TEMPUS

A PROPOSAL FOR AN INTERNATIONAL TIME TRANSFER AND PRECISION TRACKING SATELLITE

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Since W. G. Cady carried his piezo resonator to seven laboratories in England, France, Italy and the United States in 1923, the primary method of coordinating time between international stations has involved the use of traveling clocks. These were first transported by ship and train, more recently by aircraft. Project TEMPUS also requires traveling clocks but these will revolve thousands of kilometers above the earth in artificial satellites.

Several methods of international time transfer are now available and a comparison of various concepts derived from data published by the European Satellite Agency is shown below.

Method	Accuracy	Remarks
VLBI (pulsars)	1 nsec	Slow, expensive ground stations.
TV relay via satellite	10 nsec	Requires wide-band satellite transponder with satellite visible from all stations.
Portable clocks	30 nsec	Slow, spasmodic, expensive.
NTS	200 nsec	Better clocks and orbits are needed.
Loran-C	200 nsec	Limited by propagation phenomena.

In addition to these systems, ESA is scheduled to launch the SIRIO 1 in 1979 and the LASSO/SIRIO 2 experiment in 1981. SIRIO 1 will employ microwave transponder time synchronization and LASSO/SIR10 2 will combine both microwave and optical tracking capabilities since it will carry laser retroreflectors. Basically, the system will allow for the comparison of a ground station timing signal with that of a satellite time reference clock. It will be an excellent demonstration of satellite capability to synchronize time and at the same time furnish a source of data for the study of atmospheric path time delay errors in the electromagnetic frequency spectrum. The SIR10 satellites are scheduled to be placed in geostationary orbits.

Satellite experiments to provide time synchronization began with the launch of Timation II in 1969 by the U.S. Naval Research Laboratory. The Timation series were the forerunners of the present Navigation Technology Satellites (NTS) which NRL is providing to support the NAVSTAR Global Positioning System Program. Figure (1) illustrates the method used. The satellite clock is updated by time from the U.S. Naval Observatory and is used to correct the time of remote clocks. The accuracy of time closure is sensitive to errors caused by unknowns in the clock drift and satellite position (ephemeris) as well as refractive errors in the atomospheric transmission path.

By the summer of 1978 there was considerable world-wide interest in time transfer by means of satellites, and stations in England, France, Germany, Spain, Japan, Australia and Canada as well as those in the U.S. were working with the NTS spacecrafts. Figure (2) shows the extensive network involved.

During 1978 an experiment was conducted to compare the results of time transfer via portable clock with that achieved by the use of NTS time receivers. As can be seen from figure (3), the agreement in all cases was within a microsecond.

In 1973, the NAVSTAR Global Positioning System (GPS) program was established by the U.S. Department of Defense, and it combined NRL's Timation with the U.S. Air Forces' 621B satellite navigation project. This action had a considerable impact not only on the development of navigation satellites, but also on the future of satellite time transfer.

Solution of the navigation equation by the use of satellites is inextricably tied to satellite time transfer since both require the same fundamental elements; excellent clocks with highly predictable drift and accurate knowledge of the satellite ephemeris. In addition, if reliable continuously available world-wide time transfer is to be accomplished from space, a multiple satellite system will be required for it is only by the use of a number of orbiting satellites, each having excellent clocks and well defined orbits, that a dependable on-demand time transfer system can be developed.

Similar characteristics are required for a satellite which can be used in conjunction with either lasers or electromagnetic receivers for precision tracking purposes such as the determination of earth plate movements and the refinement of our knowledge of the relativity and gravitational constants.

Perhaps the most obvious and practical satellite candidates for such a system are a selected and modified version of a number of the NAVSTAR GPS spacecraft which are now in development. These will become operational within the next decade. It is not necessary that all of these spacecraft be configured as TEMPUS satellites. The full NAVSTAR system will contain 24 birds arranged in three planes, each at an inclination of 45 degrees. They will be spaced in such a manner that at least four satellites will be in view anywhere on the globe at all times. Each will carry an updated ephemeris and four or more will provide users with the elements of a three dimensional navigation fix plus a time update. The full NAVSTAR constellation is shown in figure (4). The system will orbit the earth at 17,300 kilometers, easily within laser range if adequate retroreflectors are carried.

