

SATELLITE TWO-WAY TIME TRANSFER: FUNDAMENTALS AND RECENT PROGRESS

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Abstract

Experiments in precise clock comparisons using the two-way time transfer technique via satellite began in 1962. Experience gained from a variety of experiments since that time steadily improved the precision and accuracy of such comparisons. Recent growth in the fixed satellite service, or FSS, has created new opportunities at moderate costs for high-accuracy time transfers using geostationary satellites. We discuss fundamental aspects of two-way timing and show an implementation of a satellite two-way time transfer system which has been used for two-years between USNO, Washington, D.C. and NIST, Boulder, CO. The raw data collection procedure will be discussed. We also outline the rationale for the choice of satellite uplink/downlink frequencies, signal structure, and reduction of data.

Short-term noise in the time transfer limits the precision to about 300 ps in a 300 s average. Uncertainty in accuracy is due to uncertainty in the non-reciprocity of the two-way signal path. Accuracy limits due to the atmosphere, earth-satellite rotating system (Sagnac effect), and the equipment are discussed. The goal is to achieve an accuracy level of 1 ns after a suitable calibration of earth-station (differential) equipment delays.

Satellite Two-way Time Transfer

We discuss fundamental aspects of two-way time transfers first. Synchronization of clocks between two locations A and B in the two-way mode involves three elements. These are: the clocks which generate a signal, usually a pulse once per second, some method to transmit the pulses between locations A and B , and a time-difference measuring instrument, or time-interval counter (TIC), at each location. Figure 1 illustrates the principle of the two-way technique using two cables as the interconnecting medium. The difference of the clocks is given by

$$A - B = 1/2[R(A) - R(B)] + 1/2[d_{AB} - d_{BA}] \quad (1)$$

where $R(A)$ and $R(B)$ are the counter readings at A and B respectively and d_{AB} and d_{BA} are the cable signal delays from locations A to B and B to A respectively. If the electrical length of each

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cable is the same, i.e., $d_{AB} = d_{BA}$, then the clock difference is simply one-half of the difference of the time-interval counter readings.

Figure 2 shows the two-way time transfer method through a satellite. The scheme is basically the same as in Fig. 1 except both signals are transmitted through a satellite rather than through cables. Note that additional delay terms indicated represent the earth station transmitters (d_{TA} and d_{TB}) and receivers (d_{RA} and d_{RB}), the propagation delay to and from the satellite at A and B (d_{AS} , d_{SA} , d_{BS} , d_{SB}) and the delay through the satellite itself (d_{SAB} and d_{SBA}). Taking into account the various delays and using the formalism of Eq. 1, we have

$$A - B = 1/2[R(A) - R(B)] + 1/2[(d_{TA} - d_{RA}) - (d_{TB} - d_{RB})] \\ + 1/2[(d_{AS} - d_{SA}) - (d_{BS} - d_{SB})] + 1/2[d_{SAB} - d_{SBA}] - 2\omega A/c^2 \quad (2)$$

where the last term ($2\omega A/c^2$) is due to the Sagnac effect which will be discussed later. Figure 2 does not explicitly indicate the subtraction (the difference) of the TIC readings as in Fig. 1. The TIC readings can be exchanged by any means such as via telephone modem or through the satellite itself using its own communications capability. Cables of equal electrical length in Fig. 1 are analogous to equal, free-space path lengths to and from each earth station through the satellite in Fig. 2^[1].

Factors Affecting Signal Reciprocity

A fundamental issue of high accuracy synchronization in the satellite two-way technique is the determination of the value and uncertainty of path nonreciprocity. A direct-sequence, spread-spectrum (DSSS) signal structure has benefits for satellite two-way time transfer. This type of signal has good time transfer resolution at low power density^[2]. Using DSSS, each data bit is represented by a pseudo-random noise (or PN) sequence. Different PN sequences having low cross-correlation allow two DSSS signals to pass through a satellite transponder simultaneously with minimal interference. This so-called code division multiple access (CDMA) allows signal path reciprocity through the satellite transponder, i.e., $d_{SAB} = d_{SBA}$ in Eq. 2 (hence the term is zero).

The transmission and reception of a timing signal through a satellite involves waveguides, cables, amplifiers, converters, and filters, as well as the spread-spectrum, modulator-demodulator (modem). The non-reciprocal time delay through the earth station equipment is the difference between the equipment-related, receive-signal delay and transmit-signal delay, or the "differential" delay. Referring to Fig. 2 and Eq. 2, the equipment-related nonreciprocity involving two stations, A and B , is given by

$$\Delta E_{QA,B} = 1/2[(d_{TA} - d_{RA}) - (d_{TB} - d_{RB})] \quad (3)$$

in the case of a measurement of $A - B$.

