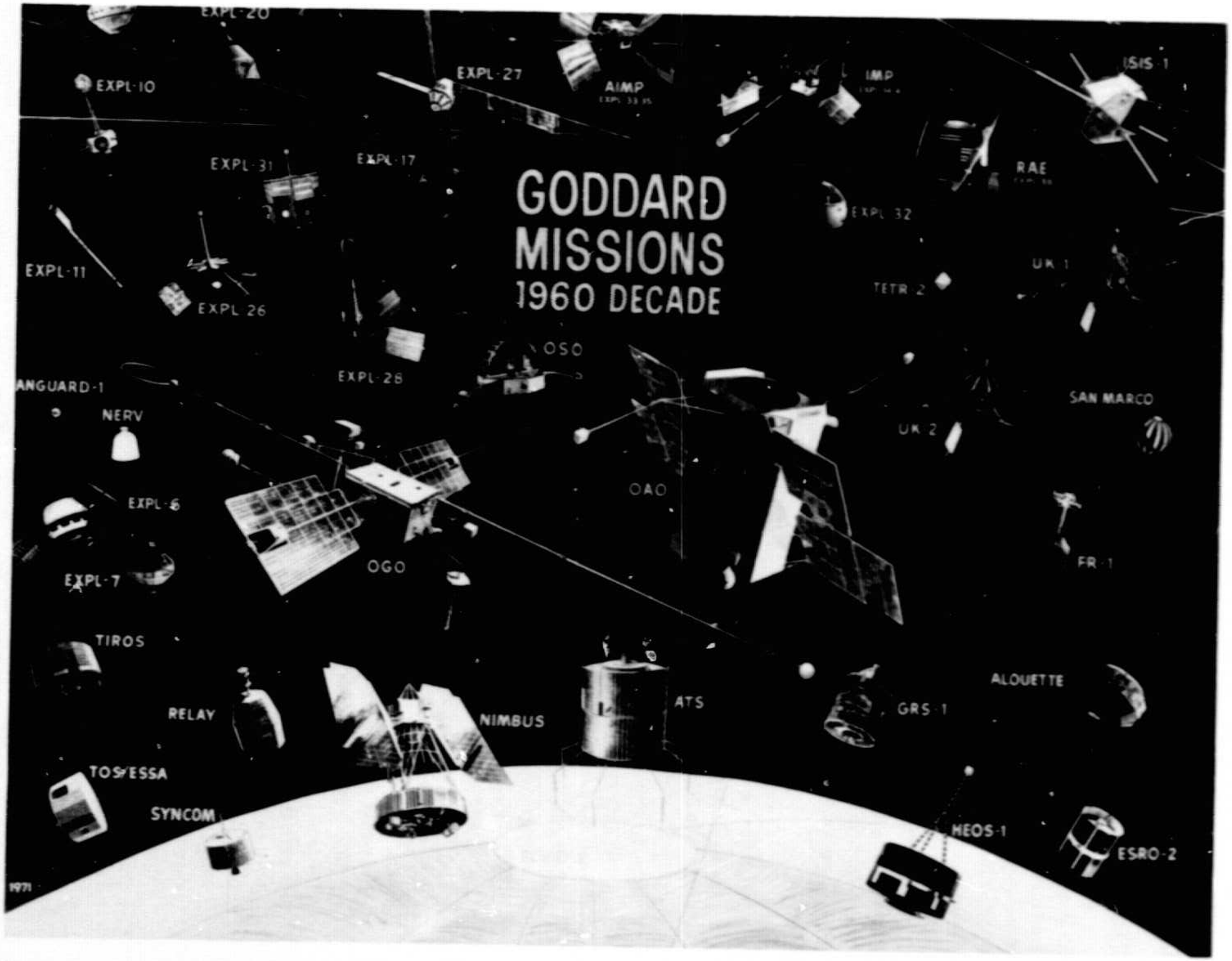

Figure 3. NASA's Goddard Missions in the 1960 Decade

Figure 4. First Photograph of the Earth Taken on November 19, 1967 from ATS 3

1967]. Both experiments used S-band frequencies for up and down links; although after the lunar reflector experiment was implemented in the Deep Space Network in 1967, X-band frequency at 7150 MHz was used [Higa 1972].