The three dimensional navigation accuracy available from the NAVSTAR satellites will be extremely high by today's standards. Initial tests at Yuma, Arizona, conducted under controlled conditions, have reported position fixing to better than 10 meters. However, this accuracy is probably not good enough for many precise scientific research projects in geodynamics and relativity theory. For these and similar purposes accuracies in the centimeter range are necessary.

For this reason it has been interesting to design a TEMPUS package which, when added to a satellite similar to NAVSTAR would provide a precision scientific tool capable of meeting the stringent requirement of the scientific community, while at the same time not interfering with the basic GPS operational mission. This package should be designed to have minimum impact upon the basic NAVSTAR configuration and should be able to function normally in the GPS operational constellation. An initial estimate of the number required to provide worldwide time synchronization as well as a precise tool for research experiments needing such a capability is two TEMPUS satellites in each plane for a total of six. Properly spaced, this number should provide a constellation of four in view for almost all parts of the world on a periodic basis. Properly configured the TEMPUS package will define position accuracies in the centimeter range for stationary locations on the earth's surface in addition to international time synchronization to about one nanosecond.

In order to provide the frequency stability necessary for such accuracies, the TEMPUS satellite must take advantage of a navigation package similar to that already avilable in the NAVSTAR system. Using the NAVSTAR principle, the clock in the satellite is synchronized with that of the user. The satellites signal is time coded thus allowing accurate measurement of the distance from satellite to observer. In the case of a station whose position is known, the signal from one satellite only is required to effect time transfer.

It can be readily seen that the heart of such a system is an accurate and very stable clock. The first clocks flown in Timations I and II were quartz and had stabilities of about 10^{-11} parts per day. NTS-1 contained a rubidium atomic clock whose stability was about 10^{-12} parts per day while NTS-2, launched in June 1976, had a cesium standard whose stability is on the order of 10^{-13} NTS-3 which is scheduled for flight in 1982 and the operational NAVSTAR system are designed to contain advanced cesium or hydrogen maser clocks whose stability should approach 10^{-14} per day. Accuracy of this order is required to provide international nanosecond time synchronization and positioning in the centimeter range. Figure (5) is a diagram of NTS-1 and figure (6) shows NTS-2. The configuration of NTS-3 will be quite similar.

To provide the capabilities desired for the TEMPUS satellites, more than the NAVSTAR navigation package and an accurate clock is needed. For additional precise tracking, laser retro-reflectors are desirable. These were carried on NTS-1 and again on NTS-2 which has 44 corner reflectors on the bottom of the satellite. These were successfully tracked with the Smithsonian Astrophysical Observatory's laser on Mt. Hopkins, Arizona. Figure (7) shows a picture of the laser corner reflectors and figure (8) indicates the results of the Mt. Hopkins laser tracking experiment which produced errors whose sigma was less than two meters in this first attempt.

In addition to laser retroreflectors, the TEMPUS package should contain accelerometers to measure external forces on the satellite such as solar pressure since this is probably the largest single source of ephemeris error. An event timer should also be added to record significant happenings aboard the spacecraft. Because of the development of very long baseline interferometry receiver capability, and the measurement precision available with this tool, the TEMPUS package should also provide a signal for VLBI reception.

Since the navigation package will already be aboard the NAVSTAR satellites, the modified TEMPUS spacecrafts should contain at least the following extra units:

- Hydrogen maser/advanced cesium clock,
- Laser retroreflectors,
- Accelerometers,
- Event timer,
- VLBI transmitter.

A relatively simple TEMPUS parkage can be designed to provide all these components at relatively small cost in weight, space and power. In addition to providing much greater accuracy this package will also allow improved resolution of the ephemeris error budget components and thus a better ephemeris prediction model. The NTS-3 satellite can provide all these capabilities. Since this satellite is scheduled for launch in 1982, it will be an excellent prototype TEMPUS satellite, particularly since it is to act as a replenishment spacecraft in the NAVSTAR constellation.

