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FUNDAMENTALS OF TWO-WAY TIME TRANSFERS BY SATELLITE*

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Abstract

Two-way time transfer by satellite will eventually offer one of the highest accuracy systems at reasonable costs. Advantages of two-way transfer over other techniques include (1) leased space segment rather than specialized space hardware, (2) satellite location is required only to point antennas and not to compute distances, (3) effects on the accuracy of time transfer by the ionosphere and troposphere are sub-nanosecond without modeling, (4) locations of the clocks on the ground do not need to be known better than that provided by a geodetic map -- precise positions are not required, (5) simple averages of 100 one-second measurements yields about three hundred picoseconds resolution -- no elaborate data analysis is required, and (6) equipment delays are easily calibrated through the use of a standard earth station acting as a transfer standard.

This paper introduces the principles of two-way time transfer with emphasis on its use with commercial communications satellites. It discusses the limitations imposed by the atmosphere, the equipment, and the rotating, noninertial reference system on the assumption of reciprocal paths.

Introduction

Two-way time transfer is potentially one of the most accurate ways to compare clocks. The high accuracy is obtained by the users simultaneously exchanging signals via a communications satellite. If the paths between the clocks are reciprocal or very nearly so, the delays cancel. The difference between the clocks is then half the difference in time interval counter readings. The main advantage of the two-way technique is that no knowledge is required concerning the location of the clocks or satellite with a minor exception--the Sagnac effect, which is easily calculated. The main disadvantage of the system is the participants must be able to simultaneously transmit and receive signals.

Synchronization of clocks by the two-way method is not new. The technique coupled with communication satellites is also not new. Experiments have been conducted for more than 25 years using numerous different satellites, signal structures, modulation techniques, and carrier frequencies. A summary of these developments is given in Figure 1. Early experiments were characterized as using large satellite earth stations, inefficiently using the space segment (that is, unnecessarily large amounts of satellite power and bandwidth) earth stations that were located far from the laboratories housing time scales, and experimental satellites rather than operational systems with telecommunications traffic. Each subsequent experiment usually included improvements in one or more areas until today we have small on-site, user-owned earth stations. The power and bandwidth demanded of the satellite are only a small percentage of the transponders' power-bandwidth product when operating in the code division multiple access (CDMA) mode using the highly efficient signal structure called spread spectrum.

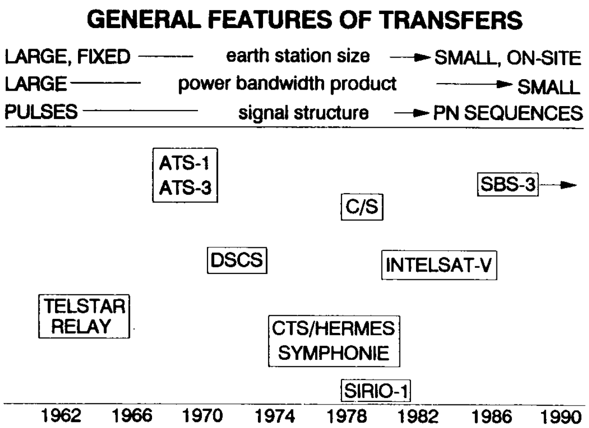
The first satellite-based, two-way time transfer took place between the United States and the United Kingdom in 1962 using the Telstar satellite, an early telecommunications satellite [1]. Later experiments used Telstar II and Relay and included participation by Japan [2]. Experiments during this period (1962-1965) employed large fixed earth stations, pulses as the signals, and frequency division multiple access (FDMA), and gave results of 0.1 to 20 μs accuracies. These experiments, while far from using facilities to the best advantage, did illustrate the potential of the technique for great improvements in time coordination on a global basis.

Between 1967 and 1975 the Application Technology Satellites (ATS) series operated by the National Aeronautics and Space Administration (NASA) supported a host of clock synchronization experiments. These experiments for the most part involved laboratories in the USA and Japan [3]-[7]. Some of these experiments for the first time involved small on-site earth stations and pseudo-noise sequences that allowed better use of the space segment. They possessed good time transfer qualities and allowed the use of code division multiple access (CDMA)--a technique that better satisfies reciprocity of path assumption which the two-way technique depends. These experiments led to a 5 μs accuracy and helped identify the Sagnac effect as significant to this application. Many improvements were made during this period but still with only experimental satellites, because commercial offerings were not fully suitable or affordable for time transfer.