The one-way relay time transfer technique was investigated in detail by many experimenters [Jesperson et al. 1968, Gatterer et al. 1968, Hanson and Hamilton 1971, Murray et al. 1971]. They used different satellites (figure 7) and carrier frequencies because of the frequency allocations for these satellites. This technique effectively places the ground clock in the satellite.

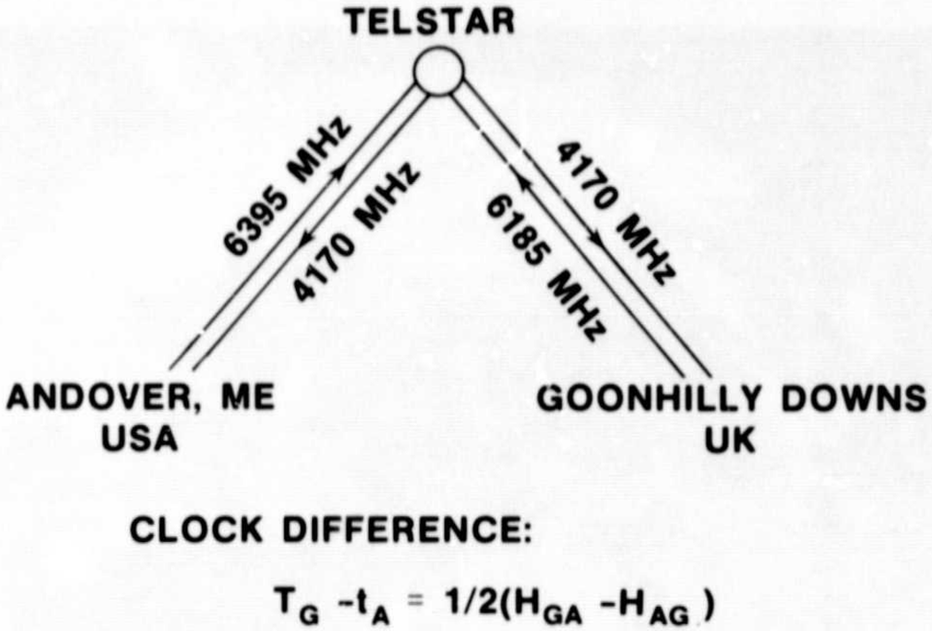

Figure 5. Telstar Two-Way Relay Noncoherent Time Transfer Experiment

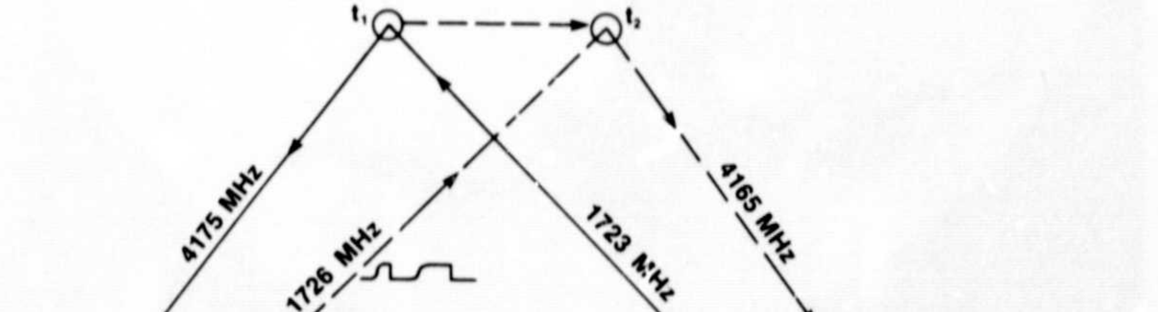

Figure 6. Two-Way Relay Coherent Time Transfer Experiment Using Relay II
(After Markowitz, et al.)