One can measure equipment-related nonreciprocity by using a transportable earth station which can perform a two-way time transfer at each of two main earth station locations, A and B . The procedure is as follows. A common clock is used for both the main and transportable earth stations as shown in Fig. 3. The transportable station is located in close proximity to the main station in order to

minimize propagation and Sagnac nonreciprocity which is discussed next. If we call the transportable earth station "C", then the differential equipment delay between A and C would be given by

$$\Delta E_{q_{A,C}} = 1/2[(d_{TA} - d_{RA}) - (d_{TC} - d_{RC})] \quad (4)$$

where d_{TC} and d_{RC} are the delays through the transmitter and receiver respectively at C. A - C between the stations is known since a common clock is used; therefore Eq. 2 makes the differential equipment delay between A and C determinable. (Other factors are assumed to be zero or, in the case of the Sagnac effect, determinable as will be discussed next.) The transportable earth station is then moved to location B where the same setup is again used to measure a differential equipment delay between B and C. The difference of the values obtained at A and B is thus the difference of their differential delays which is the equipment related nonreciprocity between locations A and B. The differential-equipment delay for A - B is thus given by

$$\Delta E_{q_{A,B}} = \Delta E_{q_{A,C}} - \Delta E_{q_{B,C}} \quad (5)$$

or

$$1/2[(d_{TA} - d_{RA}) - (d_{TB} - d_{RB})] = 1/2[(d_{TA} - d_{RA}) - (d_{TC} - d_{RC})] - 1/2[(d_{TB} - d_{RB}) - (d_{TC} - d_{RC})] \quad (6)$$

and the expression on the right in Eq.6 is determinable. Day-to-day measurements of differential-equipment delay variations between earth stations typically do not exceed 1 ns with the present NIST hardware^[3].

The Fixed Satellite Service (or FSS) in the U.S. has frequency allocations in the Ku-band. The uplink and downlink frequencies are approximately 14 GHz and 12 GHz respectively. A frequency-dependent delay through the ionosphere causes the transmit and receive path delays to be different. For a given operating frequency f , the time delay varies as $1/f^2$. The use of Ku-band is favorable for satellite two-way time transfers because of the high signal reciprocity. Ionospheric signal dispersion at C-band (6/4 GHz) is substantially greater. Figure 4 shows nonreciprocal time difference for uplink and downlink frequencies of 14.307 and 12.007 GHz respectively as a function of elevation angle. The calculation assumes a total electron content in a vertical column of 1×10^{18} electrons per meter squared, considered a worst-case condition. Typical propagation (ionospheric) nonreciprocity, given as $1/2[(d_{AS} - d_{SA}) - (d_{BS} - d_{SB})]$ in Eq. 2, is expected to be of the order of 100 ps^[4].

The level of nonreciprocity due to the troposphere is regarded as insignificant at the frequencies used in these experiments. Tropospheric delay is dependent predominantly on water vapor, elevation angle, user altitude, temperature, and pressure. At our frequencies the error due to tropospheric delay is well below 100 ps.

The last noteworthy, nonreciprocal term is caused by the Sagnac effect. This effect is due to the rotation of the earth relative to universal coordinates. Clocks on the surface of the earth are not in a fixed inertial frame due to earth rotation. The exchange of timing information is subject to a relativistic correction, but the effect can be described if one simply considers that the relative locations of two points (A and B) have moved after information is received at A, for example, from B. This is shown pictorially in Fig. 5 where the view is from above the North Pole. At transmission of a timing pulse from earth station B, the location of station A, station B, and the satellite are shown as "1"

The satellite has moved to "2" by the time it receives and retransmits the pulse. Station A has moved to location "3" by the time the signal arrives at A. The signal path has been effectively lengthened in the case of a pulse communicated from west to east. Conversely, the path is shortened for a signal going from east to west. These changes in path length are equal to $2\omega A/c^2$ where c is the speed of light, ω is the earth's rotation rate, and A is the area defined by the projections onto the equatorial plane by the line segments connecting the satellite and the earth's center to the earth stations. This nonreciprocity is easily calculatable without high accuracy knowledge of satellite and earth station positions. For example, a time transfer between NIST (Boulder, CO) and USNO (Washington, D. C.) through SBS-3 at 95°W involves only a 100 ps error for a 1° error in satellite longitude. A position error of 300 m in any direction at NIST's station produces an error of no more than 100 ps. In addition, if a perfectly circular geostationary orbit is assumed for the satellite, the slight eccentricity actually encountered produces less than 50 ps error^[4].

NIST-USNO Time Transfers

NIST and USNO have been making routine two-way satellite time transfers in the Ku-band since August 1987. The configuration at each location is the same except that NIST has a steerable 6.1 m dish and USNO has a 4.5 m dish with a fixed mount. Figure 6 shows a diagram of the principal earth station components. Reference [3] contains a description of the earth station equipment at NIST. The 1 pps signal is transmitted from each earth station and received by the other earth station by means of a spread-spectrum modem that operates with an intermediate frequency of 70 MHz^[5].

