SATELLITE COMMUNICATIONS SYSTEM

by J. A. Murray*

INTRODUCTION

The responsibility of the Naval Observatory to maintain precise time coordination on a worldwide basis requires frequent comparisons of distant time standards with the Observatory reference clock. Perhaps the best available means of making these comparisons has been to transport accurately calibrated atomic clocks from the Observatory to the distant locations and to make direct on-site measurements. This method however accurate, is also expensive.

TIME TRANSFER VIA SATELLITE

The use of communications satellites to perform the long-distance comparisons (or time transfers) has been investigated and proved feasible. The Defense Satellite Communications System (DSCS) contains the potential for making the accurate Observatory reference economically available to many vital areas of the world.

Under sponsorship of the Naval Electronics Systems Command and with the cooperation of the Observatory and Defense Communications Agency (DCA), the Laboratory has produced techniques for using certain DSCS links in a noninterfering manner, and successful time transfers have been made on an experimental basis. Use of DCA facilities on an operational basis is planned for the near future.

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The planned time-distribution system would place Observatory-controlled, precise reference clocks at satellite communications (SATCOM) terminals in key areas (see Figure 1). Further distribution will be accomplished by short-distance clock transports or any of a number of short-range techniques to be described in other presentations.

A clock maintained at a SATCOM location near the Observatory will be disciplined by the Observatory standard through comparisons over a direct microwave link or by carrying clocks regularly from the Observatory to the terminal. The clock maintained at the distant SATCOM facility will be updated periodically by comparisons through the DSCS satellite. Since the clocks at the two terminals are held to a nearly constant rate by atomic frequency standards, they need not be compared continuously, but time transfers may be made daily, weekly, or monthly, depending upon the stability of the clocks, the availability of the satellite link, and the required time accuracy.

Use of the satellite system, however, is not unidirectionally beneficial. The time-reference equipment may be used to considerable advantage by the SATCOM terminals in their synchronization procedures, as shown in Figure 2.

Basically, the time-transfer system is not required to insert signals or disturb the operation of station equipment if the terminals are equipped with AN/URC-55 communications modems. The synchronizing signals shown being injected into the modems (see Figure 2) are used only to aid in modem synchronization and are not required for the time transfer. All signals required by the time-transfer unit are available at test points on the modem.

The feature of the modem that makes it useful in time transfers is its high speed pseudo-random code stream. The transmitter section of each modem generates such a stream (see Figure 3), and a code generator