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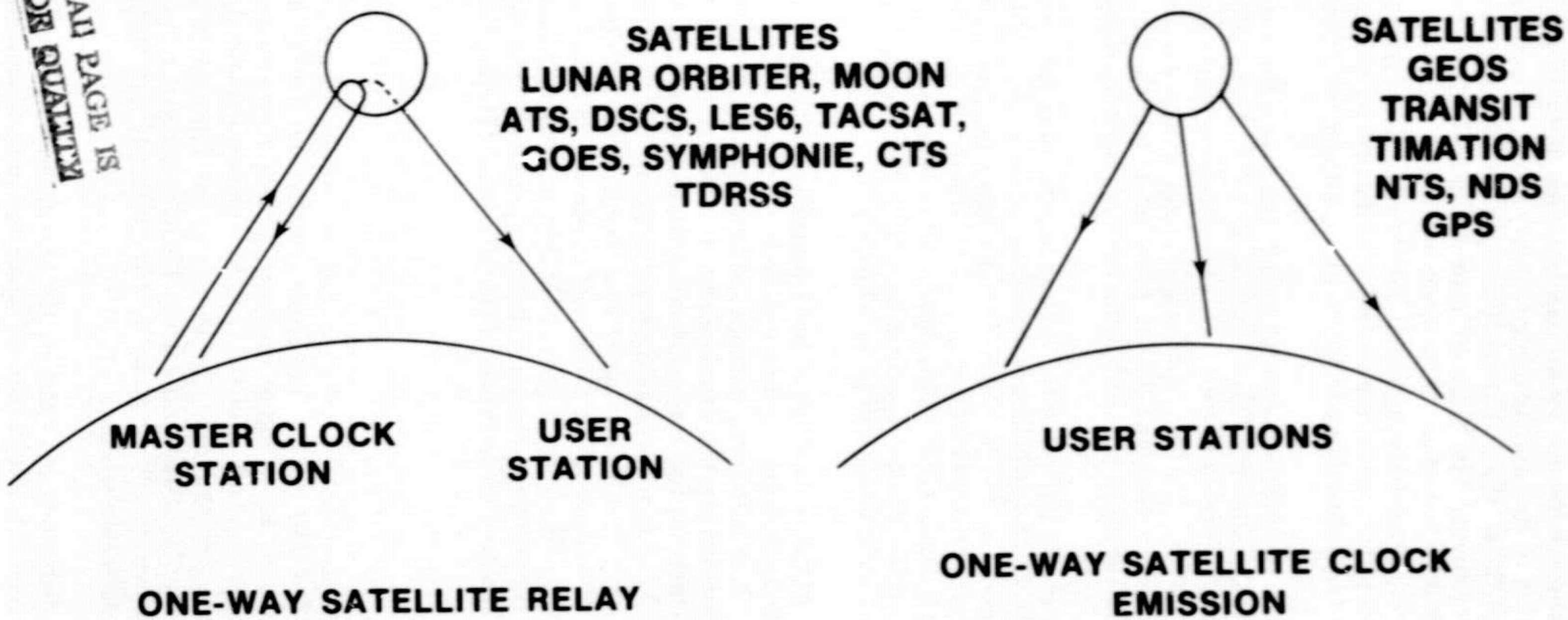

Figure 7. One-Way Satellite Time Transfer Techniques

This is achieved by removing the one leg propagation time delay from the master clock located in a ground station to the satellite using two-way ranging or post corrected orbital position determination of the satellite. The on-time signal delays from the satellite to the users are left to the users to remove. The National Bureau of Standards made extensive investigations to transmit the WWV type of signals in space using ATS [Hanson and Hamilton 1974] and Geostationary Operational Environmental Satellites (GOES) [Hanson et al. 1976]. They developed an ingenious slide rule method to calculate the one leg propagation time delay for the users based on position information of the satellite, subsatellite point, and the users' sites.

4. The one-way emission techniques using a satellite-borne clock was first demonstrated by the geodetic satellites (GEOS) [Lerch et al. 1971, Laios 1971]. GEOS-I, which was launched on November 6, 1965, carried a crystal oscillator clock with a frequency stability of 1×10^{-11} per day. Although similar crystal oscillators with lower frequency stability were used in earlier satellites for time tagging of data such as Transit-3B launched on February 21, 1961, they were not used for time transfer purposes.

The first atomic clock placed in a satellite for time transfer purpose was the Navigation Technology Satellite (NTS). NTS-I, which was launched on July 14, 1974, carried a rubidium gas cell standard [Ringer et al. 1975]. NTS-II, which was launched on June 27, 1977, carried a cesium beam tube standard [White et al. 1976]. The NTS series are the forerunners of the Global Positioning System (GPS) [Shoemaker 1975] which ultimately will have 24 satellites in three circular orbital planes separated by 120°. Each satellite will carry a clock to which its radio frequency emissions will be synchronized.