During two-way time transfer, NIST and USNO simultaneously transmit and receive two spread-spectrum signals. Each signal is initiated by a 1 pps clock signal that represents UTC(NIST) and UTC(USNO), respectively. The time difference between the locally transmitted 1 pps signal and the received 1 pps signal from the other station is measured and recorded at each site for a 300 s interval. The time differences are recorded at both sites and stored on a central computer at USNO. These data are then aligned for matching one second times, and one-half the difference of the two values is obtained. The resulting data show a second-by-second time difference between the clocks at NIST and USNO. At this point the data are not yet compensated for earth station equipment differential delay, Sagnac effect, and cable or other equipment delays. This is referred to as the raw, uncalibrated, two-way time comparison.

The mean and standard deviation are computed for each 300 s measurement session to obtain a single estimate and measurement precision for the time scale difference. Regression analysis shows no discernible slope above the residual white noise, and tests of the residuals show that they follow white noise behavior. Thus, the simple mean is the best estimate of the time comparison midway (at 150 s) through the measurement. Values of precision (standard deviation) are typically about 300 ps^[6].

The internal signal delay in each spread-spectrum modem (one at NIST and one at USNO) is measured and recorded before starting each measurement run. These delays are subtracted from the average, raw, time comparison to obtain an (uncalibrated) final comparison. Figure 7 is a plot of time comparison results for almost two years of scheduled two-way sessions. Each point represents a 300 s average.

Future International Comparisons

Intelsat, the International Telecommunications Satellite Organization, provides a satellite service which can accommodate two-way time transfers of the type described here. This is a specialized Ku-band service which is intended for digital links to small earth stations. An Intelsat satellite located at $307^{\circ}E$. longitude ($53^{\circ}W$) can support two-way time transfers between Europe and North America using antennas as small as 1.8 m. A transmitter power of 1W is sufficient to yield a carrier-to-noise-density ratio (C/N_0) of at least 54 dB-Hz, a minimum level for the modem involved here. Figure 8 shows the West and East Ku-band spot-beam coverages. A thorough explanation of the Intelsat service including implementation requirements, link calculations, and agencies to contact is included in reference [7].

NIST-USNO Facilities

NIST, in cooperation with USNO, has expanded its facilities to include the mobile earth terminal shown in Fig. 9. This is a self-contained earth station with a 1.8 m-offset, Gregorian-feed, steerable dish. The mobile system will be used to provide a "calibration" between two-way, satellite time-transfer earth stations. Its principal function is to determine equipment-related nonreciprocity as described earlier in this paper.

NIST Facilities

Figures 10 and 11 show NIST's 6.1 m, motor-steerable, dish antenna and earth-station laboratory, respectively. The dish is permanently located on the roof of a wing of a NIST building and the associated earth station equipment is in a room about 30 m away. Data reduction and equipment control are partially handled using a PC-type computer. The computer has enough control that a two-way time transfer can be scheduled to run automatically without an operator. As the number of participants in two-way time transfer increases, computer support of operations will be needed to minimize operational costs.

Conclusion

Starting with fundamental principles, we examined the application of two way time transfer using present-day commercial satellite resources. The four notable sources of signal nonreciprocity (directly affecting accuracy estimates) which were described are:

1. Satellite transponder effects
2. Earth-station equipment-related effects
3. Atmospheric (tropospheric and ionospheric) effects
4. Relativistic (Sagnac) effect

Using Ku-band (14/12 GHz) equipment, combined uncertainties yield a projected accuracy in the neighborhood of 1 ns.

Results of NIST-USNO, two-way, satellite time transfers taken for two years were presented. Time transfers were done three times per week through SBS-3 at 95°W longitude. Second-by-second time differences were measured for 300 s (5 min); the simple mean and standard deviation were computed for the value and precision of the time comparison, respectively. Typical precision was approximately 300 ps.

The Intelsat satellites offer an opportunity for two-way satellite experiments between Europe and North America using small dish antennas. These experiments are in the planning stages. NIST facilities have been expanded to support these and other satellite experiments.