TIME REFERENCE SERVICE VIA SATELLITE

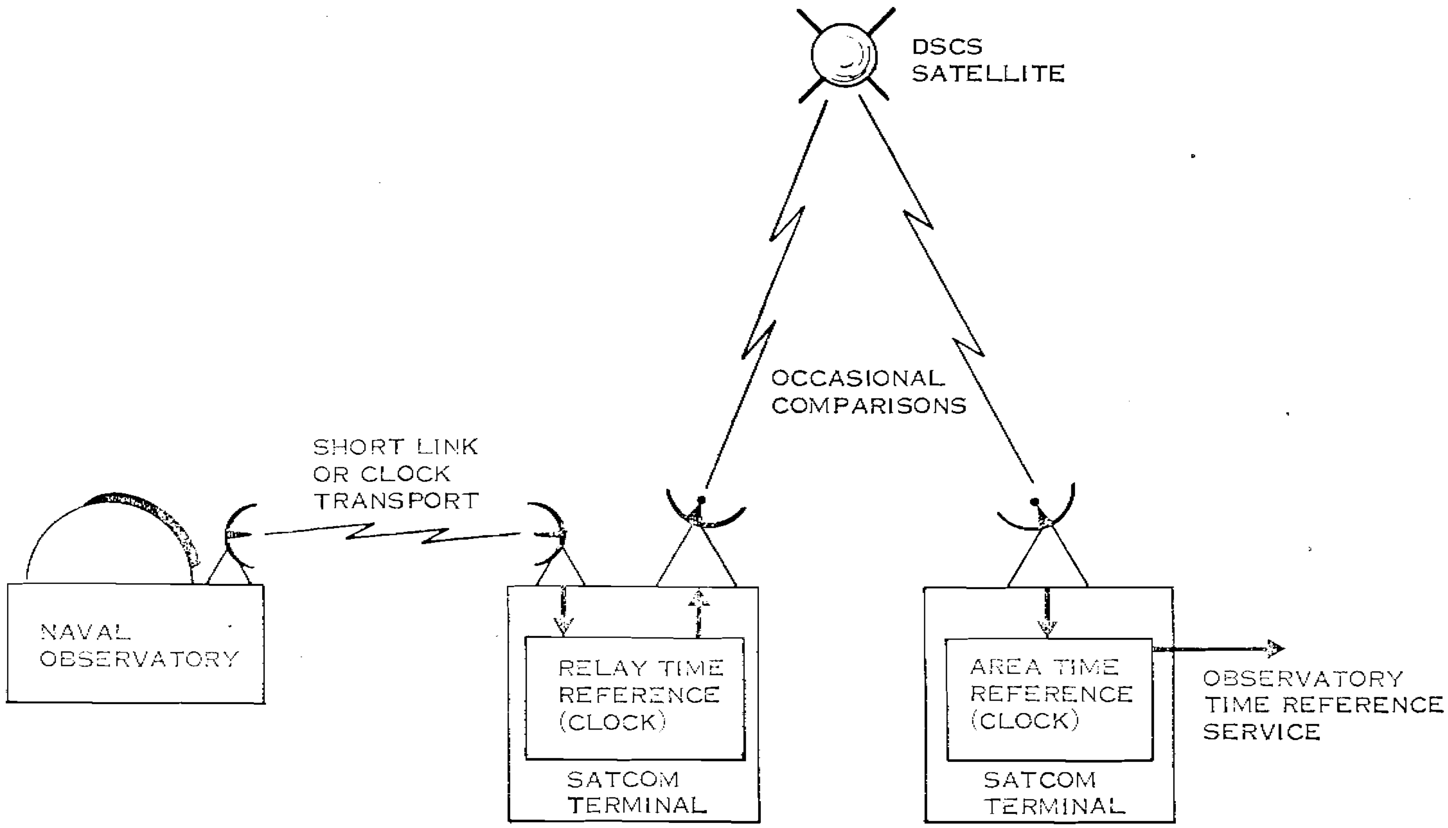


FIGURE 1

TIME TRANSFER BY COMMUNICATION SATELLITE

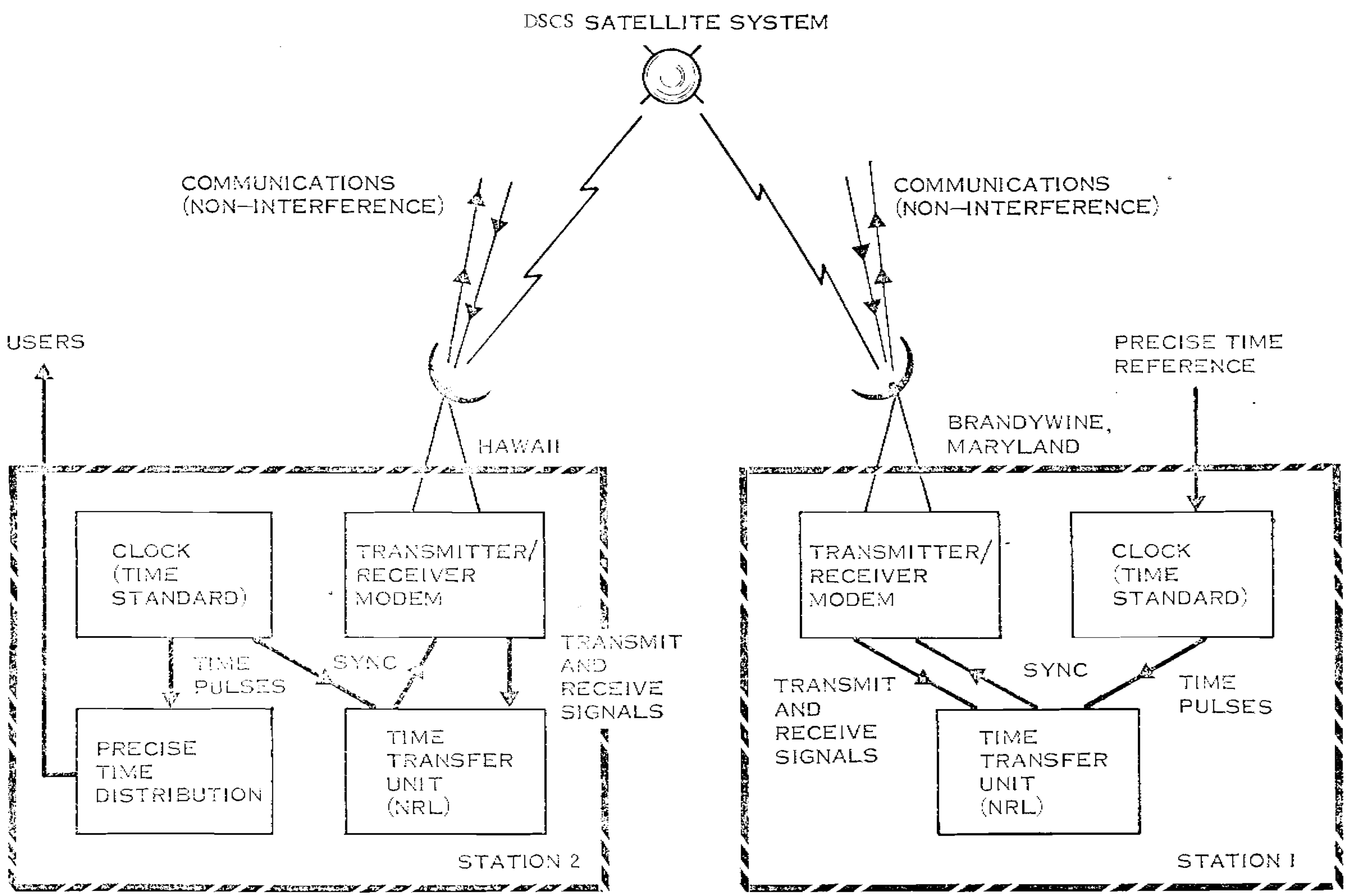


FIGURE 2

XMIT-RCV PN CODE

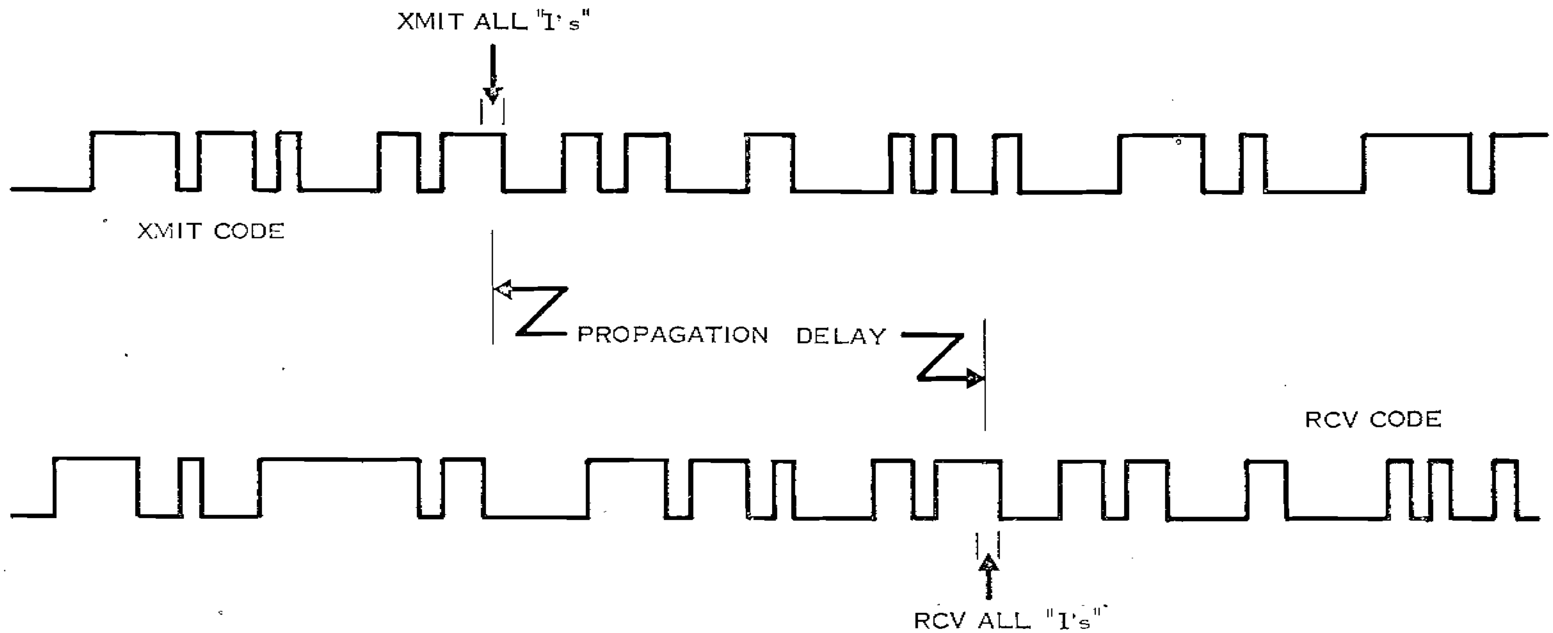


FIGURE 3

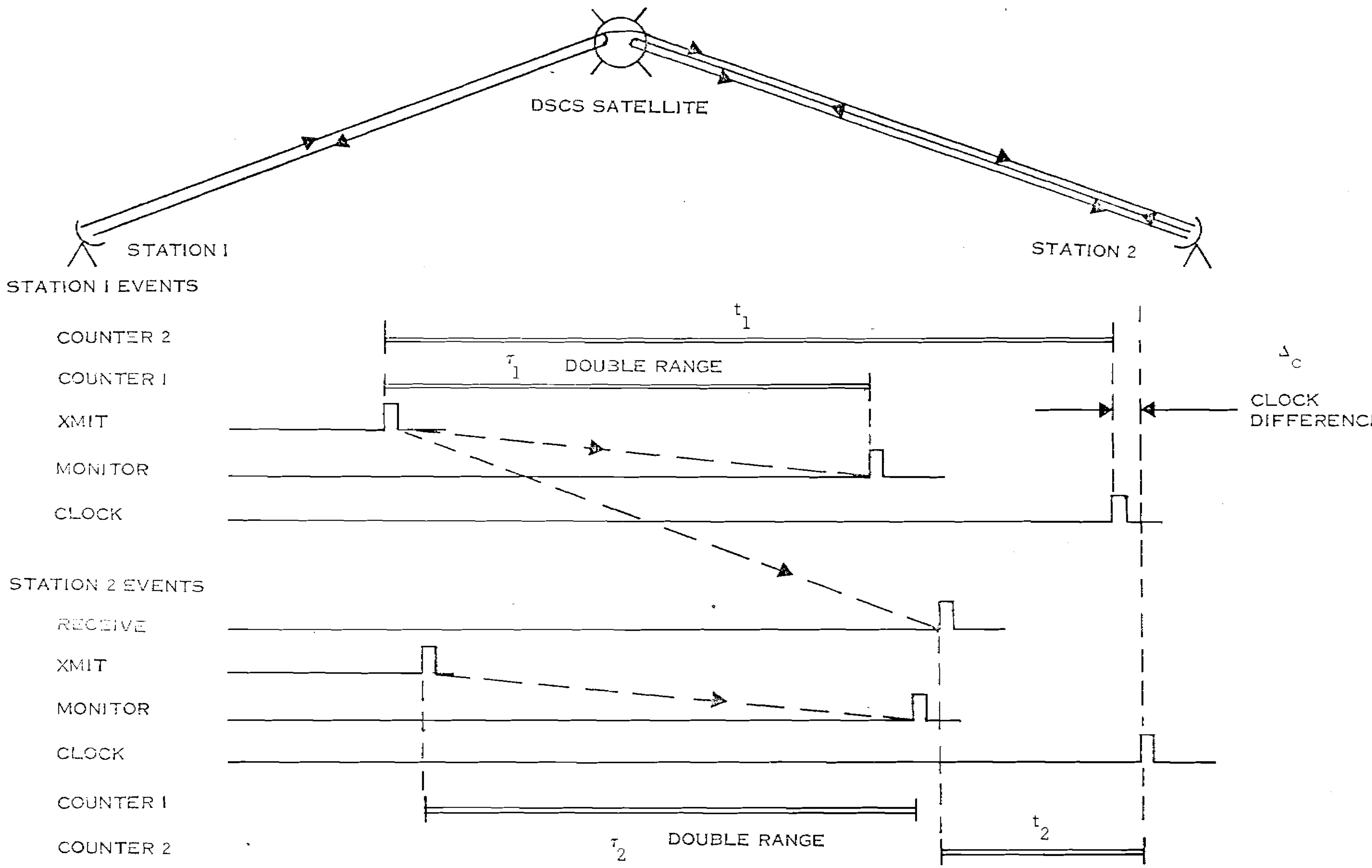
in the receiver section of the modem at the other station matches the stream as received. It is possible, then, to extract from each modem certain recognizable code generator states, or "ticks" (designated "all-one's" in the diagram), that can be treated as though they were very short pulses transmitted by one modem and received by the other. The tick at the receiver is delayed, of course, by the time it takes the transmitted signal to travel from the transmitter to the satellite and back down to the receiver. In addition to the transmit tick and receive tick, each modem provides a "monitor" tick that corresponds to the reception of its own transmit tick after a round trip to the satellite and back.

TIME-TRANSFER TECHNIQUES

Two methods of time transfer have been used. In the method shown in Figure 4, each station measures its round-trip distance to the satellite; at the same time, station 1 compares its transmit tick with its own clock to obtain the time interval t_1, and station 2 compares the corresponding