In a review paper such as this, it is obvious that I cannot cover all the satellite time transfer experiments which have been done, nor do I wish to burden you with the details which many of you already know. It is sufficient, perhaps, to summarize the experiments as given in table 3. It is to be noted that the most precise time transfer using a satellite is achieved by those experiments in which the two-way coherent relay technique was used, such as by Chi et al. [Chi and Byron 1975] in the United States and Saburi et al. [1976] in Japan using ATS and Brunet et al. [1977] in France using Symphonie. This is to be expected since the propagation delay can be accurately measured and corrected. Similarly, very long baseline interferometer (VLBI) can also be used to transfer time once the positions of the baseline stations are accurately determined. Such a series of experiments was recently conducted in the United States and achieved an accuracy of the 10 ns level [Hurd 1973, Rogers et al. 1977].

APPLICATIONS

When I talk about applications of space science and technology, I view the topic broadly as any use to which mankind puts the fruits of space research and development. Through beneficial applications of space science and technology, we may help search for new resources and energy and better our standard of living, thereby maintaining and strengthening the dignity and the aspirations of all mankind. Certainly, the view from space gives us the perspective to better manage human activity on earth. Therefore, space research is intrinsically global and beneficial in nature. We have witnessed unprecedented technological advancement in space in the last two decades.

As we view our accomplishments and examine the vast amount of valuable data and information collected through scientific exploration of space, we must view with alarm the future

Table 3

A Summary of Satellite Time Transfer Experiments

SATELLITE	ONE-WAY		TWO-WAY RELAY		TECHNIQUES	FREQUENCY (MHz)		STATED PRECISION OR ACCURACY (μS)	EXPERIMENTER
	EMISSION	RELAY	NONCOHERENT	COHERENT		UPLINK	DOWNLINK		
TELSTAR			✓		5μS PULSES, RATE: 10 PPS	6390	4170	1	STEEL ET AL 1964
RELAY II				✓	5 AND 11 μS PULSES, RATES: 0.1, 1 & 10 k pps	1723	4175	0.1	MARKOWITZ ET AL 1965
GEOS I II	✓ ✓				SQUAREWAVE 186.880 Hz PHASE REVERSAL TIME MARKER		162.324 648.972	100 20	LERCH ET AL 1967 LAIOS 1971
LUNAR ORBITER		✓			MARK 1A RANGING CODE 4 PN CODES LENGTH: 11, 23, 63, 127 BITS RATE: 996 kHz	2113	2295	10	MARTIN ET AL 1967
MOON		✓			SCANNING PN CODE AT 10 - 90 μS/S RATE, CODE LENGTH 2^{n} - 1 (for 7150 MHz)	2113 7150	2113 7150	10 0.01	BAUMGARTNER ET AL 1967 HIGA 1972
ATS 1		✓			VOICE COMM. AND PULSES RATES: 1 AND 100 pps	149.2	135.6	5	JESPERSON ET AL 1968
		✓	✓		PULSES RATES 1, 10, 100 pps	149.2	135.6	10 6	GATTERER ET AL 1968
			✓		60 μS BIPOLAR PULSES 1 pps	6301	4178	0.05	MAZUR ET AL 1971
				✓	PN CODE LENGTH: 2^{n} - 1 RATE: 16.376 MHz	6301	4178	0.01	CHI ET AL 1975
				✓	PN CODES LENGTHS: 2^{n} - 1 AND 8000 (2^{n} - 1) RATE: 16.376 MHz	6301	4178	0.005	SABURI ET AL 1976
ATS III AND SMS II		✓			WWV FORMAT SAME AS ATS III	149.22 2113	136.625 468.825	25-50 100	HANSON AND HAMILTON 1974
GOES I II		✓			TIME CODE 30 SEC FRAME 50 BITS SAME AS GOES I		468.825 468.8375	<20 <20	HANSON ET AL 1976
SYMPHONIE			✓		50 Hz PULSES 1 pps	6380 6340	4155 4115 4115	0.005	BRUNET ET AL 1977

Table 3 (Continued)