Cost and timescale information for TEMPUS will depend upon requirements and future world economic conditions, however the basic technology is currently available and will be tested in NTS-3. By the 1982 timeframe the space shuttle should greatly reduce launch costs.

It should be emphasized that the development of a time synchronization and precision tracking satellite package such as TEMPUS for installation aboard selected NAVSTAR satellites or some other system with similar characteristics should be a truly international program with the participation of many countries if we are to derive maximum scientific research benefits from its use.

If the need for such a capability in space is visualized for the period beginning in 1983, now is the time to begin the planning. It is suggested that those scientific groups who foresee a requirement for such a precise time synchronization and tracking system take the lead in establishing the system parameters.

NAVSTAR GPS
NAVIGATION TECHNOLOGY SEGMENT
STATION SYNCHRONIZATION BY TIME TRANSFER

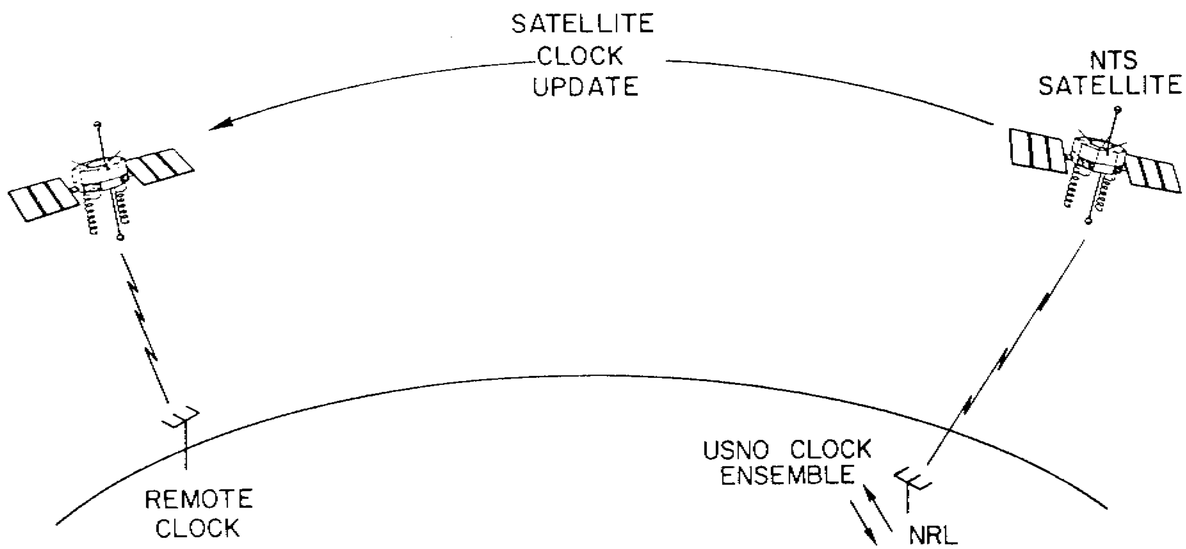


Figure 1

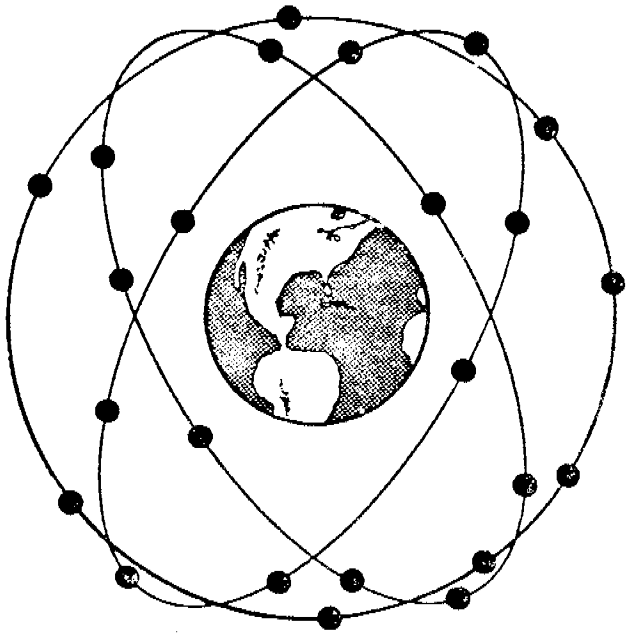
Figure 2

INTERNATIONAL TIME SYNCHRONIZATION VIA NAVIGATION TECHNOLOGY SATELLITE (ITS / NTS)

SUMMARY OF
PORTABLE CLOCK CLOSURES
VS
NTS TIME TRANSFER RESULTS

STATION	DAY (1978)	PORTABLE CLOCK NTS TIME TRANSFER (US)
BIH	124	-.57
CERGA	117	.70
DNM	282	.09
IFAG	199	.03
NBS	221	.19
NRLM	299	-.53
RGO	115	.44
RRL	303	.13
USNO	186	.04