References

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Two-Way Technique

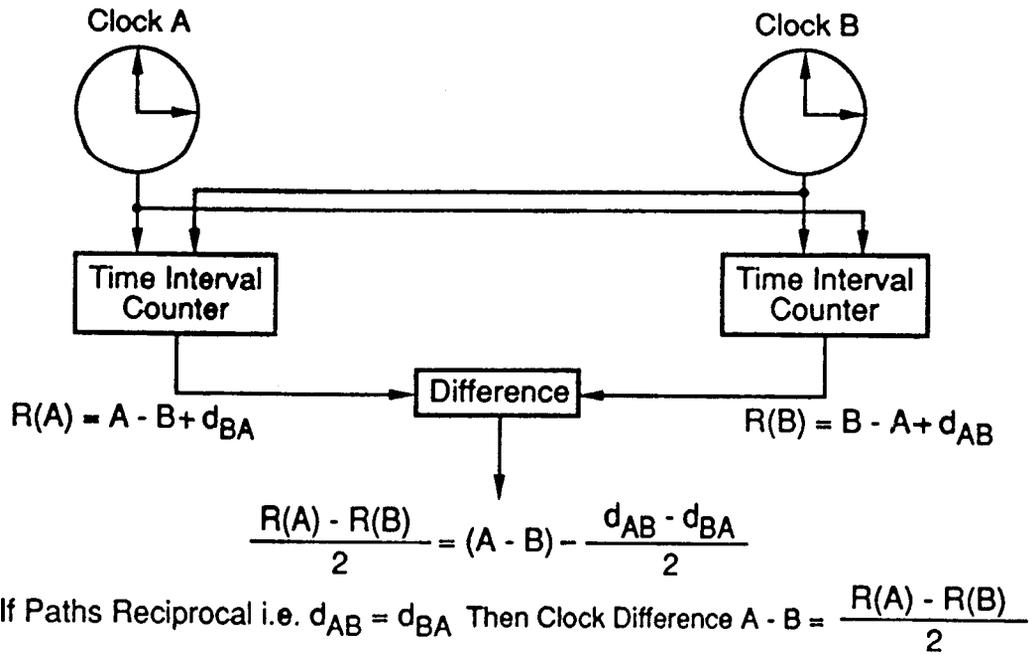


Fig. 1. Two-way technique using cables.

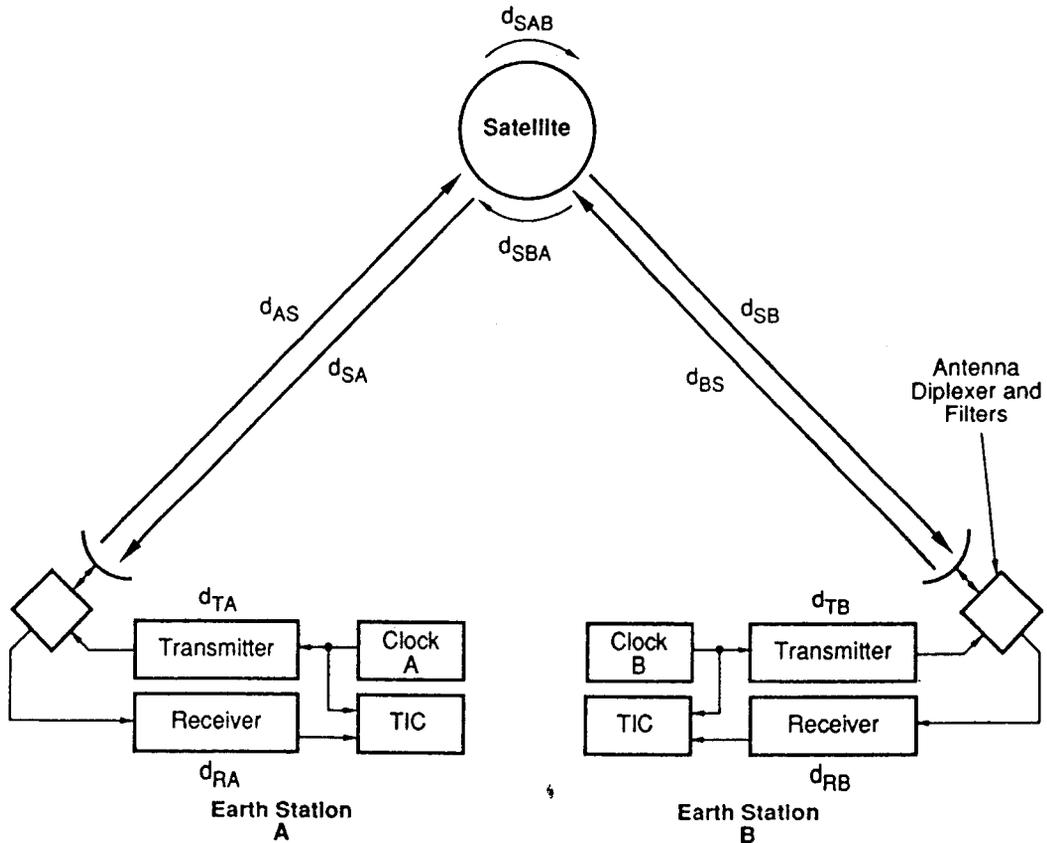


Fig. 2. Two-way time transfer using a satellite.