receive tick with its own clock to obtain t_2. By using half the sum of the two double range measurements τ_1 and τ_2, the time of flight from station 1 to station 2 is determined and, in effect, added as a correction to the receive tick at station 2. The difference between the transmit reading at station 1 and the corrected receive reading at station 2 is the difference between the station 1 and station 2 clocks. After the two time-interval measurements, t_1 and τ_1 recorded at station 1 or the interval measurements t_2 and τ_2 recorded at station 2, are communicated to the opposite station, the clock difference may be determined and corrected.

In the second time-transfer method (see Figure 5), each station measures its own transmit tick with respect to its clock and also measures the tick received from the other station with respect to the same clock. If the sum of the measurements at one station is subtracted from

EXPERIMENTAL TIME TRANSFER TIMING DIAGRAM



$$\Delta_c = \frac{\tau_1}{2} + \frac{\tau_2}{2} + t_2 - t_1$$

FIGURE 4

TIME TRANSFER TIMING DIAGRAM

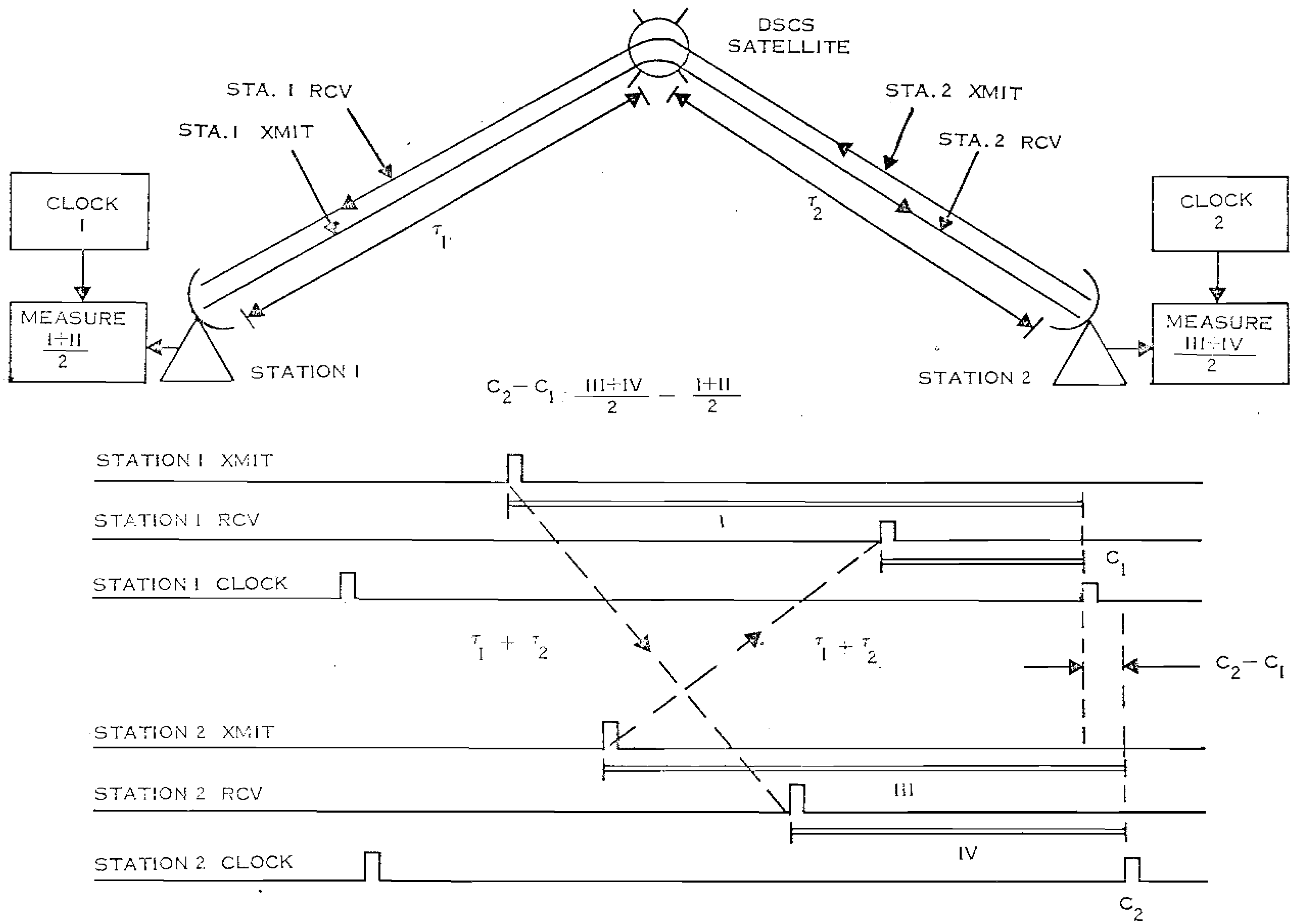


FIGURE 5

the sum of the measurements taken at the other station, the result is twice the difference between the two clocks. This method uses identical equipment and procedures at the two stations.