A Summary of Satellite Time Transfer Experiments

SATELLITE	ONE-WAY		TWO-WAY RELAY		TECHNIQUE	FREQUENCY (MHz)		STATED PRECISION OR ACCURACY (μS)	EXPERIMENTER
	EMISSION	RELAY	NONCOHERENT	COHERENT		UPLINK	DOWNLINK		
LES 6		✓			TONE MODULATION 1, 10, 100, 1,000, 10,000 Hz	302.7	249.1	25	HANSON ET AL 1971
TACSAT						303.4	249.6	150	
TRANSIT	✓				PN CODE LENGTH: $2^{11}-1$ RATE: 1.67 MHz		400 150	0.075	TAYLOR 1974
TIMATION I	✓				TONE MODULATION 100 kHz		400	0.5	EASTON ET AL 1968
II	✓				100, 250 Hz AND 1, 4, 16, 64, 100 400, AND 1,000 kHz		399.4 149.5	0.5 - 0.1	EASTON ET AL 1973
NTS I	✓				TONE MODULATION 100, 250 Hz AND 1, 4, 16, 64, 100, 400 kHz AND 1.6, 6.4 MHz		335.3 1580.7	0.13	SMITH ET AL 1975
II	✓				SAME AS NTS I		SAME AS NTS I		BUISSON ET AL 1977
NDS I	✓				PN CODES: CLEAR CODE LENGTH: $2^{10}-1$ AT 1.023 MHz AND PROTECTED CODE: THE PRODUCT OF SEVERAL SHORTER SEQUENCES WITH A SHORT CODE LENGTH OF 7 DAYS AND LONG CODE LENGTH, 267 DAYS AT 10.23 MHz RATE		1575.4 (L_1)	0.010	UNDER TEST
II							1227.6 (L_2)		
CTS		✓			13 μS PULSES 1pps	14.2 GHz	11.88 GHz	0.004	UNDER TEST
TDRSS		✓	✓	✓	PN CODE LENGTH: $2^{10}-1$ $2^8(2^{10}-1)$ RATE ≈ 3 MHz	2.1 GHz	2.2 GHz	10 - 0.010	CHI 1977

when ever-expanding torrents of data will be transmitted from space. We must find new ways to manage the data collection, handling, and utilization of this data for the maximum benefit to mankind. For this reason, we have recently reviewed the NASA mission operation and data management practices to determine what changes in philosophy, concept and design of our data systems are needed [Ferris and Greene 1976]. Through this review we have developed a new concept of data management and handling which we named the NASA End to End Data System (NEEDS).

NEEDS is a concept which includes the idea of "spacecraft autonomy." Spacecraft autonomy implies "self-sufficient" spacecraft which can independently execute the functions of attitude control, sensing, navigation, and data collection, handling and transmission. Experimental or observational data such as that from Landsat (figure 8) are today collected and handled separately from auxiliary navigation, timing and attitude information. In the NEEDS era, observations will be grouped as data packets coherent to each other within the experiment and provided with all needed auxiliary data. Through such a system, not only is data pre-selected, formatted and annotated through the use of the on-board computer, but also it will be time-tagged through the life of the experiment. It is obvious that accurate on-board time will be required by each experiment as well as to maintain the long term time tagging of the data packets. In short, there is a requirement for an on-board clock to generate accurate time intervals as well as to provide a continuous time scale consistent in accuracy with the overall timing requirement. The on-board clock must be monitorable and steerable from the ground.

Some programs still in the planning stages at NASA which will incorporate this new philosophy will be the Earth Radiation Budget Satellite (ERBS), the Upper Atmospheric Research Satellite (UARS), and the Origin of Plasma in the Earth's Neighborhood (OPEN).

As I stated previously, the timing requirements for space programs have increased at a rate of about one order of magnitude per decade. These new programs will continue that trend. Figure 9 shows the NASA timing requirements of the last twenty years. As I project the needs of our planned programs, the requirements for time are expected to reach the submicrosecond level soon. For example, you all know the VLBI experiment which requires a priori time synchronization of 10 μs for initial data reduction and needs or perhaps desires to have a stability of 10 ps for the order of a day. This requirement obviously calls for a hydrogen maser with a stability of the order of 10^{-15} per day or better. Baselines currently being determined by VLBI are approaching the uncertainties of the order of a few centimeters using the present generation of hydrogen masers. A proposal now in the conceptual stage is the space VLBI terminal. For example, if the United States space Shuttle and USSR Salyut space stations were used as a means of transporting and operating a radio telescope antenna and receiver in orbit around the earth, then taken together with ground based VLBI stations, a dynamic interferometric network would be formed. This network could be used to map, with greatly expanded coverage, galactic and extra-galactic radio sources. It would have the potential to improve the angular resolving power for many sources to a size equivalent to perhaps the diameter of the earth. Such a spaceborne VLBI terminal requires not only an accurate and stable clock but also a wideband data handling system for telemetering to the ground.