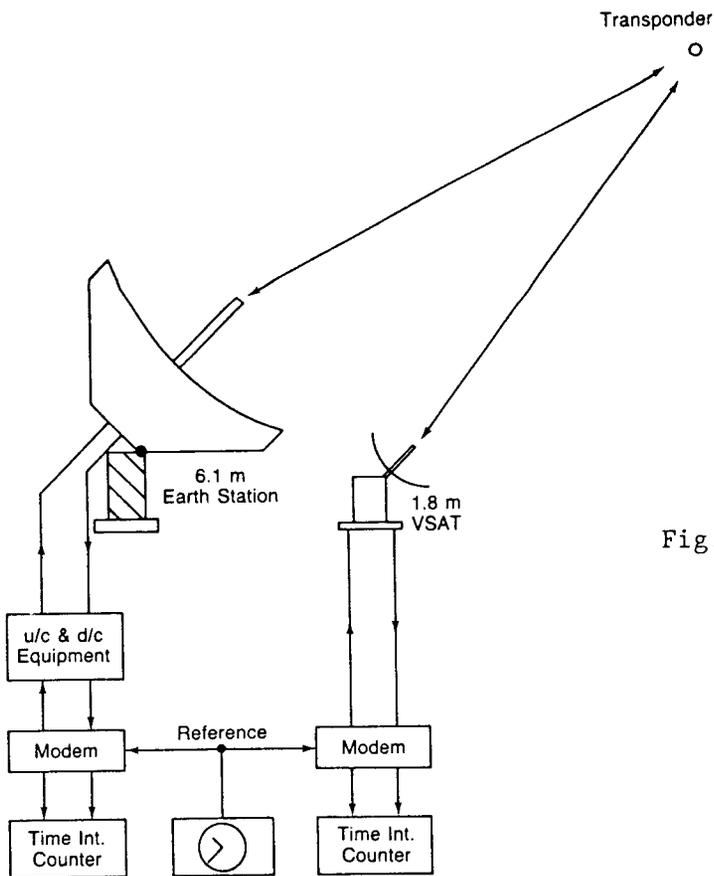


Fig. 3. Measurement procedure for differential delay between a fixed earth station and a transportable earth station, both collocated with a common reference clock.

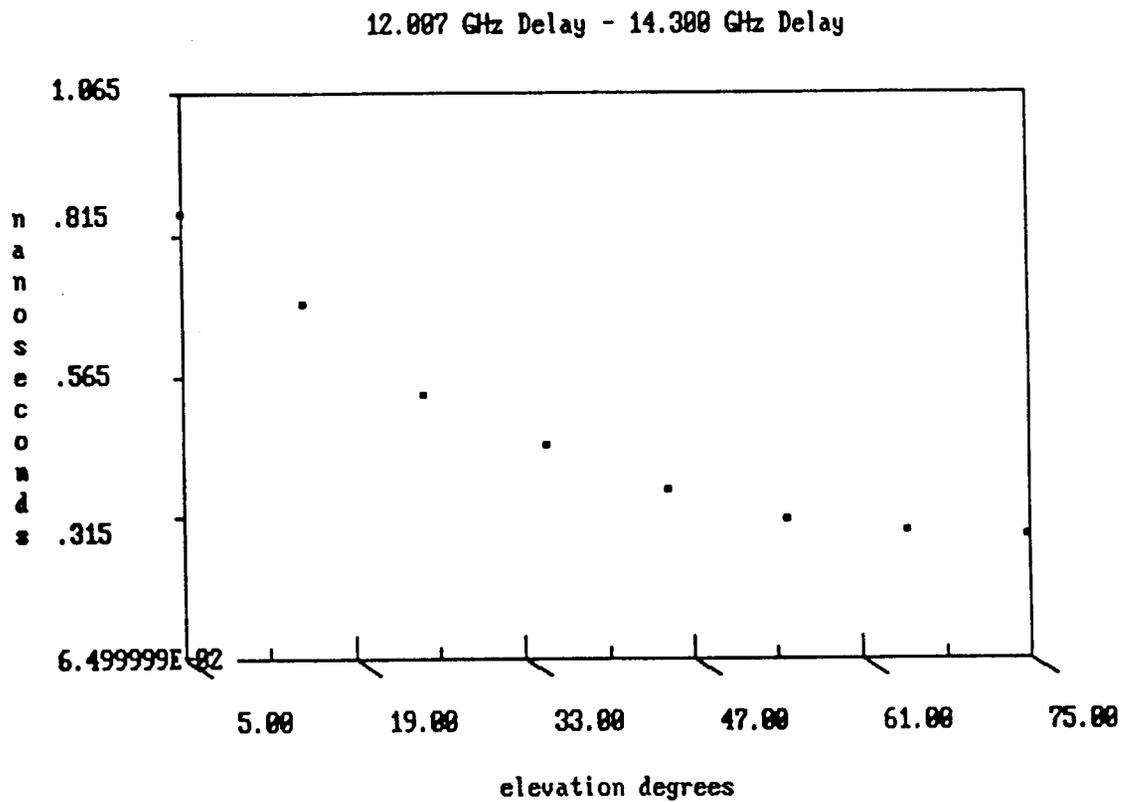


Fig. 4. Ionospheric nonreciprocity at Ku-band for various elevation angles.