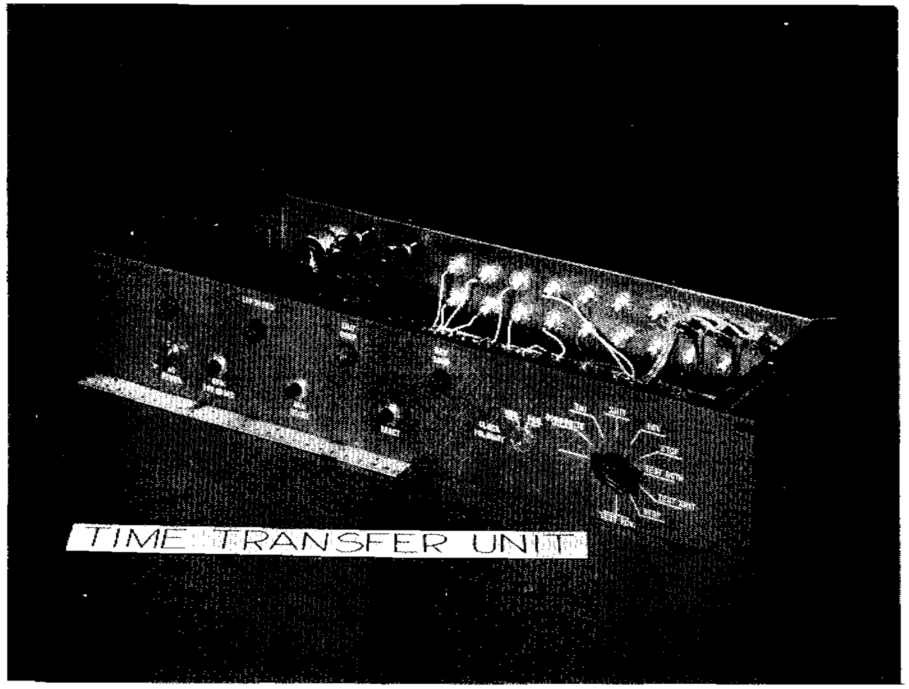
INTERFACE EQUIPMENT

A time-transfer unit (see Figure 6) has been designed as an interface to operate automatically in the latter method and yield a single reading at each station. The difference between clocks is simply the difference between the numbers produced at the two stations.

With either time-transfer method, however, it is necessary to transmit data from one station to the other in order to make the clock-difference determination. This is normally done through the order wire between stations.

The two methods are valid, in general, only if the transmitted ticks from both stations arrive at the satellite at nearly the same time. This is ensured if the modems of the two stations have made a tick start, an easily accomplished procedure when accurate local clocks are available. Although provisions have been made in the time-transfer unit for making tick starts with the accurate clocks of the time-transfer system, under some circumstances, a "reset" start of the modems might be made instead. In this case, the ticks of the two stations might pass through the satellite at widely separated times and the motion of the satellite between the two passages could produce an unacceptable error in the time transfer.

To compensate for this error, the range measurements may be interpolated in the first method. For the second method, an interpolation procedure has also been worked out. Although it is inconvenient to use the interpolation procedures, they apparently add little to the inaccuracies of the time transfer.


TIME TRANSFER UNIT

EXPERIMENTAL RESULTS

In February 1970, time-transfer tests were run between the SATCOM stations at Brandywine, Maryland, and Ft. Dix, New Jersey, to prove the feasibility of using the pseudo-random code stream. Further tests were run between Brandywine, and the SATCOM facility at Helemano, Hawaii. Figure 7 shows a quite consistent grouping of results for that test. (No explanation is offered for the single reading approximately 0.7 μsec away from the mean. It could have resulted from a misread counter.) Much of the spread (approximately 0.3 μsec) may be attributed to quantization error, since the least significant digit of each counter was 0.1 μsec. Somewhat better results were obtained on a smaller sample later during the same test period.

In a still later series of tests, a small sample of measurements yielded a standard deviation of less than 0.1 μsec. A group of measurements made by interpolation disagreed with the group made with synchronized modems by less than 0.1 μsec. During the same period, a time transfer made by transporting a clock to Hawaii and back to Maryland disagreed with the satellite time transfer by approximately 0.3 μsec. The clock transport, however, was not ideal because of a relatively large rate offset in the portable clock and some delay in making the comparison after its return to Maryland. In spite of these shortcomings, it appeared that the inaccuracy of the satellite time transfer was not greater than 0.5 μsec and possibly much smaller. Future tests are expected to yield a more accurate picture of its performance.

An improvement in measurement resolution is likely to improve overall repeatability, if not accuracy, because most of the observed spread in readings can be attributed to instrumentation uncertainty. After the least significant digits of the readout devices have been reduced to .01 μsec, it is planned to make more detailed assessments of the systems capabilities.

DSCS TIME TRANSFER EXPERIMENT
HELEMANO, HAWAII - BRANDYWINE, MARYLAND
(TEST A)

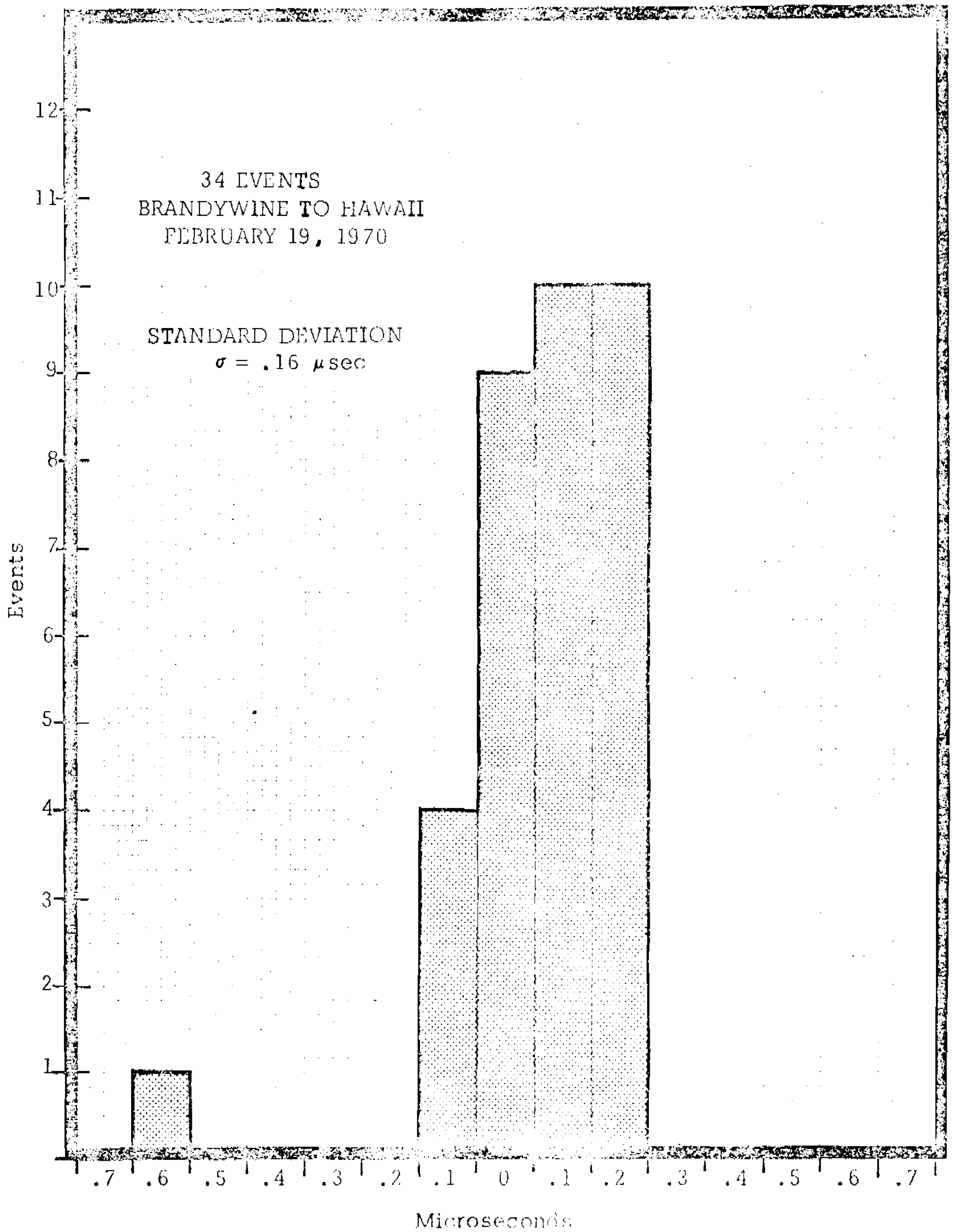


FIGURE 7

Differential time delays between transmitting and receiving terminal equipment produce small fixed time offsets. Since the individual contributions of the various station components are small and are complicated by frequency conversions, it may be difficult to analyze them individually. Instead, it will probably be necessary to make overall station comparisons to determine the absolute accuracy of the satellite time transfers. It is expected that the effects of the differential delays will prove to be less than 0.1 μsec.

