# Dissemination of Time and Frequency by Satellite

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*Abstract*—A survey is given of the field of satellite time dissemination covering past experience, present activities, and future planned services with their respective precisions and accuracies.[1] Transponder satellites, clock-carrying satellites, satellite systems, and two-way satellite links are discussed.

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## I. Introduction

IONOSPHERIC EFFECTS on radio propagation limit the precision of terrestial time and frequency dissemination services. The use of satellites offers better precision and hope of eventual relief from the problems of mutual interference of the existing time and frequency services in band 7 (HF). Three different modes of satellite time and frequency transfer have been developed and have come into practical use. Table I summarizes these techniques. These three methods have rather different performance characteristics and each is best suited for a particular class of application.

Method A uses geostationary satellites to distribute WWV-type time signals of the U.S. National Bureau of Standards to a large number of users. This method could eventually

TABLE I

| METHOD | SATELLITES & SATELLITE SYSTEMS |
|---|---|
| A Broadcast from synchronous satellites | ATS (Applications Technology Satellite)<br>SMS/GOES (Synchronous Meteorological Satellite/ Geostationary Operational Environmental Satellite) |
| B Clock carrying satellites | Transit - TIP (Transit Improvement Program)<br>Timation<br>NTS (Navigation Technology Satellite)<br>GPS (Global Positioning System) |
| C Satellite relays | DSCS (Defense Satellite Communications System) |

replace some of the existing radio time and frequency broadcasts.

Method B uses navigation satellites carrying time standards. Since the positions of these satellites are well-known and navigation and time are interrelated, such satellites are important sources of accurate time dissemination. In Table I are listed the types of satellites that have been and will be used.

Method C uses two-way repeaters on communications satellites. This method has been used extensively by the U.S. Naval Observatory. Its main use is restricted to linking distant time stations because ground stations are very expensive and in fixed locations. Time must be disseminated further from these sites by other methods. Path delays, however, can be nearly eliminated with this method; it is, potentially, the most accurate method available. In the following, the three methods are discussed. The discussion is carried out in a summary form with more details available from the references.

It is not perhaps obvious to the nonspecialist that the submicrosecond precision, which is possible with some of the techniques described, is a practical and present requirement. To answer this very complex question, a major portion of the May 1972 special issue of the PROCEEDINGS was devoted to this subject.

## II. BROADCASTS FROM SYNCHRONOUS SATELLITES

Fig. 1 shows a schematic of the ATS-3 satellite experiment using the regular WWV format [1]. The WWV information was sent from a ground station at NBS, Boulder, CO, to the ATS-3 geostationary satellite and rebroadcast on 135.625 MHz. The ATS-3 satellite had a significant amount of residual motion and, as a result, the signals received in the Western Hemisphere were modulated due to the first-order Doppler effect. This is shown in Fig. 2, which gives the Doppler modulated time of arrival information from the ATS-3 satellite for different receiver locations as a function of time.

From Fig. 2, it is obvious that the raw data could be used for getting time information to the order of 1 ms by unsophisticated users making only crude corrections for path delay, satellite motion, and location.

One of the principle advantages of the satellite broadcast is its signal strength. In Fig. 3, multiple oscilloscope sweeps of the WWV tick are compared to the ATS-3 ticks using equipment of similar sophistication.

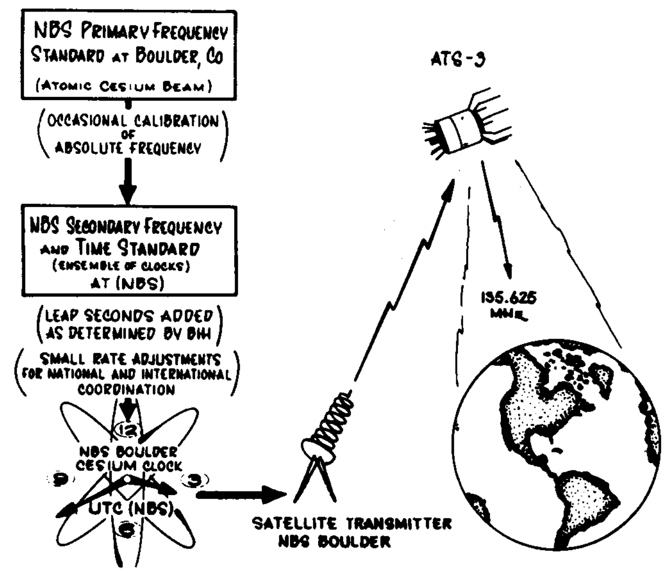


Fig. 1. Time and frequency broadcasting from the ATS-3 satellite.

For those users who would like to extract more precise timing information, data on the precise position of the satellite and its motion were made available in the broadcast format. This information along with the position of the user and of NBS, Boulder, allowed calculation of path delays and provided a timing precision of tens of microseconds. To facilitate these computations, NBS developed a slide-rule calculator and programs for programmable calculators, including hand-held calculators.

The ATS-3 experiment was discontinued in the Fall of 1973. The present NBS activity in satellite dissemination uses the SMS-2 satellite, a photo of which is shown in Fig. 4. The present position of the satellite is approximately 135° west longitude over the Pacific. The satellite provides a coverage of the Pacific Basin, most of North America, and the western half of South America. Fig. 5 shows a schematic of the up- and downlink for the SMS-2 satellite. The uplink is an *S* band signal and the downlink is placed on 468.825 MHz. The