Another important space research discipline where precise time is important is the modeling of the gravity potential of the earth. Based on the improvement of earth geopotential models, we can see from figure 10 that we have also increased the accuracy of satellite position determination by about one order of magnitude per decade.

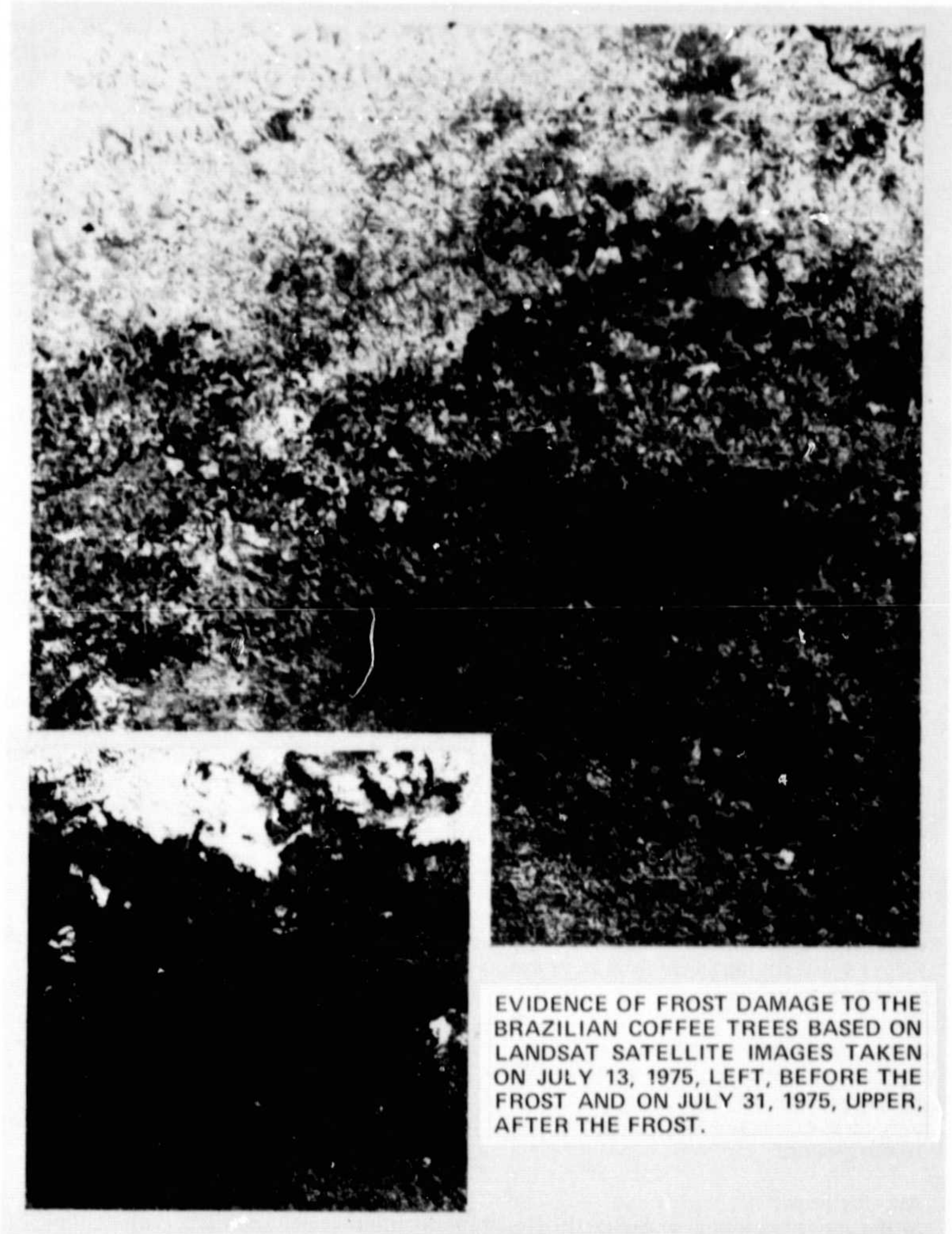

Figure 8. Photographs Developed From Landsat Sensor Images Covering 13,225 Square Miles of Brazil