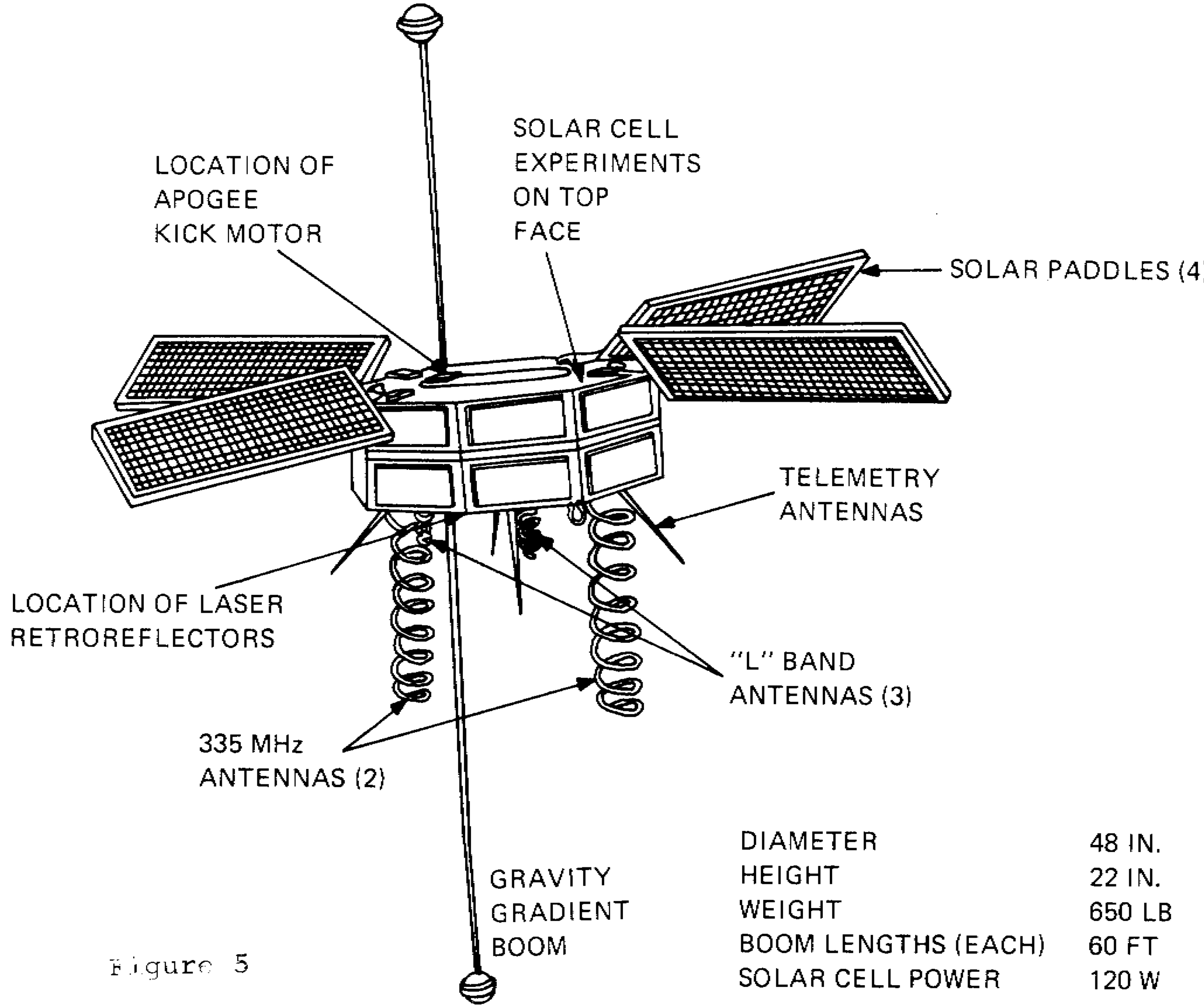
Figure 3



FULL CAPABILITY
24 SATELLITES (MID 1980's)