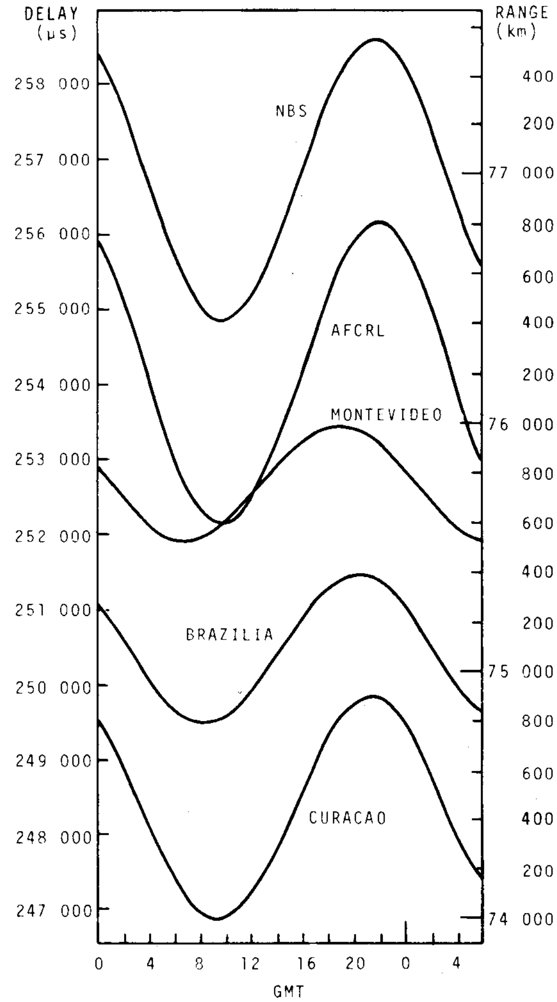


**Fig. 2. Delay variation due to satellite motion (AFCRL = Air Force Cambridge Research Laboratory).**

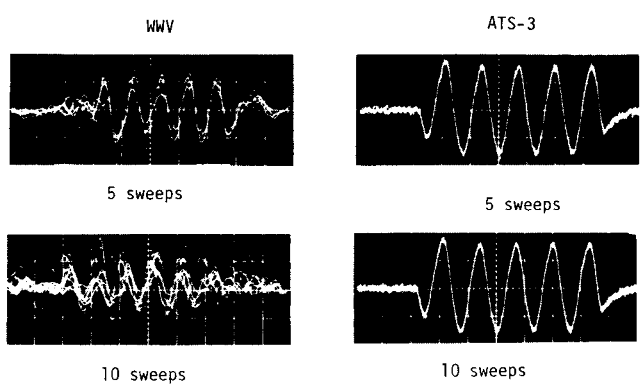


**Fig. 3. Multiple oscilloscope sweeps of the WWV and ATS-3 ticks.**

ground station is located at Wallops Island. Orbital elements for the satellite are sent by NASA via Teletype to Boulder. The satellite ephemeris is computed by NBS and then sent to Wallops Island.

The format of the time information, a time code, is shown in Fig. 6. Present information is geared to allow a reasonable precision for users having dedicated equipment available. Thus the time code includes not only the full date information, the day, hour, minute, and second, but also the position of the satellite. Thus a user with equipment capable of receiving

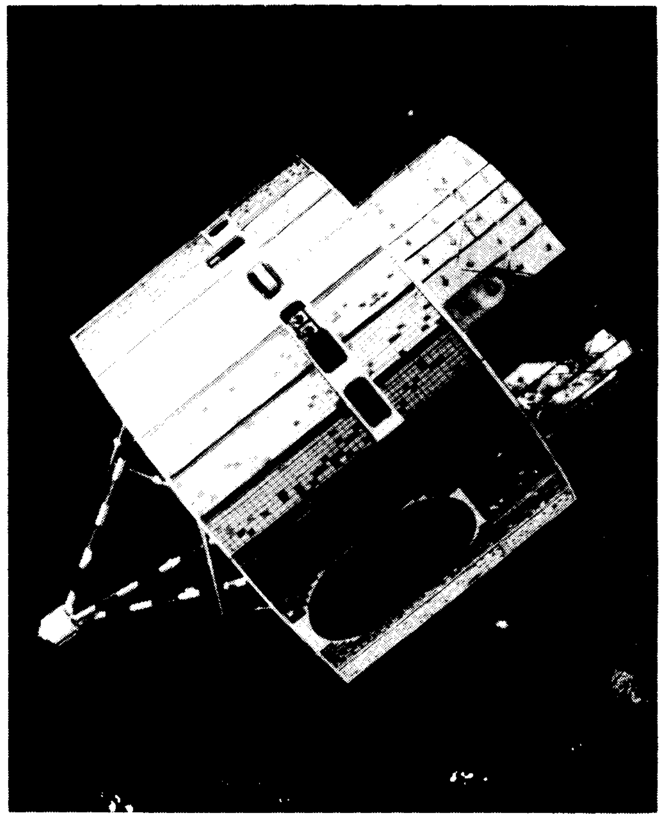

**Fig. 4. Synchronous meteorological satellite (SMS).**

and decoding the message can synchronize his clock to UTC (NBS) with a precision of about 100 $\mu$s. Receiving equipment was developed utilizing a microprocessor for the decoding. A photo of the decoder receiver and decoder clock, which actually displays the time, is shown in Fig. 7.

## III. Clock-Carrying Satellites

Fig. 8 shows a schematic of Timation III which carries a crystal clock and two rubidium standards on board. This satellite orbits the earth in eight hours and allows the synchronization of clocks at distant locations around the globe. One of the earlier experiments ([2], [3]) is shown in Fig. 9 where the data from a time comparison between Australia and the U.S. Naval Observatory using the Timation II satellite are depicted [4].[2] The important aspect of Fig. 9 is not the slope, which simply indicates the frequency difference between the two compared clocks (clock systems), but the scatter of the points which indicates that a precision of about 0.1 $\mu$s was realized. The absolute accuracy of the time comparisons was better than 0.2 $\mu$s when checked with portable clocks. The experiments with Timation were carried out by the Naval Research Laboratory.

The Applied Physics Laboratory of Johns Hopkins University was involved in the Transit system development [5], [6]. In Fig. 10, the propagation delay contributors encountered in clock-carrying satellites are shown. Delays and corresponding errors are encountered in the distance between the satellite and the user, the ionosphere, the troposphere, and, of course, in the equipment itself, such as antenna and receiver.

[2] Timation II is similiar to Timation III; it carries, however, only crystal clocks.

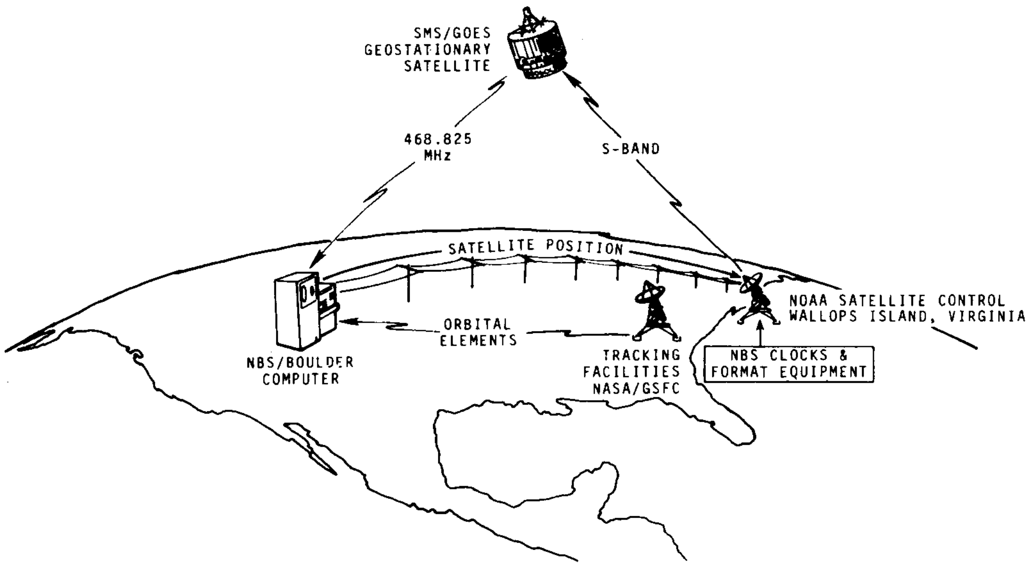


Fig. 5. SMS time-code distribution system.