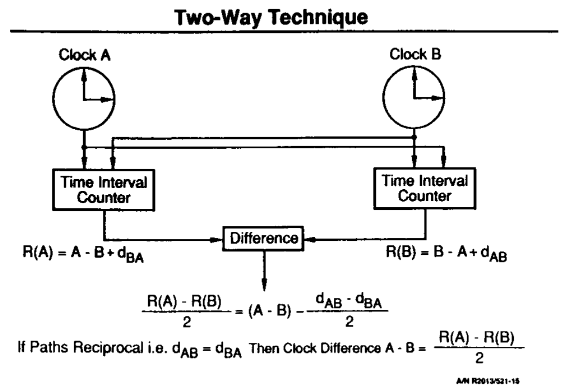
One exception to the use of experimental facilities for two-way time transfer was an application using the Defense Satellite Communication System (DSCS) of the USA [8]. Here PN sequences, large earth stations, and CDMA combined to provide a 0.2 μs operational system that satisfied specific military requirements.

More experiments followed between 1976 and 1979; each used experimental satellites [9]-[13]. A high power communications satellite, called Communications Technology Satellite (CTS) by the US and Hermes by the Canadians, operated at Ku-band and provided, for the first time, long term comparison of time scales in Canada and the US. Small on-site earth stations located near the time scales were in use, but pulses and FDMA access remained. The European satellite called Symphonie provided time scale comparisons across the Atlantic, within Europe, and between India and Europe but was generally limited to large fixed earth stations located far from the time scales involved.

During the period of 1978 to 1980 an Italian experimental satellite called SIRIO [14] was used to



1. History of two-way time transfers using satellites.



2. Two-way time transfer basics.

transfer time between sites in Italy using a single communication channel, time-shared between the participating sites--a time division multiple access approach. By interpolation for satellite motion over periods of a few seconds, accuracies of a few nanoseconds were achieved.

In 1981, the C/S satellite provided at 30/20 GHz two-way time transfers using earth stations with receivers as small as 1 m, PN sequences, and CDMA [15]. Accuracies of 13 ns were verified through terrestrial microwave links and portable clock transfers. The carrier frequencies were unusual in that they have not been available for use elsewhere.

In 1983 an Intelsat V satellite between the USA and Germany signified that the technique had finally matured to the point where operational use could be planned [16]. Small earth stations located on-site using PN sequences, CDMA, and commercially available modems routinely gave a 1 ns precision.

Today clocks at NIST in Boulder, Colorado and the United States Naval Observatory in Washington, D.C. are compared routinely using a commercial communications satellite in the two-way mode. A channel is leased for one half-hour three times a week. The earth stations are owned by the laboratories involved and connected directly to the time scales for best precision and accuracy of time transfer. The transfer uses spread spectrum signals, CDMA, and all commercial equipment. The uplinks are at 14 GHz and downlinks at 12 GHz, thereby providing a high degree of reciprocity through the ionosphere. Precision is less than 0.5 ns at all times. Accuracy will be determined following long term calibration exercises. Calibration is scheduled to begin in mid-1989. Two-way time transfers between North America and Europe are also scheduled to begin during late 1989 using an international communications satellite.

Theory

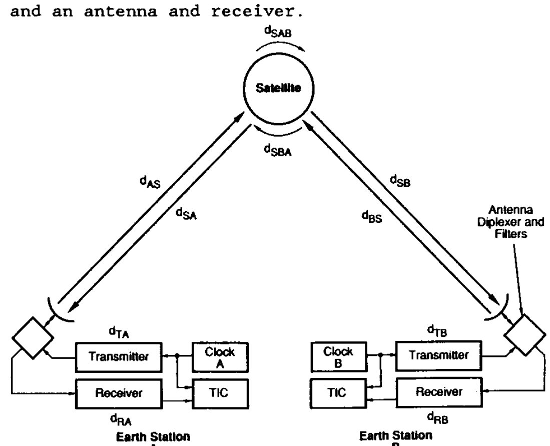
The two-way time transfer technique (without satellite) is illustrated in Figure 2 showing two clocks, clock A and clock B, and two time interval counters (TIC). The TIC on the left measures the difference between the 1 pps from clock A and the 1 pps from clock B delayed by the cable delay d_{BA}. That measurement is given as R(A). Likewise, the TIC on the right measures R(B), the difference between clocks B and A with the cable delay d_{AB}. It is assumed that the delays in the cables connecting clocks to the start channels of the TIC's are very small or effectively 0. The readings on the two TIC's are subtracted to determine the time difference, A-B, in the two clocks as

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

If the paths are reciprocal, that is, if the two cable delays are equal, then $d_{AB} = d_{BA}$, and the clock differences are just half the differences in the TIC readings, or

$$A - B = [R(A) - R(B)]/2. \quad (2)$$

If the two clocks are separated by large distances that cannot be spanned by cables they may be replaced by communication channels furnished by a communications satellite. In Figure 3 the cables are replaced by a transmitter and antenna, an uplink to the satellite, a path through the satellite, a downlink (at a different frequency from the uplink), and an antenna and receiver.