Figure 4

NTS-1



DIAMETER	48 IN.
HEIGHT	22 IN.
WEIGHT	650 LB
BOOM LENGTHS (EACH)	60 FT
SOLAR CELL POWER	120 W

Figure 5

NTS-2

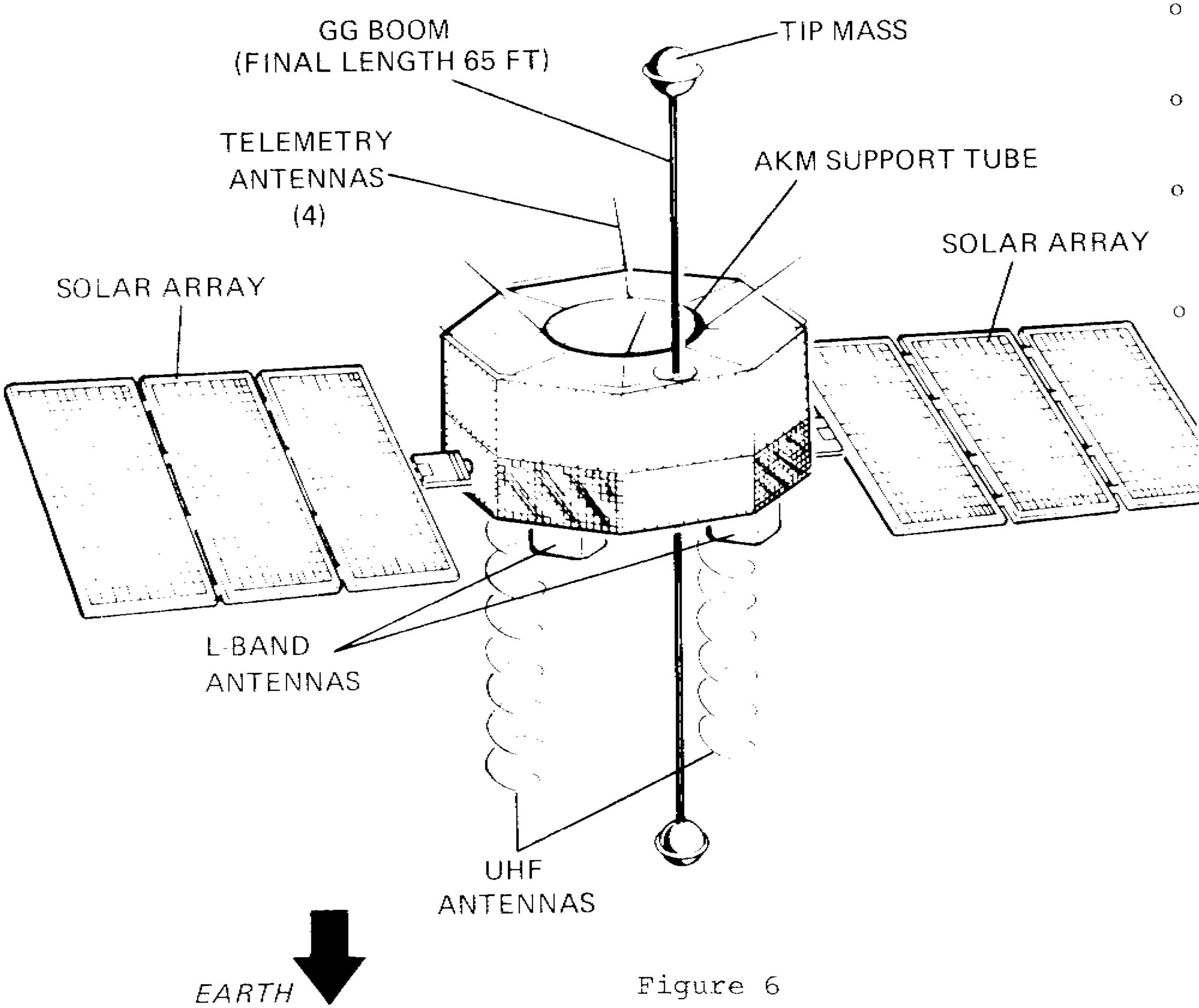


Figure 6

OBJECTIVES

- o Demonstrate Feasibility of Cesium Frequency Standard
- o Initial Demonstration of Navigation Payload
- o Function as One of Satellites in GPS-Phase I Constellation
- o Specific Technology Objectives:
  - -To Provide Orbit Prediction & Tracking Concepts
  - -Test the Use of Nickel-Hydrogen Batteries
  - -Test Side-Tone Ranging Navigation
  - -Time Synchronization Between Remote Stations
  - -Stage/Launch Vehicle Performance
  - -Laser Retroreflector
  - -Solar Cell Experiments
  - -Thermal Coating Experiment