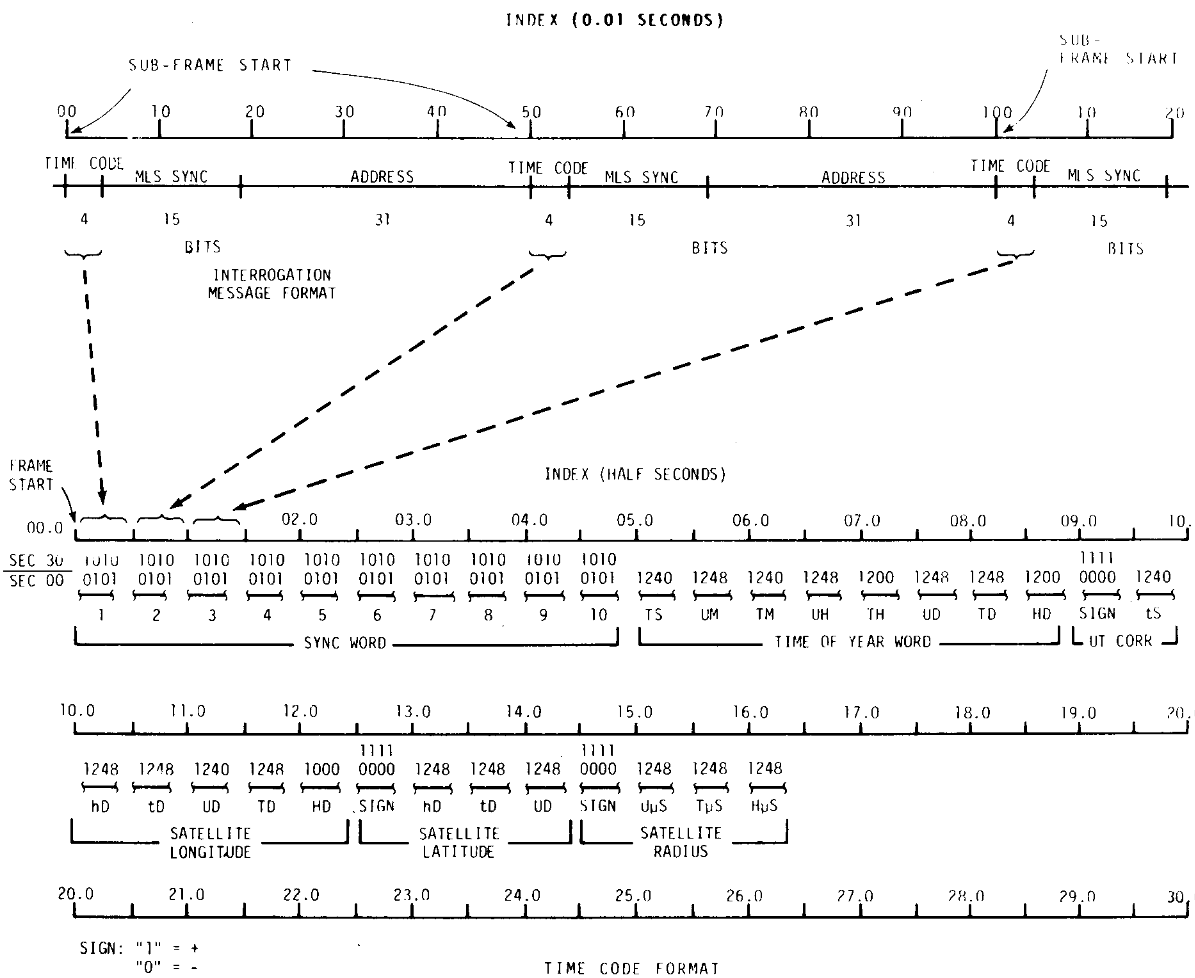


Fig. 6. SMS time-code format and multiplexing into SMS interrogation channel.

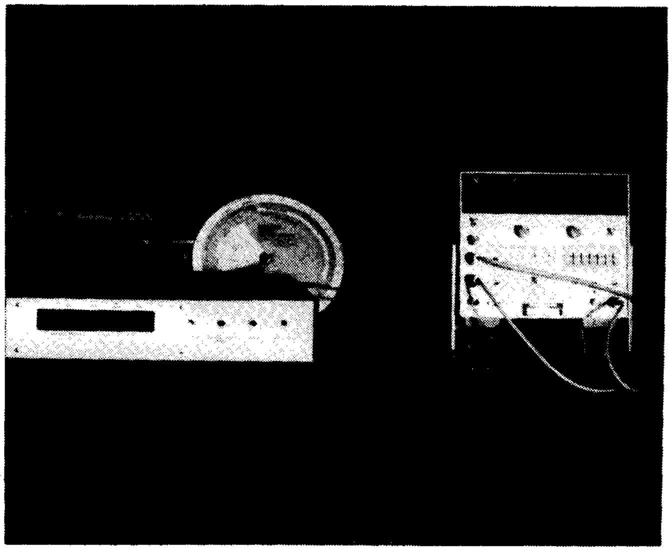

Fig. 7. Time-code receiver, decoder clock, and delay computer (slide rule).

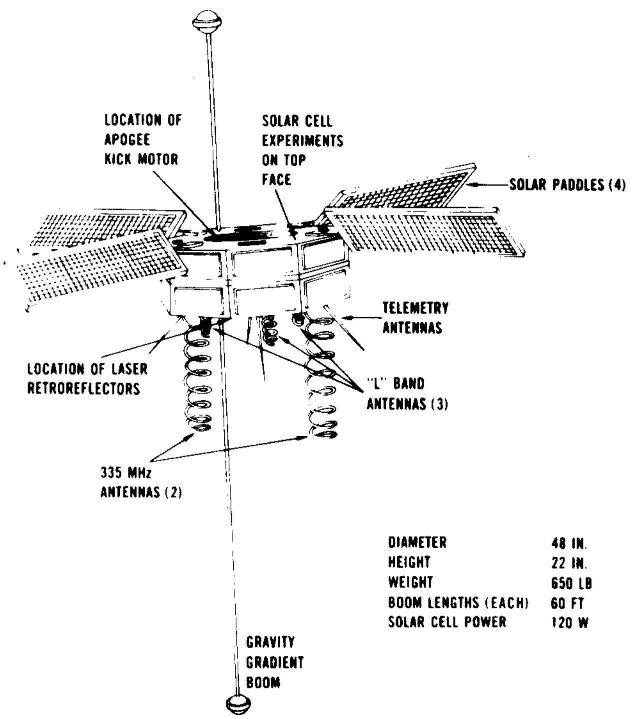


Fig. 8. Timation III or NTS-1 satellite. Timation II for which measurement results are reported has a similar outer appearance.

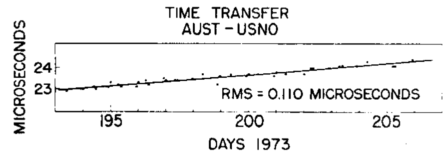


Fig. 9. Time transfer between USNO and Australia via Timation II.