3. Two-way time transfer using a satellite.

Following the form of Equation 1 and selectively grouping the delays, we have the time difference between clock A and clock B as half the difference in the TIC readings, as was the case examined before, plus a number of new terms:

$$A - B = [R(A) - R(B)]/2 - (d_{TB} - d_{RB})/2 + (d_{TA} - d_{RA})/2 + (d_{AS} - d_{SA})/2 - (d_{BS} - d_{SB})/2 + (d_{SAB} - d_{SBA})/2 - 2\omega A/c^2. \quad (3)$$

Equation 3 is also shown in Figure 4 with additional comments added for clarity. The additional terms in Equation 3 relative to the simpler Equation 1 involve the differences in time delay in the transmitting and receiving equipment, differences in the uplink and downlink delays, differences in delays through the satellite, and one final term, $2\omega A/c^2$, which is due to a rotating system and finite signal velocity. These terms or pairs of terms are discussed in more detail below.

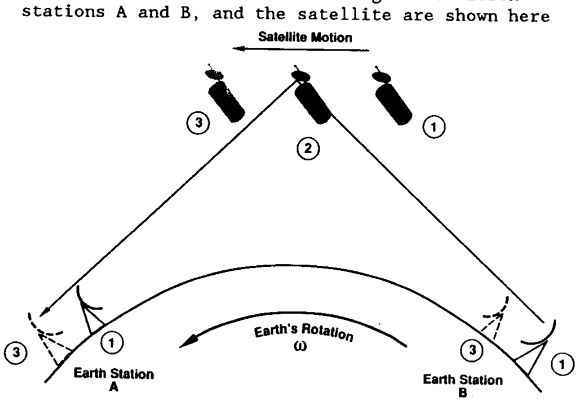
**Two-Way Technique
Using a Geostationary Satellite**

$A - B = \frac{R(A) - R(B)}{2}$	Time Interval Counter Readings
$-\frac{d_{TB} - d_{RB}}{2} + \frac{d_{TA} - d_{RA}}{2}$	Earth Station Equipment
$+\frac{d_{AS} - d_{SA}}{2} - \frac{d_{BS} - d_{SB}}{2}$	Propagation
$+\frac{d_{SAB} - d_{SBA}}{2}$	Delay in Satellite
$-\frac{2\omega A}{c^2}$	Earth's Rotation

4. Two-way time transfer equation.

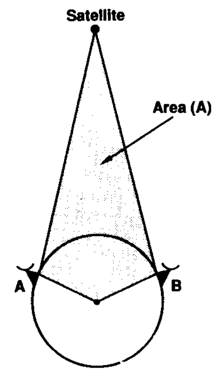
Sagnac Delay

The last term in Equation 3 is known as the Sagnac effect and can be derived using powerful theoretical tools. A simple physical understanding can be had, however, from consideration of Figure 5. Earth stations A and B, and the satellite are shown here



5. Earth's rotation introduces non-reciprocity.

at an instant of time "1" when pulses are sent to the satellite. The earth is rotating at the rate ω, causing earth station A to be in position "3" when the signal from earth station B arrives. The earth's rotation and the finite velocity of the signal have combined to increase the path length from B to A. Likewise, the signal from A to B experiences a corresponding decrease in path length. These changes in path length are equat to $2\omega A/c^2$ where c is the velocity 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 two earth stations an shown in Figure 6. This term can be calculated with sufficient accuracy for nanosecond time transfers with only approximate knowledge of the earth station's and satellite's positions. For example, in the time transfer between NIST and the USNO using the geostationary satellite at 95° West longitude, a 1° error in satellite longitude produces less than 100 ps error in the calculation of the Sagnac effect. The same is true for a 300 m error in longitude or latitude for the location of NIST. The assumption of a perfectly circular geostationary orbit does not produce more than 50 ps error for the eccentricities usually associated with a typical "geostationary" orbit. This is a significant advantage over other methods of time transfer where very accurate knowledge of these positions is required. As is often the case an accurate satellite ephemeris is difficult to come by and limits any time transfer effort.