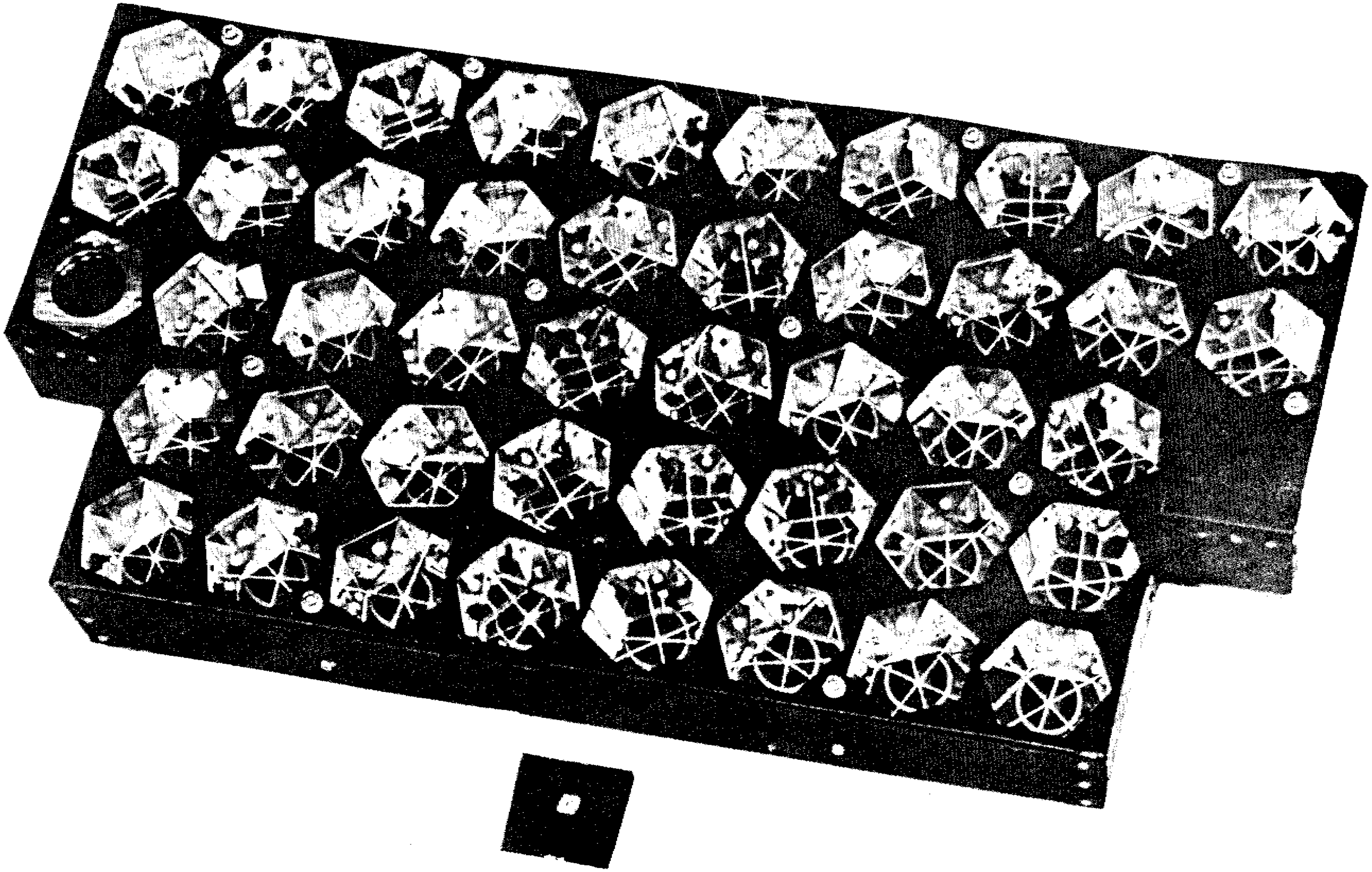


Figure 7
Laser Retroreflector NTS-2

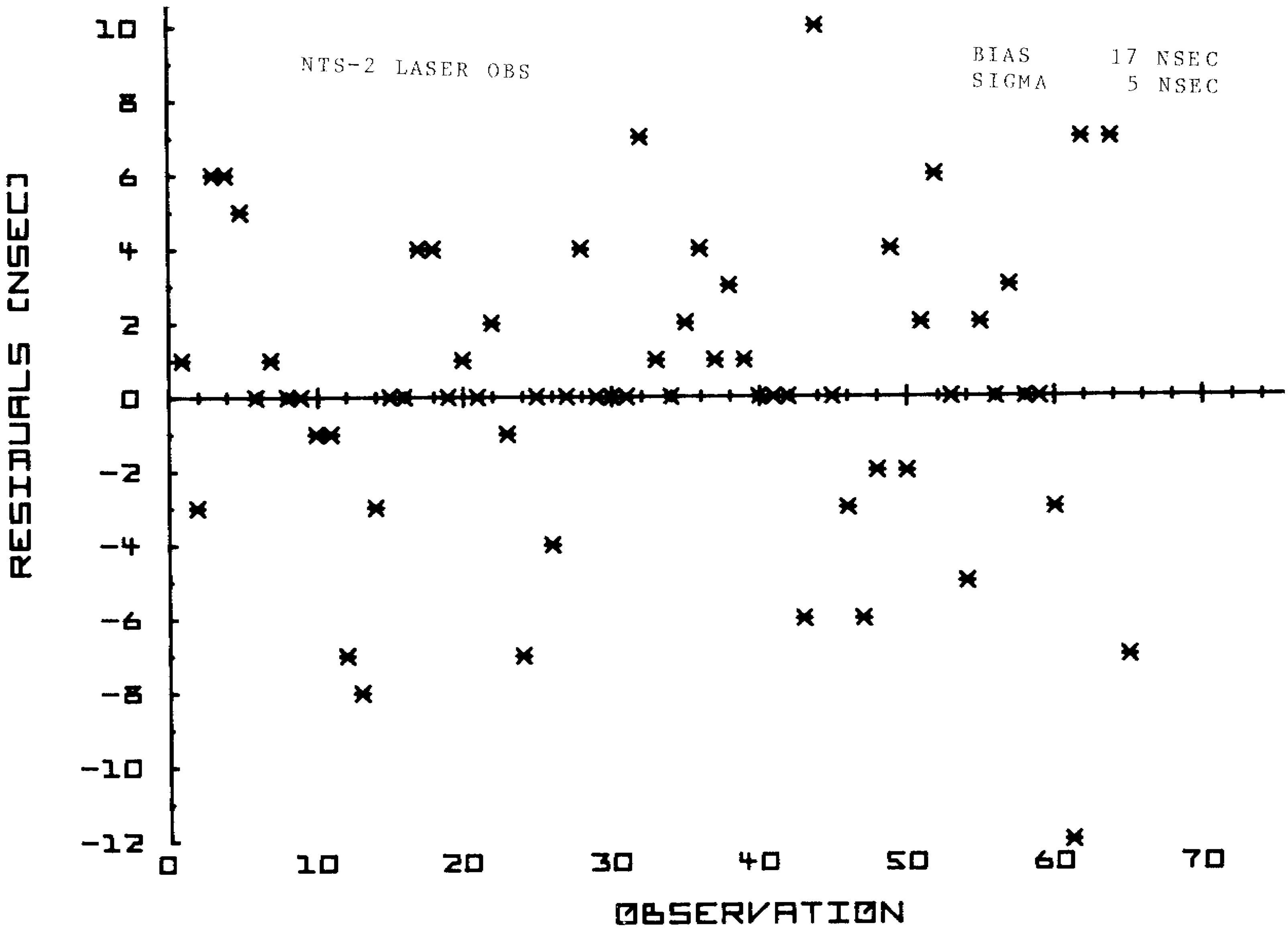

NTS-2 LASER OBS
BIAS 17 NSEC
SIGMA 5 NSEC
RESIDUALS [NSEC]
OBSERVATION
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
0
10
20
30
40
50
60
70

FIGURE 8

QUESTIONS AND ANSWERS

DR. GERNOT M. R. WINKLER, U.S. Naval Observatory:

I think I am very much in agreement with the overall concept. However, I think that your timing estimate is conservative at least by a factor of 10.

Laser ranging, two-way ranging, if it is executed from two stations within short intervals, does not really require a great stability of the clock; and the experiments at the University of Maryland and of the lunar laser ranging and others, the NASA experiments with the geodetic satellites, have indicated that nanosecond and fractional nanosecond time precisions can be expected.