TIME-TRANSFER MODEM

A modem intended specifically for time transfers at terminals not equipped with communications modems has been recently designed and constructed. This modem employs a pseudo-random code that operates at a 10-MHz bit rate and goes through its complete cycle in 819 μsecs as shown in Figure 8. Since the recognizable all-one's events recur once each 819 μsecs other information must be transmitted by the modem to identify which all-one's event is the intended time tick. As seen, the transmitter responds to an initiating pulse by reversing the phase of the code throughout the next code cycle. The all-one's event that terminates that cycle is the designated tick. At the receiver, the all-one's event that occurs at the end of the phase reversal is similarly recognized as the tick.

Time transfers are made by initiating time ticks at prearranged times, such as the beginning of each minute. The transmitted and received ticks produced by the time-transfer modem at each station are provided to the time-transfer unit, which performs the necessary time-interval measurements.

Because of the comparatively low relative velocity of DSCS satellites, it is not necessary to have the signals of both stations reach the satellite at precisely the same time. In fact, a 1-second difference in arrival time

SIGNAL TRANSMISSION BY TIME TRANSFER MODEM

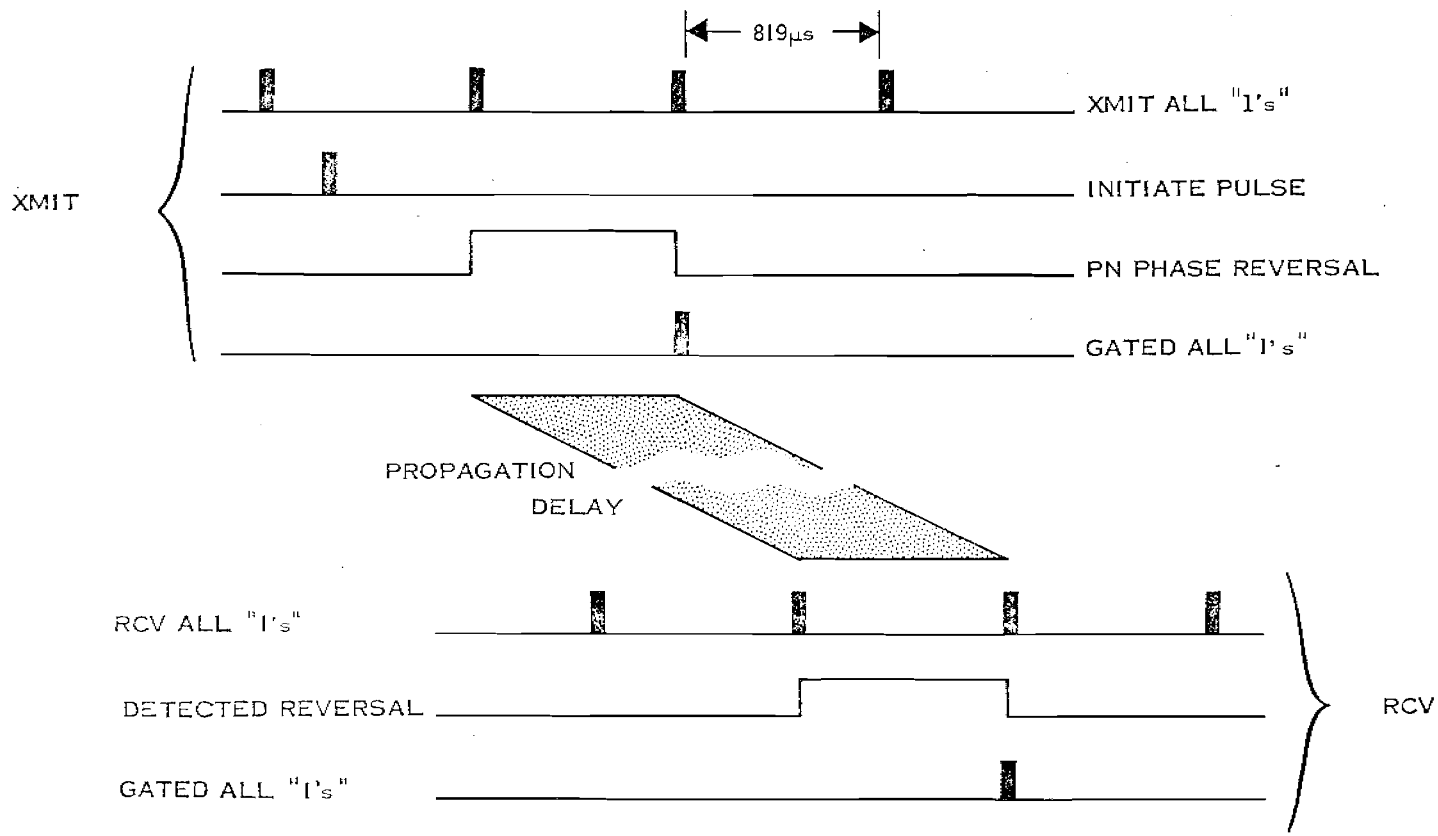


FIGURE 8

produces a time-transfer error in the order of only 0.1 μsec. Therefore, the only requirement for control of the transmissions is that they be launched within a fraction of a second of each other. When the time-transfer modem is used, this requirement is satisfied if the clocks at the two stations agree within a fraction of a second.

A very much simplified diagram of the time-transfer modem is shown in Figure 9. The lower section is the transmitter, which produces a pseudo-random modulated 70-MHz signal. The code stream polarity (hence the polarity of the output signal) is reversed for one code interval after the command pulse is received. The polarity inversion sequence circuit also produces the gated all-one's pulse that constitutes the transmit-time tick.

The receiver section shown in the upper portion of the diagram could receive the output of the transmitter and recover the time tick if the transmitter output were connected to the receiver input. However, in making a time transfer, the receiver should respond only to the transmission of the modem at the other station. This is ensured by transmitting a different code from each station. The receiver at station 1, for example, uses the station 2 transmitter code and, therefore, ignores the station 1 transmitter.

Range measurements may be made by using a common transmit and receive code at one station. The receiver then responds to the local transmitted signal after its round trip to the satellite. The time interval from the transmit tick to the receive tick then corresponds to the double-range propagation time.

In the receiver, the local conversion oscillator is bi-phase modulated with the same code that modulated the received signal. After the two codes have been aligned by a searching process, each phase inversion of the received signal is accompanied by a phase inversion of the local oscillator. The intermediate-frequency output of the modulator, therefore, is a constant-phase signal.