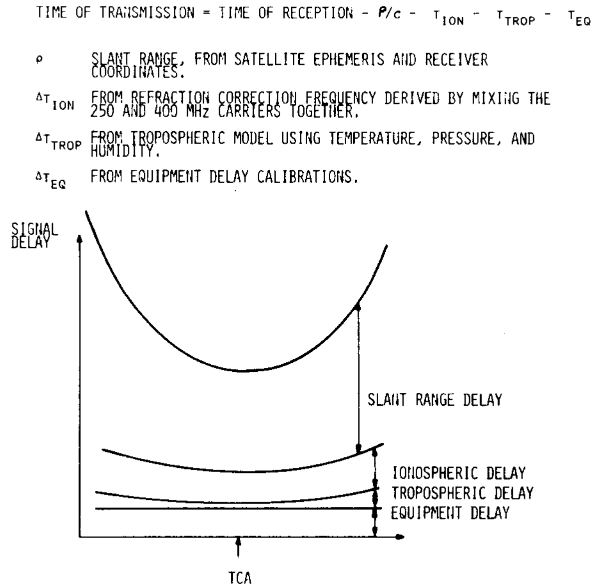


Fig. 10. Clock synchronization method.

The magnitude of the correction, and with it the error, is minimum at the time of closest approach (TCA); i.e., at the minimum of the curve in Fig. 10. It is prudent to adjust the clock on the satellite to model out coarse effects, such as clock drift, which otherwise would require considerable user-sophistication at each user-location in order to take it out. APL has developed a special synthesizer for this purpose. It allows adjustment of the output signals of the clock system with no adjustments to the clock itself. Fig. 11 shows the stability of this synthesizer compared to the stability of two cesium standards [7]. We see that below a few seconds, the synthesizer is the major noise contributor, but its noise is negligible as compared to these high-performance standards for times longer than a few seconds. The additional noise contribution at short times can be disregarded because the contribution of the synthesizer of one part in $10^{11}$ at 1 s corresponds to a time error of only 10 ps.

Tests of this system were carried out with an experimental ground station featuring two totally separate receivers, including separate antennas. These ground stations were able to communicate high-precision signals directly because they were located in close proximity in the same laboratory.

Information was obtained in the "regional mode" and the "global mode." In the "regional mode," both stations were using the same signals from the satellite in common view. The resulting data are shown in Fig. 12 where the predicted timing data from one station in terms of the other are plotted (circles) and compared to the real data obtained by utilizing the two receivers (crosses). A precision of tens of nanoseconds was achieved.

In the "global mode," the time was predicted by one station from information received from the satellite, including the clock drift on board the satellite. The predicted time was then compared to the time received and measured at the other station. Experiments at various prediction times were carried out. The most interesting data are shown in Fig. 13 where a prediction for seven full orbits was carried out; i.e., for twelve hours of operation, sufficient to reach anywhere in the world. The difference between the time as received and the time as it should be was hundreds of nanoseconds.

A look at the errors for this system (Fig. 14) indicates that the major contributors to the deterioration of precision going from the "regional" to the "global" mode were the drift of the satellite clock and uncertainties in satellite position prediction. The other contributors were of a less important

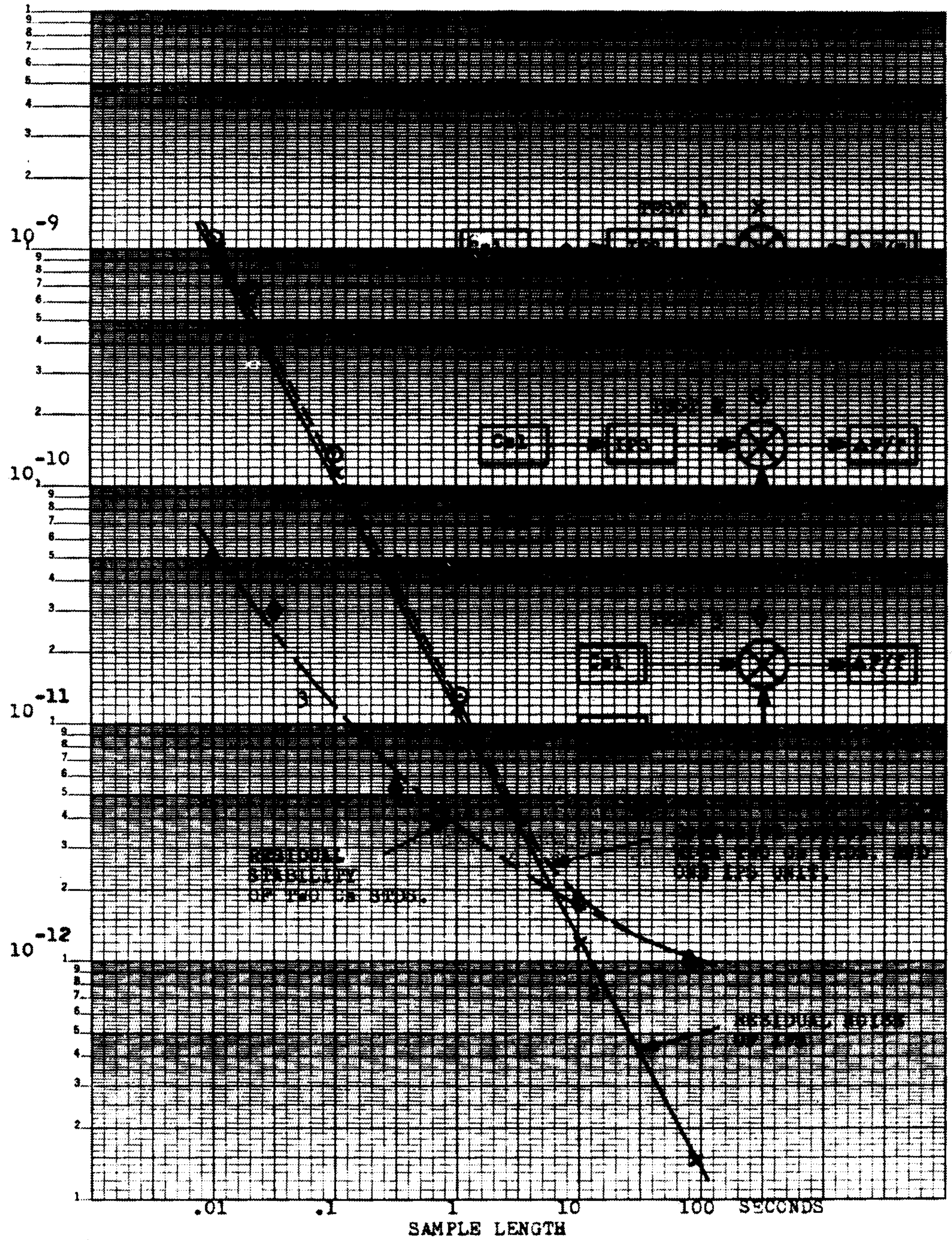


**Fig. 11.** Frequency-stability performance of the synthesizer used in the Transit system.

nature. The use of better clocks on board the satellite and improved satellite position prediction should, therefore, improve precision of global synchronization. The frequency and time performance of Transit satellites is published in the *U.S. Naval Observatory Time Services Announcement*, Series 17 [8].