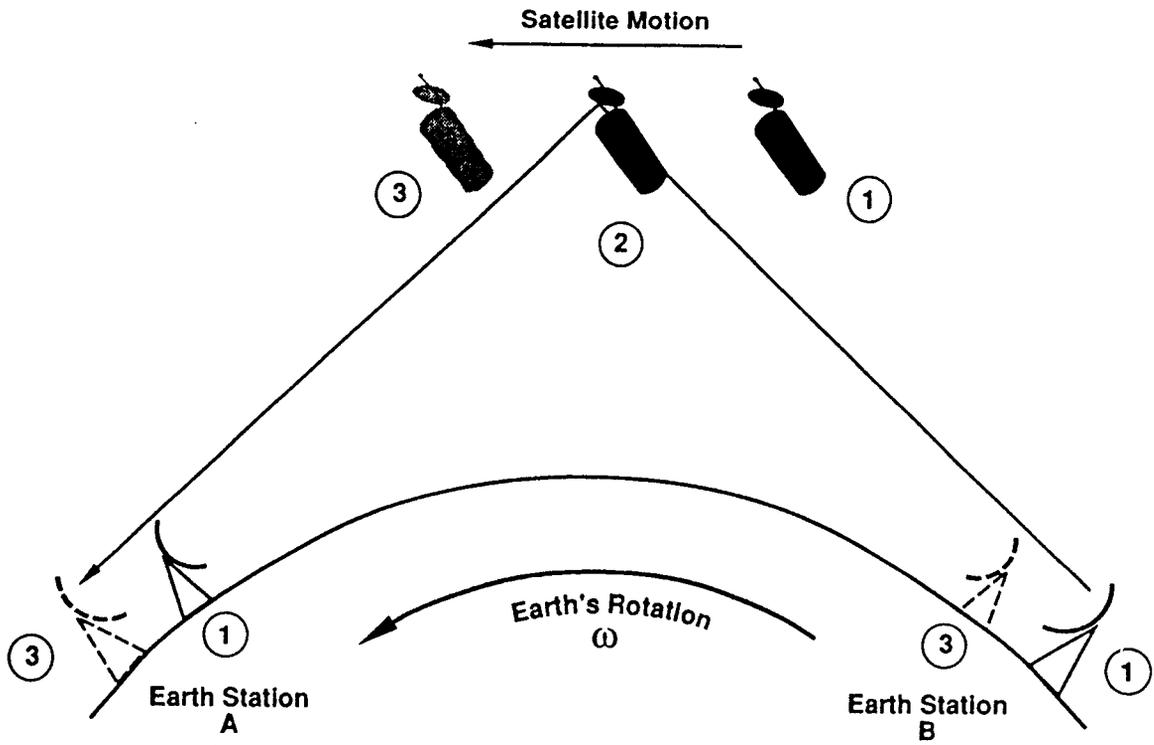


Fig. 5. Sagnac effect. View is from above the north pole.