TIME TRANSFER MODEM TRANSMITTER AND RECEIVER

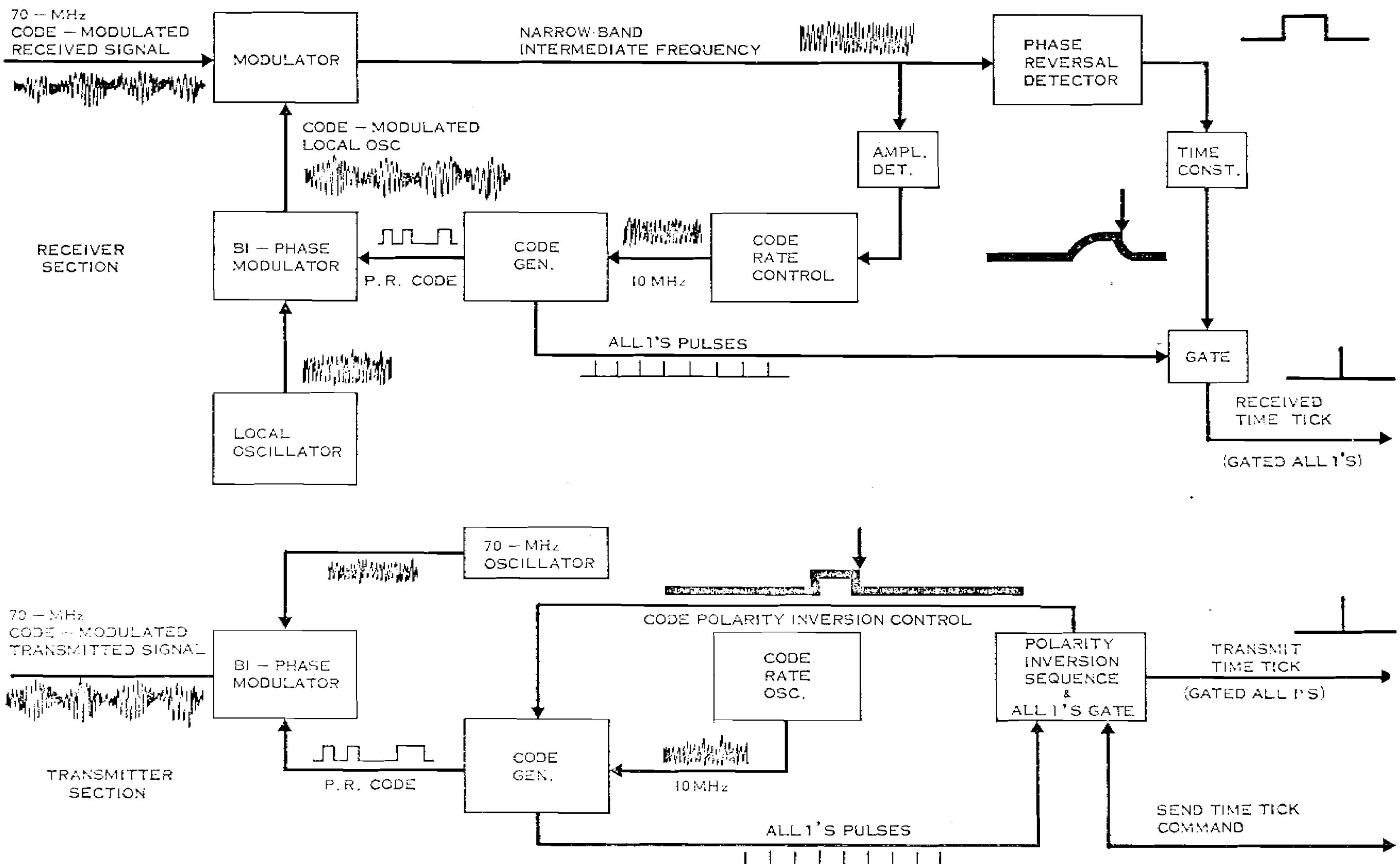


FIGURE 9

Since any misalignment of the code modulation of the two signals results in an amplitude change at the intermediate frequency, the rate of the receiver code generator is controlled to maintain peak intermediate-frequency amplitude.

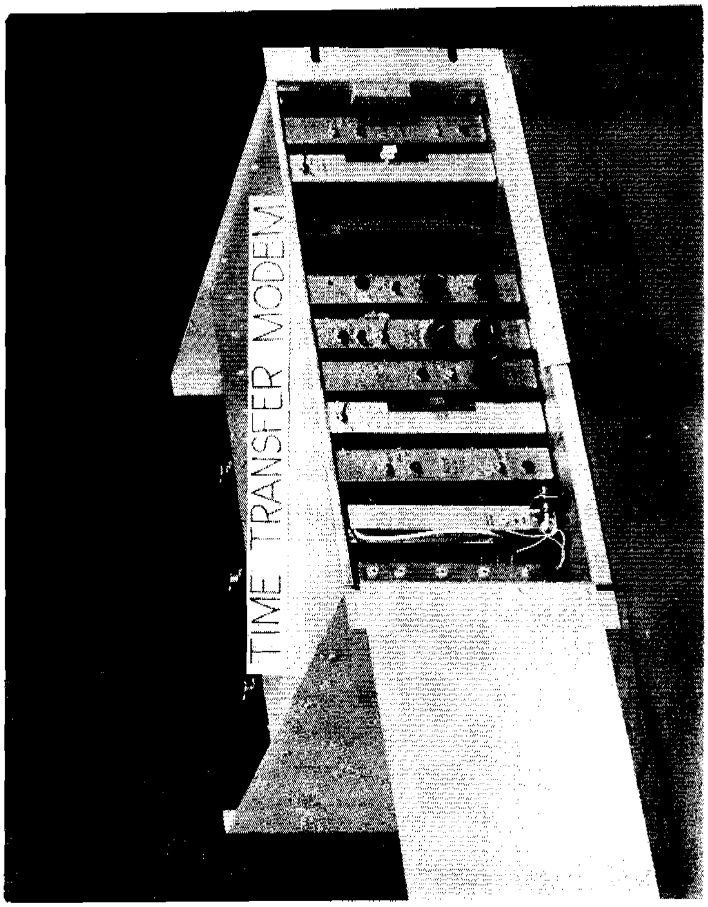
When the phase of the received signal is inverted for a whole code cycle to designate the time tick, the phase-reversal detector of the receiver detects the change and its filtered output gates the designated all-one's pulse from the code generator to represent the received tick. The phase-reversal detector consists of a slow-acting locked oscillator and phase detector to compare the intermediate-frequency signal with the oscillator.

The time-transfer modem pictured in Figure 10 is capable of operation in the presence of interfering pseudo-random or frequency-modulated signals 20 db stronger than the desired signal. Range measurements were made at Helemano, Hawaii, under normal communications conditions with the modem power reduced approximately 15 to 20 db below the station communications channel power.

RESULTS OF TIME-TRANSFER MODEM EXPERIMENTS

The modem was used in a single-access ranging mode at the TSC-54 terminal at Brandywine, Maryland, with as little as 100 w of RF power. The TSC-54 is a transportable terminal employing a relatively small antenna. Late in October a time transfer was made from the Brandywine TSC-54 to the Waldorf, Maryland, NRL satellite communications facility (see Figure 11). Although the distance between sites is an unimpressive 10 miles, the test was useful both to check out the modem and to evaluate the accuracy of time transfers in general.