## IV. Satellite Relay

Several modes of obtaining precise information of the path delay are possible. Most notably, direct round trips from each of the two stations, using the satellite as transponder, or (as shown in Fig. 15) a total round trip of a signal. The signal originates at station 1, is transponded by the satellite, received at station 2, rebroadcast immediately back to the satellite, and transponded down to the originating station 1. With the assumption of symmetry in the characteristics of the reception and transmission, or with adequate modeling of any of these differences, the satellite delay can—in principle—be taken out totally (see Fig. 16). This is also possible even in the simplest case of each station transmitting its timing waveform one way to the other site while it measures the time of arrival of the other station's waveform against the local clock.

In the mid-1960's, two experiments were conducted using such a system. IN 1964, Telstar I was used to synchronize clocks in the U.S. and U.K. This demonstration showed that clocks across the Atlantic could be synchronized with an accuracy of ± 1 μs using available equipment [9].

Two years later, Relay II was used in an experiment between the U.S. and Japan. At that time, 0.01-μs synchronization accuracy was considered feasible, the limiting factor being the

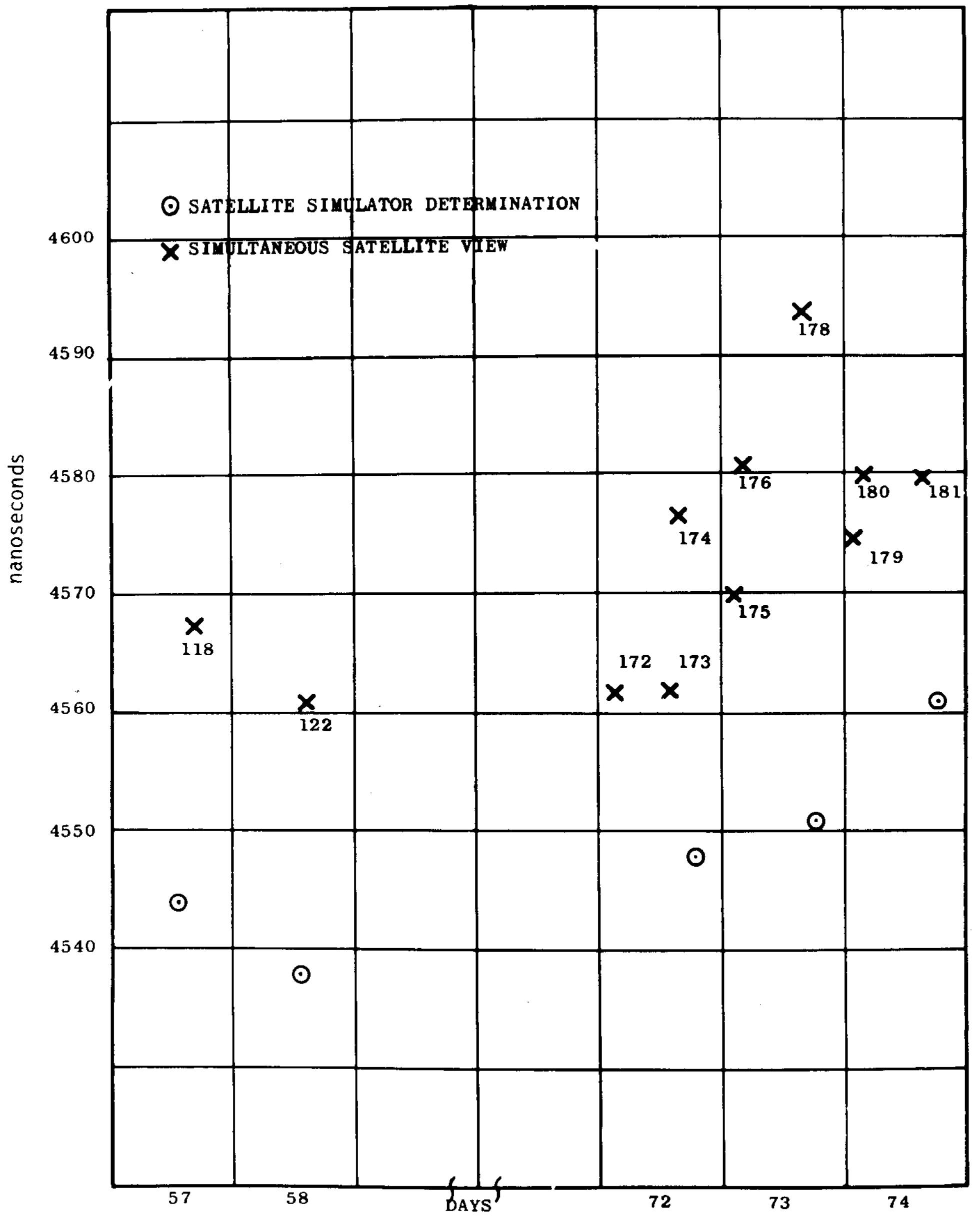


Fig. 12. Regional clock-synchronization data using the Transit system.

accuracy in the determination of the difference between the transmitting and receiving delays at the two ground stations [10]. Presently the main application of the satellite relay system, on a non-interfering basis, is over the Defense Satellite Communications System (DSCS). Several ground stations are in operation and equipped with timing electronics.

Each station is equipped with a modem [11], a time-transfer unit inserted between the modem and the clock, and a counter (Fig. 17). The time-transfer unit automatically compares the transmitted and received pseudo-random noise (PRN) coded signals at each station with the local clock. The difference between the two counter readings is then easily related to the time difference between the two clocks. With the slow-moving DSCS satellites, 0.1-$\mu$s accuracy is possible if the transmitted pulses occur within approximately one second of each other. In practice, the station clocks are within tens of microseconds and the satellite motion is completely negligible.

Since timing precision is mainly dependent on the available band-width, a low level PRN timing code can be superimposed upon the IF with negligible degradation of the communications signal-to-noise ratio. The lower the timing signal level chosen, the longer the correlation (or PRN decoding) time constant required. In the communications "test bed" at the Naval Communications Station, Wahiawa, Hawaii, NRL-developed Time Transfer Modems (TTM) have demonstrated such a capability. A DSCS circuit between Camp Roberts and Kwajalein was similarly used without excessive degradation of the primary channels.

An operational service, described in [12], is available between the U.S. and several DSCS terminals around the world. This information is published in Series 16 of the *U.S. Naval Observatory Time Service Publications* [13]. One page of this Series is reproduced in Fig. 18 to show the style and types of information available, and also the multitude of stations which are linked via this system to the Naval Observatory.