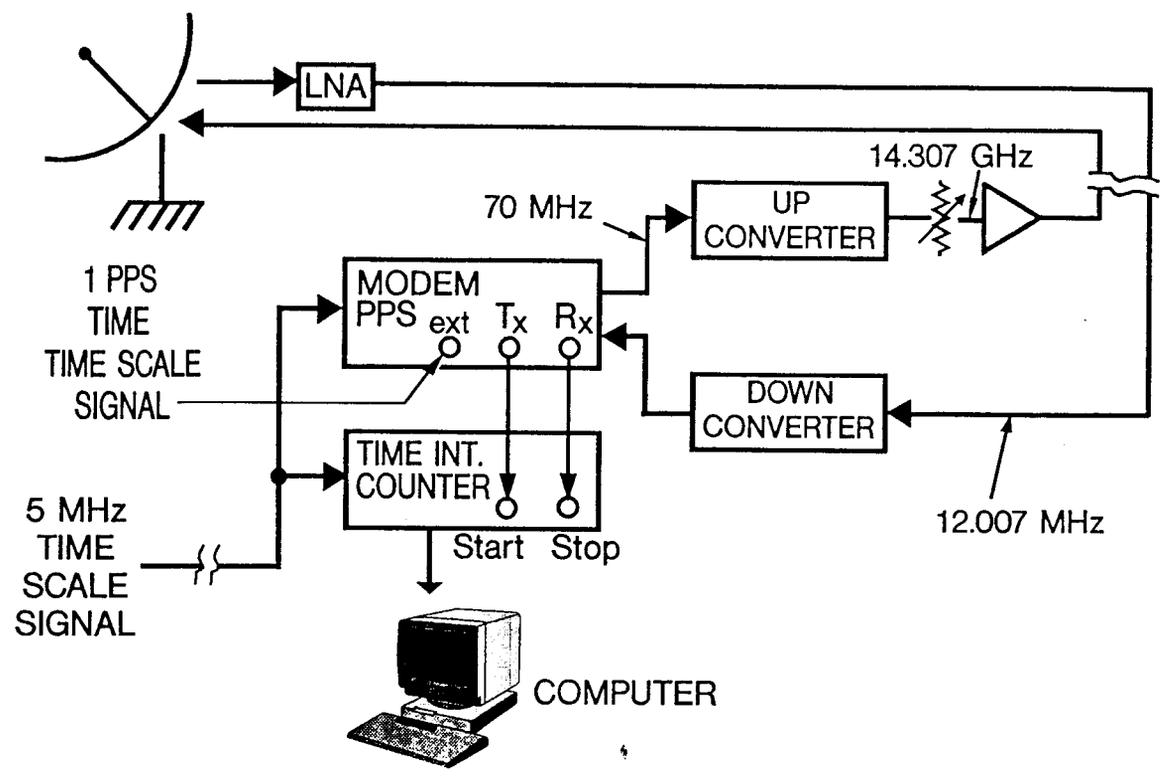


Fig. 6. Earth station equipment.