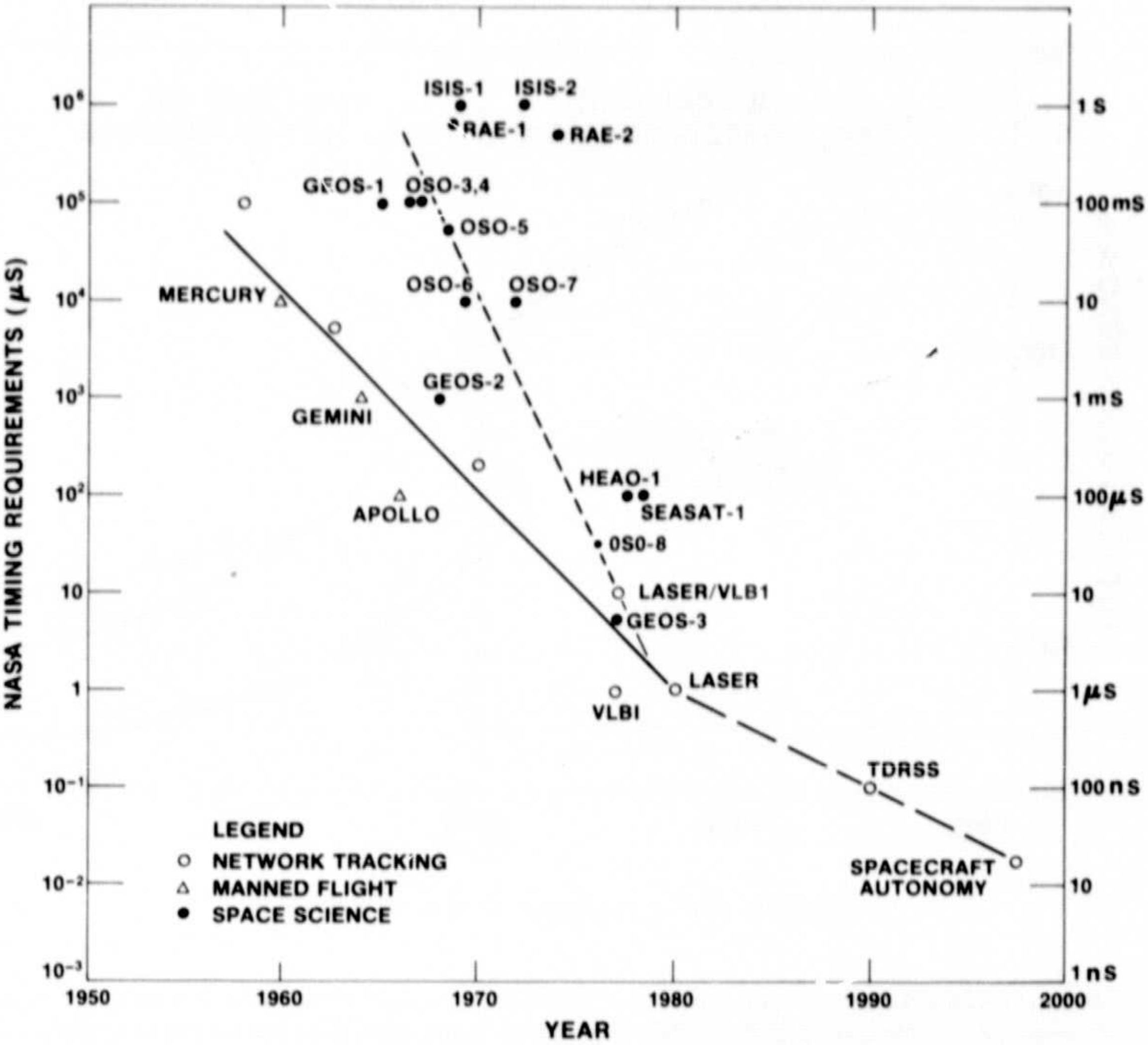

Figure 9. NASA Present and Future Timing Requirements

Figure 10 depicts the history and forecast of position accuracy for earth orbiting spacecraft. The position accuracy assumes two types of orbit determination methods, i.e., the global and deterministic methods. The global orbit determination method (which is the current system) utilizes statistical estimation techniques and accurate dynamic models to estimate the orbit from many measurements where no single measurement uniquely determines the complete state. The deterministic orbit determination method is a geometric estimation of the satellite position which is uniquely determined by a group of accurate measurements over a short time span. This is a possible system of the future.