So I think you probably are talking about a capability which will be as far-reaching and of as high precision as we can envision can possibly be used by anyone, and will be available during the foreseeable future. And this makes, of course, such a proposal very interesting.

I do not feel that the constellation may be necessary, but certainly more than one, because we have seen from past experience the fallacy of designing expensive experiments around a single satellite. I think that is a very fallacious approach.

However, the one which you have recommended is, of course, going around that. I think the whole thing makes very much sense, and I would like to express my hope that such a thing can be promoted. Thank you.

DR. HELMUT HELLWIG, National Bureau of Standards:

I would like to add a question. As most of you know, there is also a European Space Agency proposal on a related package called the LASSO experiment. Is there international coordination between that and TEMPUS?

MR. HOLMES:

I think there are probably other people who probably know more about that experiment than I do. My understanding is that it is a single shot which is piggyback, I believe, aboard an Italian satellite. It has a useful lifetime of on the order of five months; is that right, Dr. Winkler?

DR. WINKLER:

No. The useful life is much longer. However, the availability for the Western Hemisphere is only five months because it will be rescheduled to go somewhere around longitude zero, or even +15°, and it will not be available to us any more. And in addition, it is a very expensive one to instrument and it is a single one. And the objections and questions I have indicated before apply here very much.

DR. HELLWIG:

It is on a synchronous satellite. But as I understand the European people, although what you say is true, they plan for the future to put the package on other vehicles which are not necessarily just for the European sphere. It remains to be seen.