UTC(USNO) - UTC(NIST) TWO-WAY TIME TRANSFER DATA

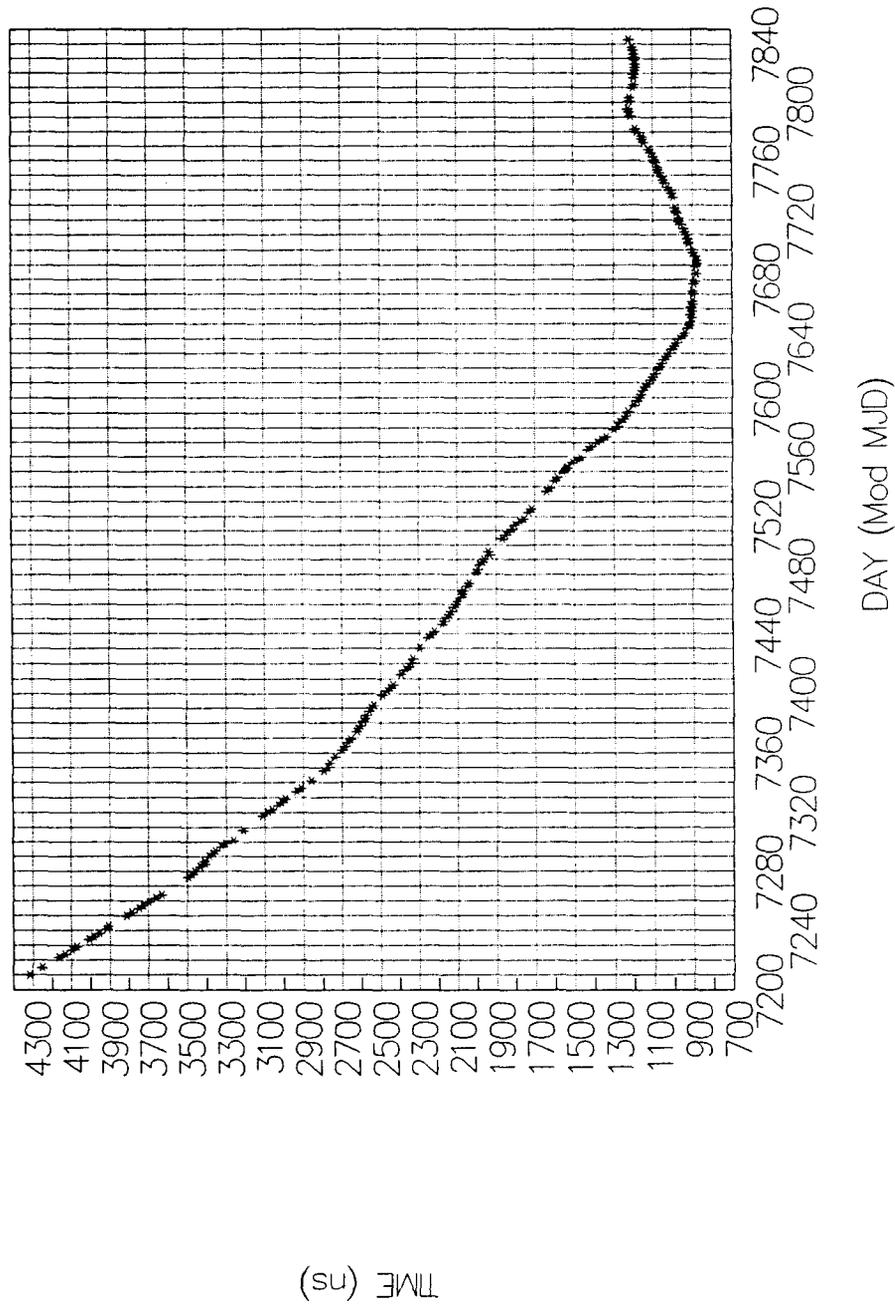


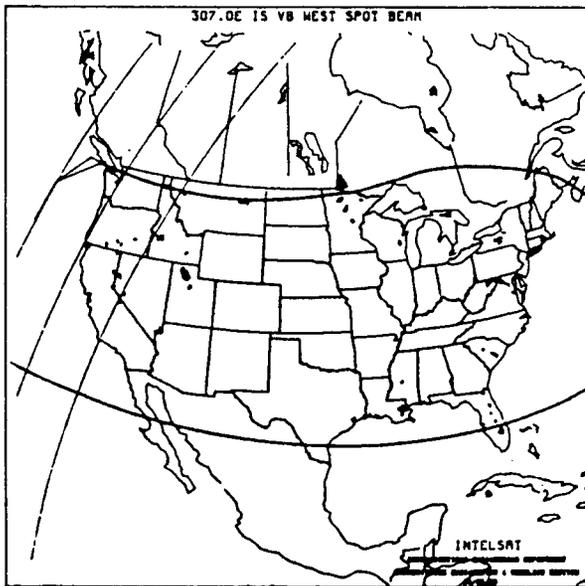
Fig. 7. Mean values of 5-minute two-way satellite sessions between NIST and USNO.

307.0E IS VB (F-13) (INCLINATION 0.0 BIAS .5E)

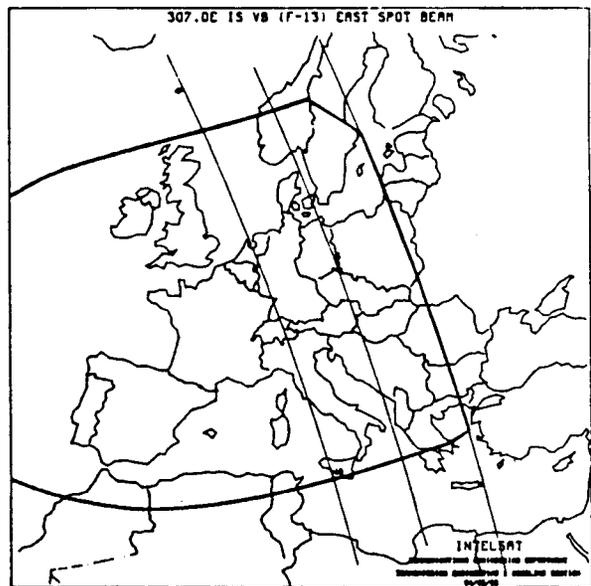


INTELSAT
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TRANSMISSION ENGINEERING & MODELING SECTION
04/08/80

INTELSAT VA(1BS) Interconnections from 307° East



INTELSAT VA(1BS) West Spot Coverage
from 307° East



INTELSAT VA(1BS) East Spot Coverage
from 307° East

Fig. 8. Coverage in North America and Europe by Intesat VA.



Fig. 9. Ku-band mobile earth station with 1.8 m dish.



Fig. 10. Steerable 6.1 m dish at NIST.

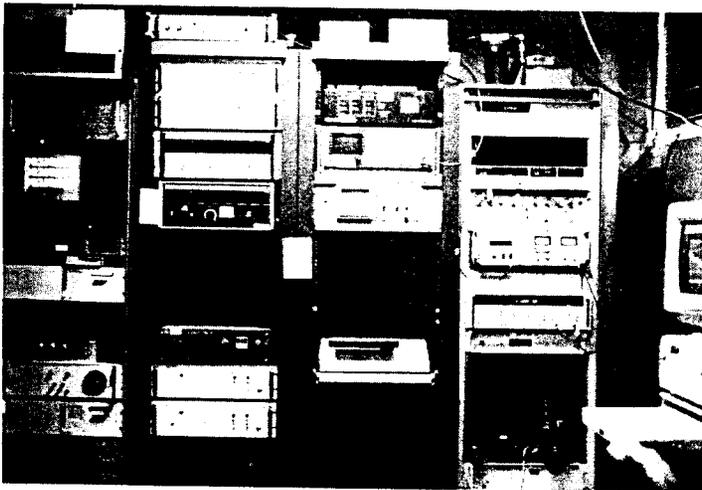


Fig. 11. NIST earth-station laboratory.