The total propagation distances actually involved were as large as those for more widely separated terminals, and satellite motion and other


TIME TRANSFER MODEM

TIME TRANSFER EXPERIMENT

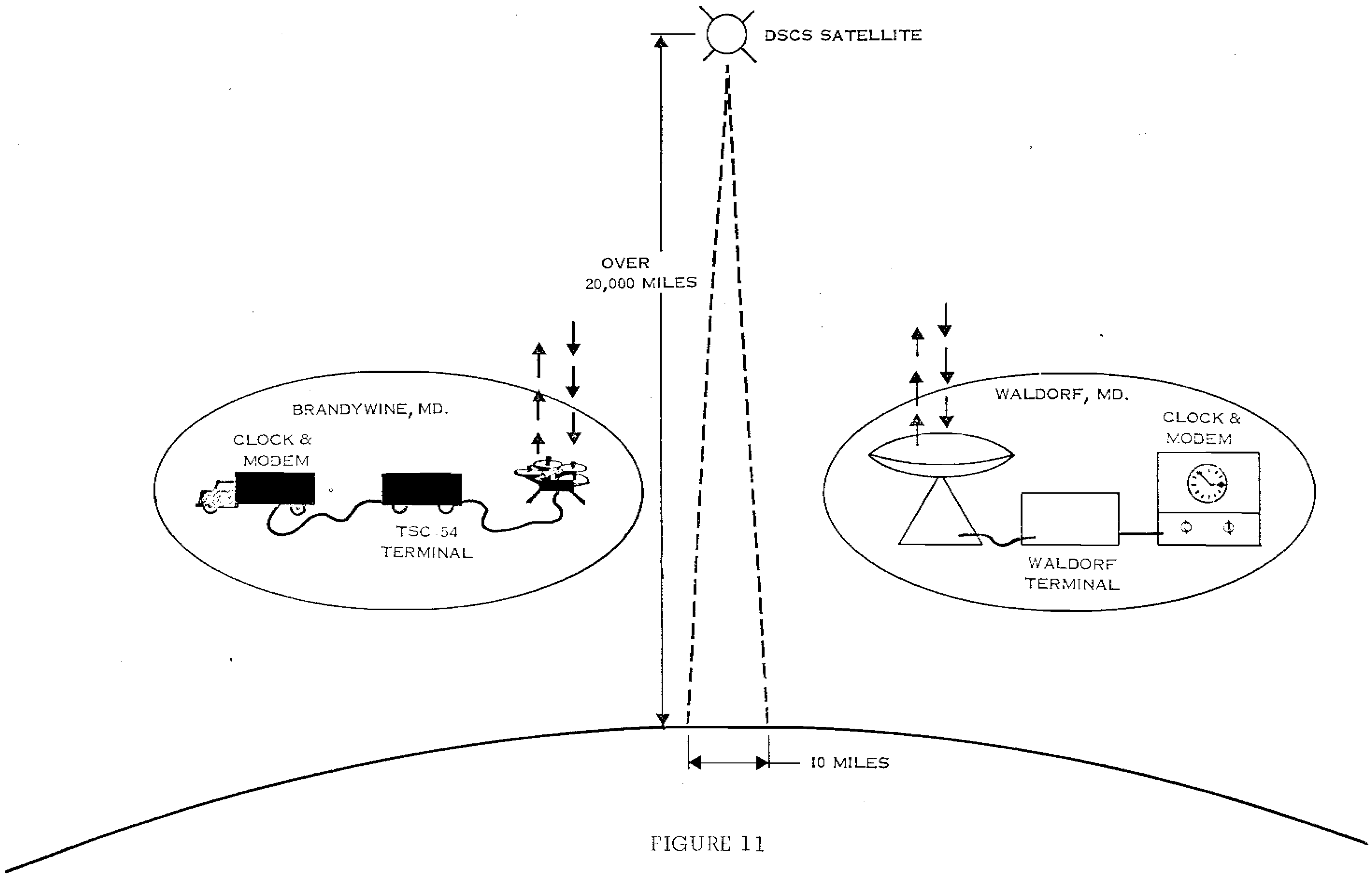


FIGURE 11

factors were believed to be typical. The advantage of using nearby terminals is that the accuracy of the time transfer can be checked reliably.

At each terminal a cesium-beam clock, a time-transfer unit, and a time-transfer modem were used. However, the equipment for the Brandywine site was mounted in a truck equipped with a 115-v AC generator. Only the receive and transmit 70-MHz RF lines of the modem were connected to the TSC-54 equipment. After the time transfer was completed, the truck was driven to Waldorf and the clocks were compared directly.

Figure 12 shows the result of the comparisons between the clocks at Brandywine and the clocks at Waldorf. The spread is typical of transfers made at other locations.

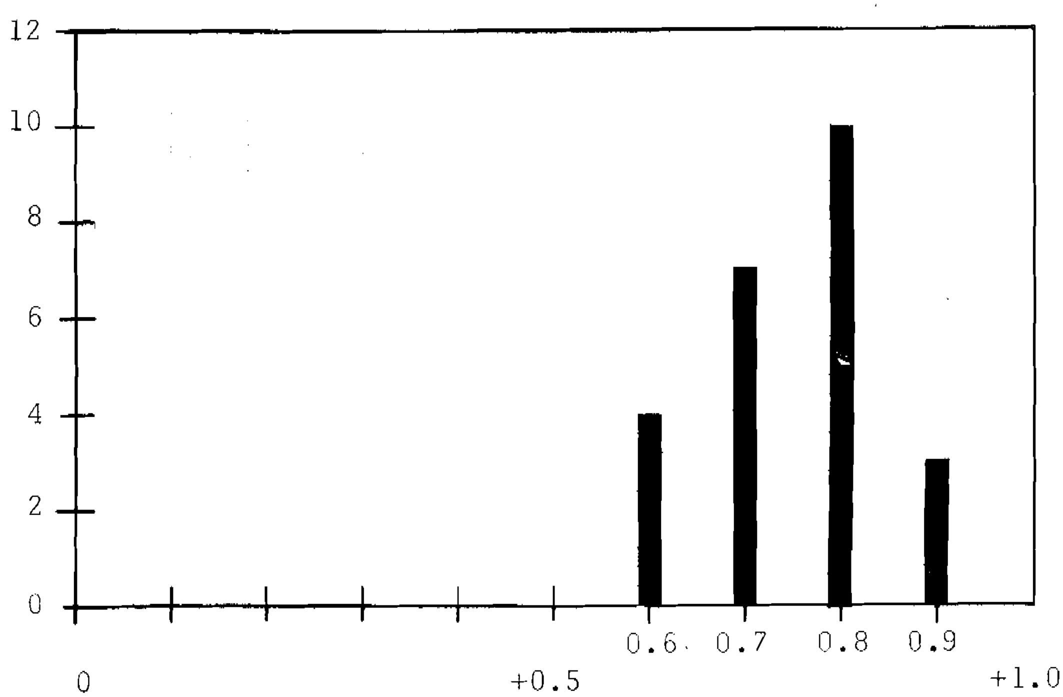
When the direct clock comparison was made at Waldorf, the indicated difference was 0.6 μsec. This would indicate a 0.15 μsec discrepancy with respect to the average of the transfer readings. There is reason to believe, however, that the disagreement is actually less than that. The 0.6 μsec figure was based on a single reading, but a series of clock comparisons made after returning both clocks to the Laboratory about one hour later, indicated that the clocks were approximately 0.7 μsec apart.

It can be readily concluded that the accuracy of satellite time transfer is within the ability of our present equipment to discern. It is thought that an improvement in resolution obtained by using a higher counting rate in the time-transfer unit would result in greater accuracy. But it will be most difficult to prove because equal or better methods are not available.

IMMEDIATE APPLICATIONS OF TECHNIQUE

With equipment already developed it is practicable to provide Observatory time to within a small fraction of a microsecond to a number

RESULTS OF TIME-TRANSFER MODEM TESTS
BRANDYWINE, MD. (TSC-54 TERMINAL) TO WALDORF, MD.



Waldorf Clock - Brandywine Clock (microseconds)

28 October 1970

FIGURE 12

of strategically situated areas. This can be done by equipping certain SATCOM stations with a time-reference facility. The difference between the two forms of this facility (illustrated in Figure 13) is simply the addition of a time-transfer modem in station pairs not equipped with communications modems.

It is not possible to communicate directly with all satellite terminals from any one station. In some cases it will be necessary to relay the time reference over two or more hops, as in the case of Australia's North West Cape (see Figure 14).

The larger (MSC-46) SATCOM terminal at Brandywine will soon be equipped with time-transfer equipment. Shortly thereafter, the time reference will be extended to Hawaii, Guam, or North West Cape, and Germany. Eight or more terminals are expected to constitute the beginnings of the satellite precise-time-distribution network.