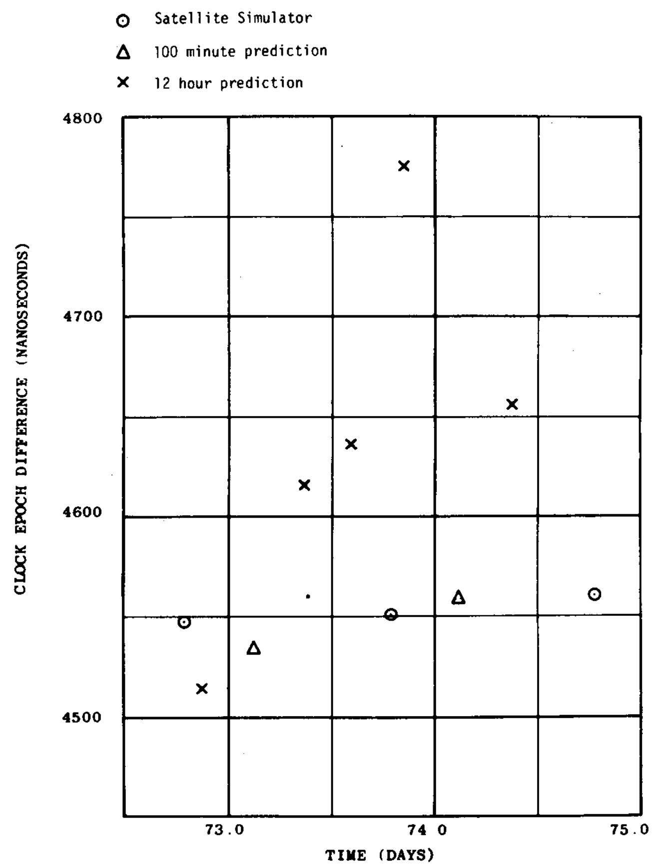


Fig. 13. Global clock synchronization using the Transit system.

| | | Time Error |
|---|---|---|
| A. | Scientific Problems: | |
| | 1. Satellite Position | ~75 ns |
| | 2. Refraction | < 30 ns |
| | 3. Gravity Red Shift[1] | 10 ns |
| B. | Engineering Problems: | |
| | 1. Satellite Oscillator | 200 ns/12 hrs. |
| | 2. Receivers (Two) | ~20 ns |

[1] WHILE ORBITING THE EARTH, THE SATELLITE EXPERIENCES A VARYING GRAVITATION FIELD AND THUS THE MAGNITUDE OF ITS VELOCITY FLUCTUATES. BECAUSE OF THIS, THE SATELLITE OSCILLATOR FREQUENCY CHANGES DURING EACH REVOLUTION. THESE FLUCTUATIONS WERE NOT MODELED DURING THIS EXPERIMENT, THUS THEY CONTRIBUTED TO THE ERROR BUDGET.

Fig. 14. Global clock-synchronization errors of the Transit system.

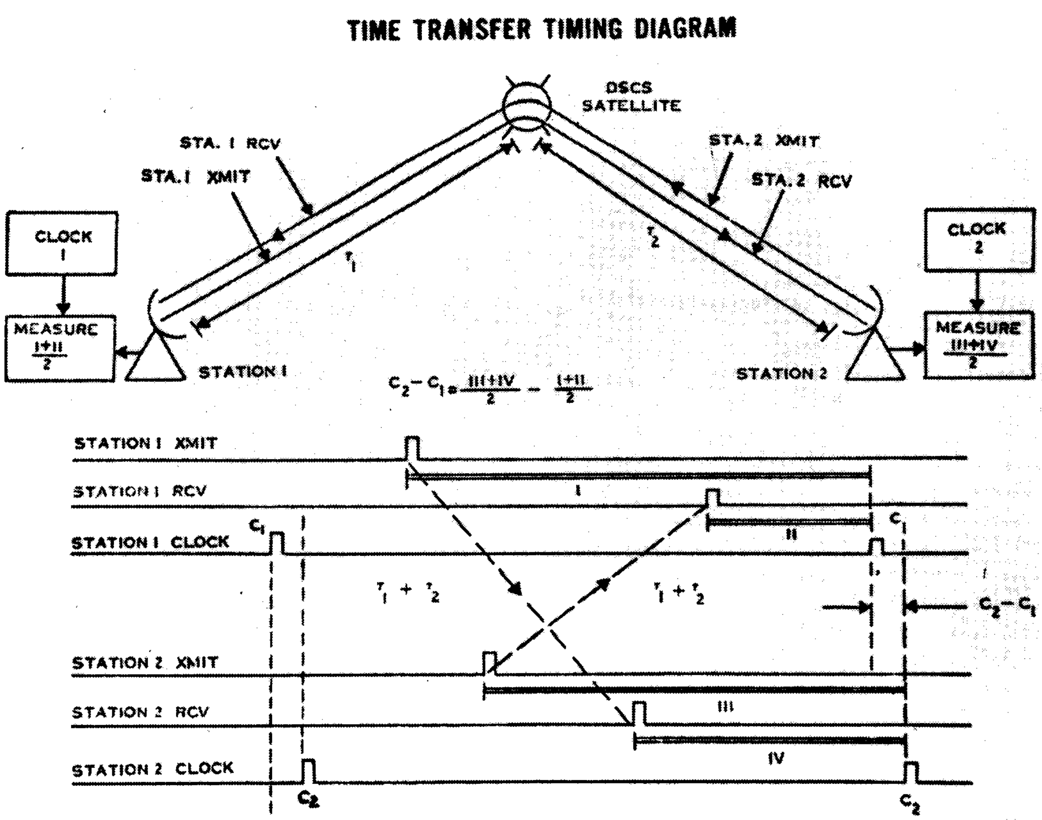


Fig. 15. Time transfer via satellite relay (round trip).

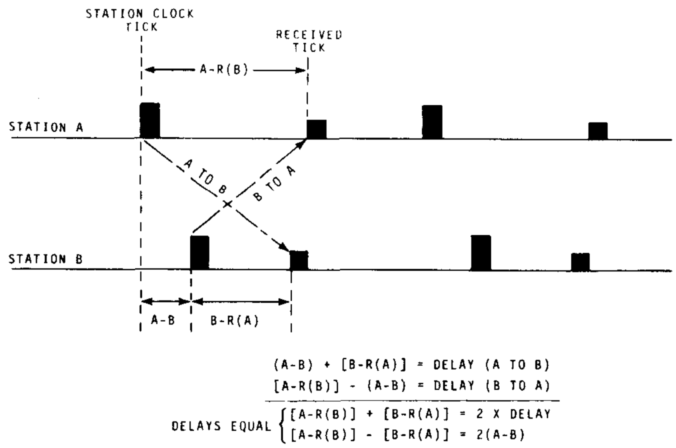


Fig. 16. Principle of simultaneous duplex time transfer.

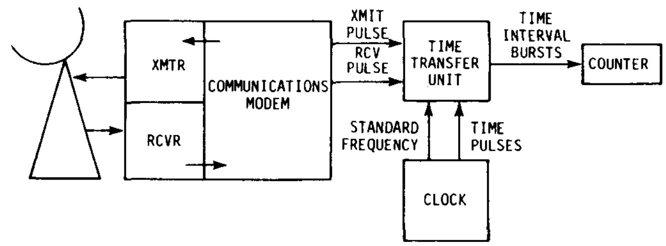


Fig. 17. Configuration for time transfer using modems.