As we project the improvement in orbit determination into the future, we are quite confident that we shall achieve another order of magnitude reduction in position error. It is based on this kind of forecast [Hearth 1976] and conceptual plans that I project the requirement for greater precision and accuracy in the measurement of time in the 1980's and beyond. These requirements will be in the hundreds to tens of nanoseconds region.

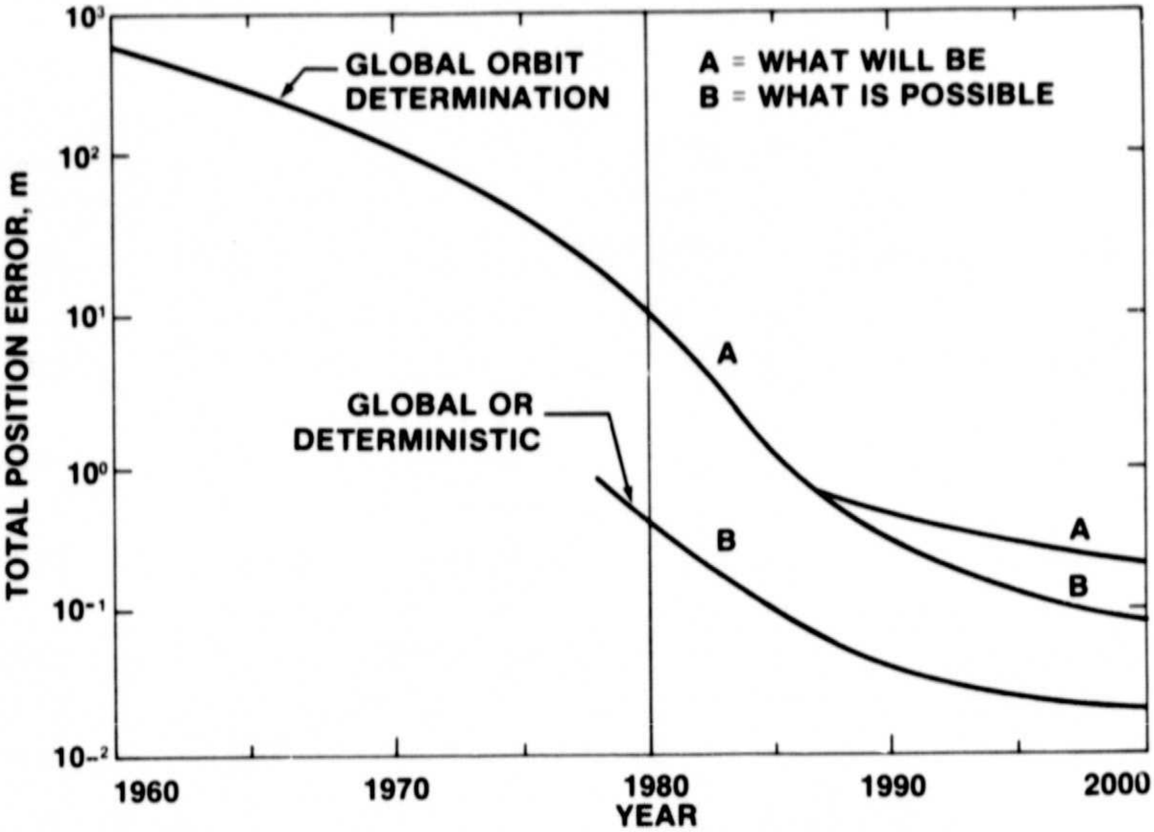

Figure 10. Position Accuracy of Earth Orbiting Satellites

Up to this point I have discussed potential applications and their relation to projected needs. To meet all these requirements, NASA is procuring a real-time data transmission system called the Tracking and Data Relay Satellite System. This system consists of two satellites in synchronous orbit which will replace the current NASA ground network in supporting low earth orbiting missions. It is equipped to transmit data from 100 b/s to 300 Mb/s rates [TDRSS Users' Guide 1978]. Through TDRSS we also plan to transfer time to satellites in near earth orbit. Satellites in highly elliptical orbits will receive timing signals from some remaining NASA ground tracking stations.

In conclusion, I would like to leave you with an optimistic note. That is, "time is what you have and time is what NASA needs." Through continued cooperation by the members of the timing community, I see a challenging and rewarding research and development program in the years to come. I look forward to the continuing participation by NASA Goddard Space Flight Center and coordinating with you in this effort in the future.