PRECISE TIME REFERENCE FACILITY

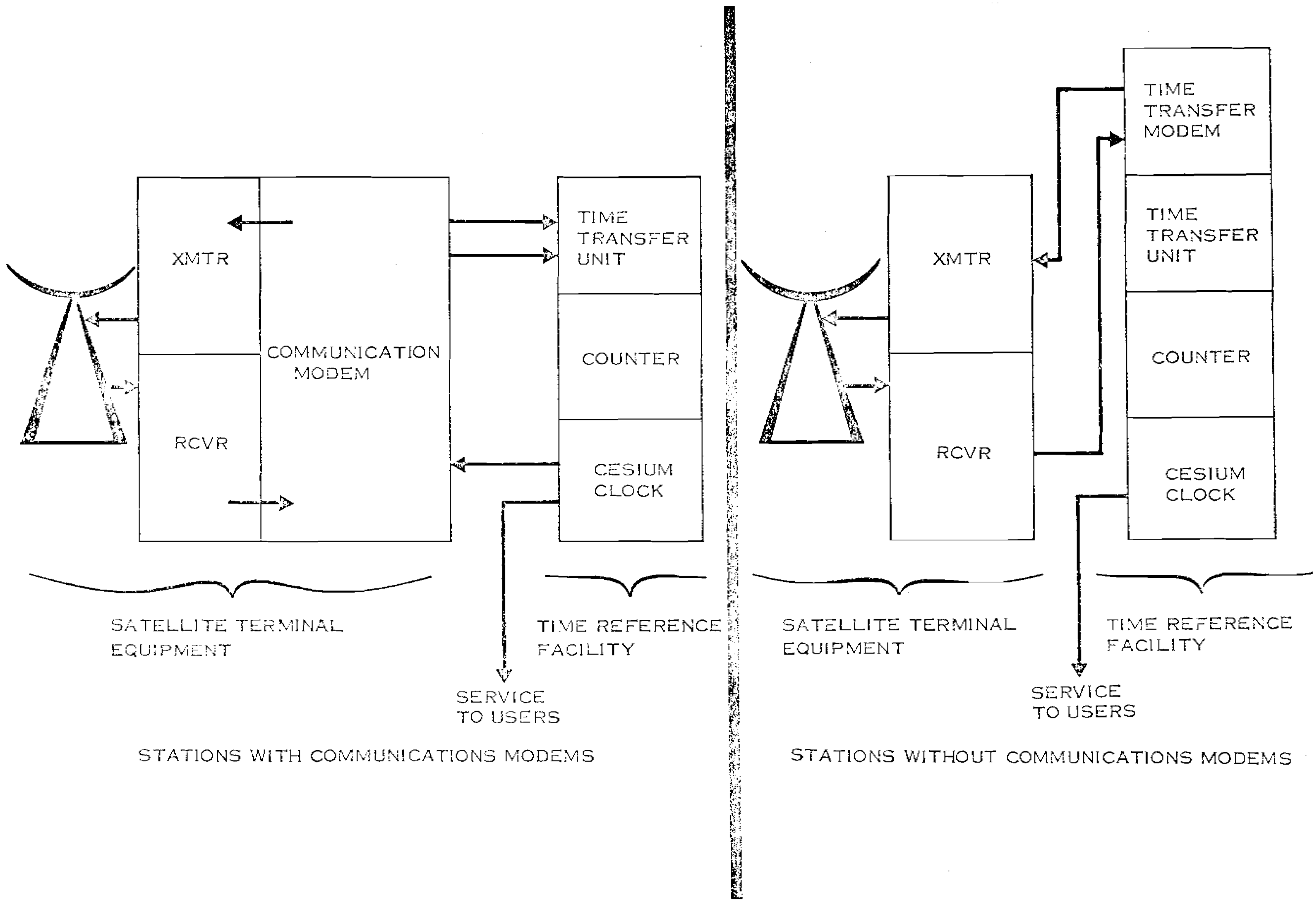
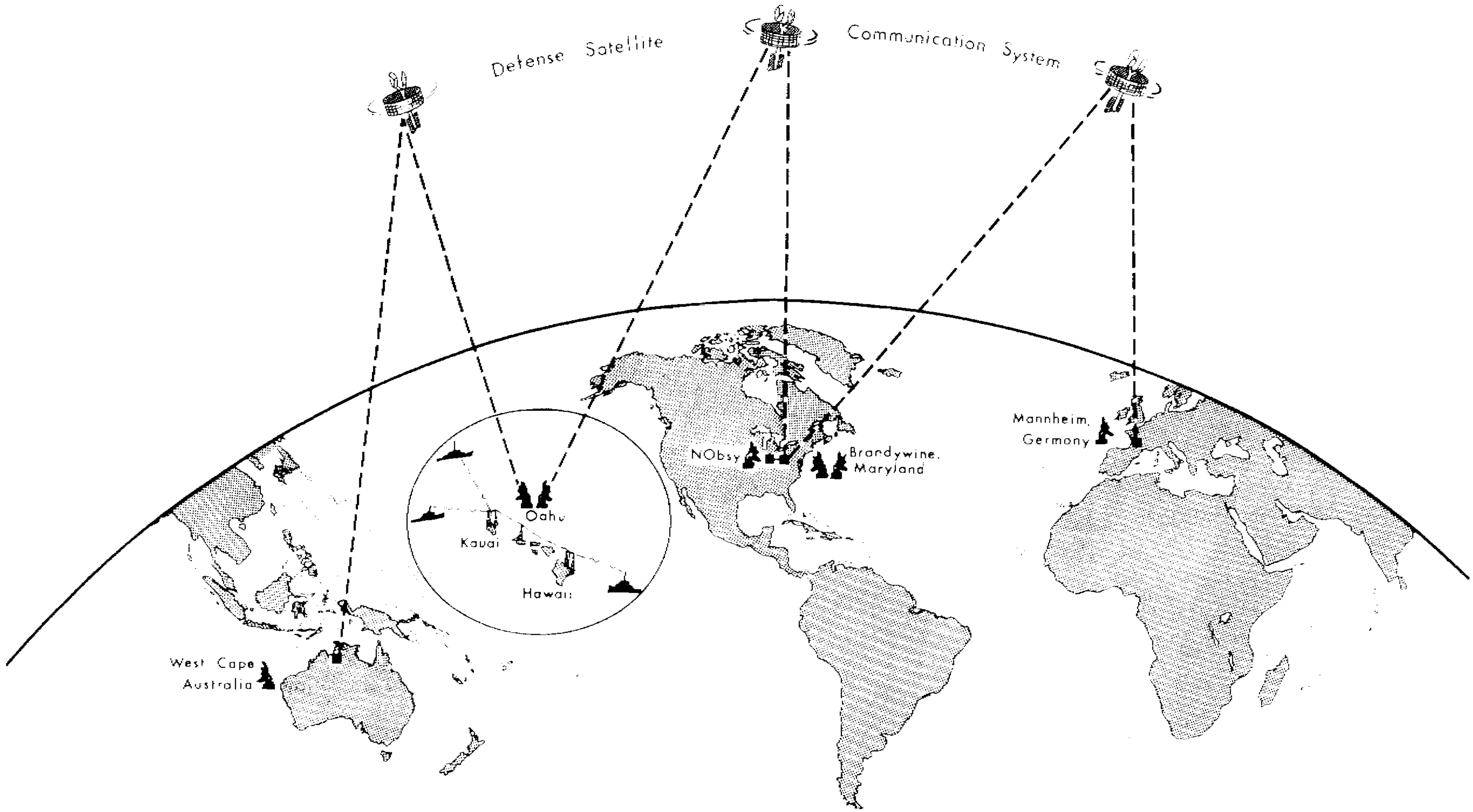


FIGURE 13



PRECISE TIME AND TIME INTERVAL (PTTI) — WORLD DISSEMINATION

FIGURE 14