U.S. NAVAL OBSERVATORY
WASHINGTON, D.C. 20390

14 NOVEMBER 1975

PRECISE TIME TRANSFER REPORT SERIES 16 NO. 71

THE REPORT LISTS UTC(USNO MC) - UTC(REFERENCE CLOCK) REFERRED TO 0000 UTC.

UNIT IS ONE MICROSECOND. ESTIMATED ACCURACY IS ± 0.3 MICROSECOND.

| | MJD | BWS/ 527 | CPS/ 576 | CPS/ 550 | DETC/ 060 | DETC/ 120 | DIS/ 343 | EDZ/ 960 | ELM/ 516 | EPTRS | FDS/ 410 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| OCT. 18 | 42703 | - | - | - | - | - | -1.7 (3) | 3.7 (3) | - | - | - |
| 19 | 42704 | - | - | - | - | - | -1.7 | 3.4 | - | - | - |
| 20 | 42705 | -0.7 (2) | 7.7 | -1.0 | 2.7 | -9.4 | -1.8 | 3.8 | - | - | - |
| 21 | 42706 | - | - | - | - | - | -1.9 | 3.6 | - | - | - |
| 22 | 42707 | - | - | - | - | - | -1.9 | 3.6 | - | - | - |
| 23 | 42708 | - | - | - | - | - | -1.9 | 3.7 | -0.6 | - | - |
| 24 | 42709 | -0.8 (2) | - | - | 2.8 | -9.6 | -2.0 | 3.8 | - | - | - |
| 25 | 42710 | - | - | - | - | - | -1.9 | 3.8 | - | - | - |
| 26 | 42711 | - | - | - | - | - | -2.0 | 3.9 | - | - | - |
| 27 | 42712 | - | 7.5 | -0.8 | 2.4 | -10.1 | -2.1 | 3.8 | - | - | - |
| 28 | 42713 | - | - | - | - | - | -2.6 | 3.8 | - | - | - |
| 29 | 42714 | - | - | - | - | - | -2.4 | 3.7 | - | - | - |
| 30 | 42715 | - | - | - | - | - | -2.3 | 3.6 | -0.4 | 50.9 | - |
| 31 | 42716 | - | 7.2 | -0.7 | 2.2 | -10.3 | -2.5 | 3.5 | - | - | - |
| NOV. 1 | 42717 | - | - | - | - | - | -2.5 | 3.7 | - | - | - |
| 2 | 42718 | - | - | - | - | - | -2.6 | 3.8 | - | - | - |
| 3 | 42719 | - | 6.9 | -0.9 | - | - | -2.6 | 3.8 | - | - | - |
| 4 | 42720 | - | - | - | 2.2 | -10.5 | -2.6 | 3.8 | - | - | - |
| 5 | 42721 | - | - | - | - | - | -2.7 | 3.8 | - | - | - |
| 6 | 42722 | - | - | - | - | - (4) | -2.6 | 4.0 | -0.6 | - | - |
| 7 | 42723 | -0.7 (2) | 6.9 | -0.9 | 2.1 | 2.4 | -2.7 | 4.1 | - | - | - |
| 8 | 42724 | - | - | - | - | - | -2.7 | 4.1 | - | - | - |
| 9 | 42725 | - | - | - | - | - | -2.8 | 4.1 | - | - | - |
| 10 | 42726 | -0.7 | 7.3 | -0.8 | 2.5 | 2.6 | -2.7 | 4.0 | - | - | - |
| 11 | 42727 | - | - | - | - | - | -3.0 | 4.0 | - | - | - |

Fig. 18. Reproduction from Time Services Publication, Series 16 of the U.S. Naval Observatory.

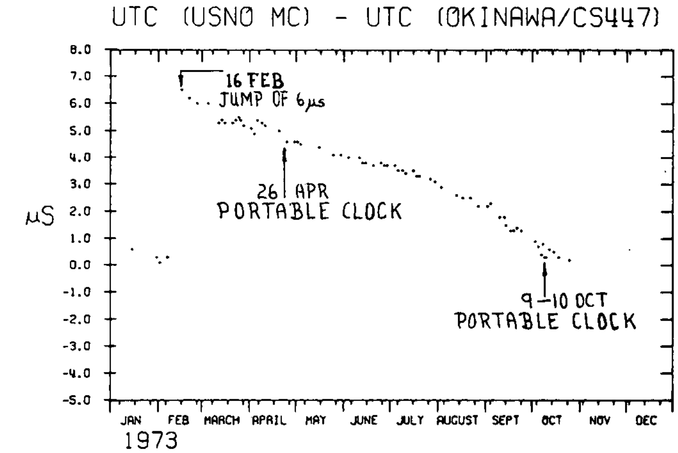


Fig. 19. Time transfer between USNO and Okinawa via DSCS.

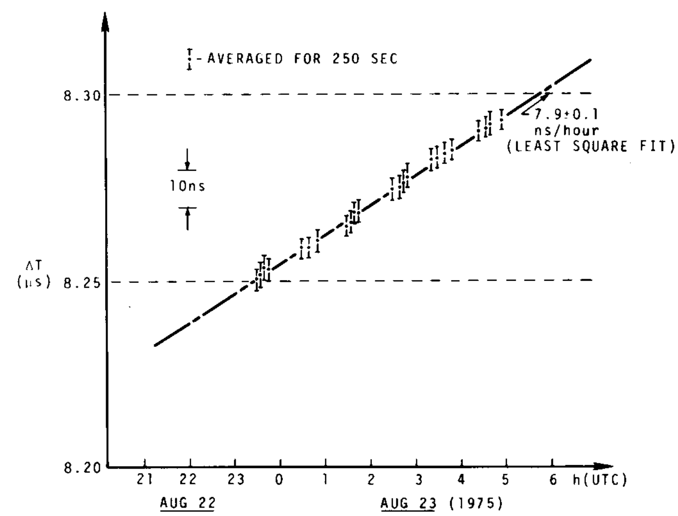


Fig. 20 Example of measured time difference via ATS-1 $\Delta T$ = reference clock (Kashima, RRL)—reference clock (Rosman, NASA).

An example of the precision of this system is given in Fig. 19, which covers a timing experiment between the Naval Observatory and Okinawa. The measurement points depict the actual time difference between these two stations, and two portable clock trips are also indicated. The agreement of the portable clock data with the satellite relay data indicates that there is no systematic unknown time-delay or time-error present beyond 0.1 μs. The scatter of the points indicates the day-to-day precision which also is of the order of 0.1 μs. Thus, the system is presently transferring time to this precision and accuracy. It must be realized, however, that the scatter mentioned is due primarily to the quantization noise (0.1 μs) in the present counters which were selected on the basis of economy. Upgrading the equipment will reduce the scatter.

That greater than 0.1-μs precision is indeed possible, was demonstrated in an experiment (Aug. 1975) using the ATS-1 satellite (see Fig. 20), organized by the Radio Research Laboratory, Tokyo, Japan [14]. Using DSCS, Fig. 21 shows the links from the Naval Observatory to Europe on the one hand, and via Hawaii to Australia on the other hand. It should be emphasized again that local time dissemination is carried out via cable, Loran-C, TV, portable clocks or other available means of time transfer at the satellite ground station. The DSCS links therefore play the role of point-to-point high precision "trunk-line" links as compared to the direct user access with the other satellite systems previously discussed.

## V. Future Developments and Possibilities

It may be of interest to the reader, that the primary reason for the existence of more than one high performance time dissemination system is not any specific time-user demand. These systems rather came into existence because of other demands relating to communication and navigation which shall not be discussed here. Being time-ordered systems, precise system timing is a prerequisite for its proper functioning. Only comparatively minor modifications render these systems useful as general time dissemination services. The time user obtains several benefits from the availability of more than one method; among these are redundancy and the ability for sophisticated error analysis based on the fact that different methods feature different error budgets in kind as well as in magnitude.

The experimental program using the SMS/GOES satellite, conducted by NBS will be continued with improved receiver equipment and decoding equipment under development. This service could ultimately take over the present WWV services and similiar services with the same precision and accuracy in time transfer at similarly low equipment cost to the user. However, it has the capability of offering higher precision by including information on the orbit elements and on the atmospheric model applicable to these transmissions. The distribution of the time code will be increased. The third satellite in this series, GOES-1, was launched December 1975 and is stationed at 75° west longitude over western South America, covering most of North and South America.

The development of the clock-carrying satellites is very promising. New satellites in the TRANSIT system will be launched with improved clocks on board; thus, an operational capability in the near future of 0.1-μs accuracy will be available and the potential of better than 10 ns accuracy exists.

The Timation series is being continued in the NTS series of satellites, which will become part of the Global Positioning System—a total of 24 satellites with global coverage providing to any point on the earth, three-dimensional position plus time information. The clocks carried on the early satellites of the system will be rubidium clocks. Plans to include cesium clocks do exist and there is a possibility that even other advanced clocks such as hydrogen standards will be used. These new clocks of high performance could allow a worldwide timing capability of possibly 10 ns, the limitation being ultimately the ability to model the atmosphere.

Further refinement of the satellite relay technique using the Defense Satellite Communication System will allow a worldwide coverage, as well as an increase in precision. The increase in precision will come from utilizing higher-performing equipment with higher resolution and better-understood delays at the stations, as well as from modeling residual effects like motion of the satellite during transmission round trip time. Future precision of time transfers will be in the order of 10 ns. Ultimately, a precision of better than 1 ns may be possible. Station clocks will normally be pre-synchronized to within a few microseconds, thus making the orbital motion of the satellite during time transfer negligible. To obtain this degree of precision from the time transfers, it will be essential to ap-

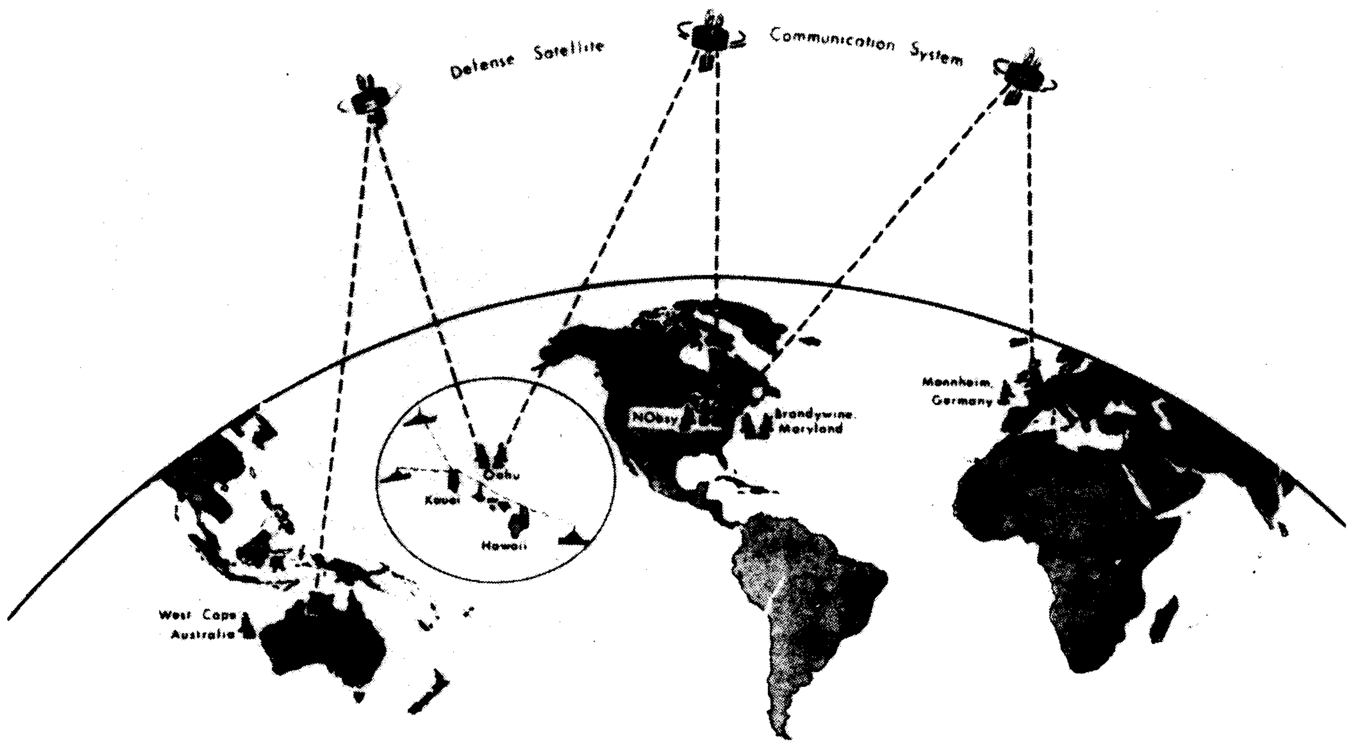


Fig. 21. Precise time and time interval (PTTI)–world dissemination.

TABLE II

| METHOD | SATELLITES & SATELLITE SYSTEMS | ACCURACY | | |
|---|---|---|---|---|
| | | no corrections | realized | possible (idealized) |
| A | ATS<br>SMS/GOES | tens of ms<br>tens of ms | tens of μs<br>tens of μs | -----<br>10 ns |
| B | Transit - TIP<br>Timation<br>NTS - GPS | tens of ms | 30 ns<br>0.1 μs<br>0.1 μs | 10 ns<br>-----<br>10 ns |
| C | DSCS | ----- | 100 ns | 1 ns |

ply corrections for relativistic effects [15]. This timing would be accurate in the forseeable future to satisfy the needs of even the most sophisticated users, who can produce time presently with a precision of 1 ns per day. The following Table II summarizes the realized accuracies and predicted possibilities of the three satellite dissemination techniques.

## REFERENCES


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