6. Area in the Sagnac equation.

Equipment Delays

The term

$$-(d_{TB} - d_{RB})/2 + (d_{TA} - d_{RA})/2,$$

from Equation 3 involves the differences in the signal delay in the transmitting and receiving sides of the satellite earth station. If the two earth stations could be collocated to assure cancelation of the propagation delays and a null Sagnac effect; if the clocks A and B were synchronized, as would be the case if clocks A and B were the same clock; if the delays through the satellite were equal, that is, $d_{SAB} = d_{SBA}$ (d_{SAB} denoting the delay through the satellite when the signal is moving from earth station A to earth station B), as would be the case for most satellite systems operating in the CDMA mode; then the difference of the TIC readings gives the desired equipment delays as

$$[R(A) - R(B)]/2 = -(d_{TA} - d_{RA})/2 + (d_{TB} - d_{RB})/2. \quad (4)$$

In most cases, however, where the two earth stations cannot be collocated even temporarily, a third or calibration earth station, a portable or mobile unit, can be used to make these measurements. With this calibration earth station collocated with earth station A the difference in the TIC readings, $[R(C)_A - R(A)]/2$, is given by

$$[R(C)_A - R(A)]/2 = -(d_{TC} - d_{RC})/2 + (d_{TA} - d_{RA})/2, \quad (5)$$

where $R(C)_A$ is the TIC reading at the calibration earth station when collocated with the earth station A. Similarly, when the calibration earth station is collocated with earth station B,

$$[R(C)_B - R(B)]/2 = -(d_{TC} - d_{RC})/2 + (d_{TB} - d_{RB})/2. \quad (6)$$

If delay, $d_{TC}-d_{RC}$, in the calibration earth station is constant the difference in these two measurements gives the desired quantity, or

$$[R(C)_B - R(B)]/2 - [R(C)_A - R(A)]/2 = -(d_{TA} - d_{RA})/2 + (d_{TB} - d_{RB})/2. \quad (7)$$

Therefore, what can be the most difficult nonreciprocal issue in the two-way time transfer is easily dealt with through the use of an earth station that may be collocated with the earth stations requiring calibration.

Propagation Delays

The signal delays associated with the up and down links are, from Equation 3, given as

$$-(d_{AS} - d_{SA})/2 + (d_{BS} - d_{SB})/2.$$

The uplink carrier frequencies for the Fixed Satellite Service (FSS) in use today are nominally 6 and 14 GHz paired with the downlinks of 4 and 12 GHz. The signal path is mainly free space with a small amount of ionosphere and troposphere. The path followed by the uplink and the downlink are essentially the same path. The free space part is reciprocal, as is the tropospherical part since, at these frequencies, the group or signal delays are frequency independent. The signal delay through the ionosphere has a $1/f^2$ frequency dependence. For typical elevation angles the differences in the delay terms are small and the total effect additionally reduced since the differences are halved. The reciprocity assumption is, therefore, likely to hold to less than 100 ps for operation in the Ku-band of the FSS.

Satellite Delays

The satellite time delay term represents the delays, d_{SAB}, to the signal by the satellite when going from earth station A to earth station B and those, d_{SBA}, going from B to A. For many satellites the equipment has a small delay variation across the transponder bandwidth so even in a FDMA mode the differences amount to only a few nanoseconds. When using the CDMA mode, made possible by the use of PN signals, signals from each earth station passes through the same satellite equipment at the same frequencies. The delays in each direction are therefore identical and the differences 0.

Data

Table 1 presents 30 s of data collected at the USNO and NIST during one of the now routine time transfers. The first column contains the time tag for each data point in hours, minutes, and seconds. The second and third columns are the 1 s averages of time interval measurements in units of seconds as shown in Figure 2. The fourth column is one-half the difference between the second and third columns also given in seconds. A simple analysis of these

Table 1. Example of two-way data.

HH:MM:SS	$R(A)=A-B-d_{BA}$	$R(B)=B-A-d_{AB}$	$A-B=[R(A)-R(B)]/2$
15:49:00	0.25103279152	0.25103074887	1.02133E-06
15:49:01	0.25103279322	0.25103075123	1.02099E-06
15:49:02	0.25103279394	0.25103075164	1.02115E-06
15:49:03	0.25103279506	0.25103075353	1.02076E-06
15:49:04	0.2510327965	0.25103075422	1.02114E-06
15:49:05	0.25103279824	0.25103075529	1.02147E-06
15:49:06	0.2510327992	0.25103075654	1.02133E-06
15:49:07	0.25103280086	0.25103075828	1.02129E-06
15:49:08	0.25103280127	0.25103075928	1.02099E-06
15:49:09	0.25103280291	0.25103076115	1.02088E-06
15:49:10	0.25103280471	0.25103076182	1.02144E-06
15:49:11	0.25103280502	0.25103076328	1.02087E-06
15:49:12	0.2510328066	0.25103076463	1.02099E-06
15:49:13	0.25103280807	0.25103076615	1.02096E-06
15:49:14	0.2510328085	0.2510307668	1.02085E-06
15:49:15	0.25103281102	0.2510307682	1.02141E-06
15:49:16	0.25103281041	0.25103076943	1.02049E-06
15:49:17	0.25103281232	0.25103077098	1.02067E-06
15:49:18	0.25103281311	0.25103077217	1.02047E-06
15:49:19	0.25103281557	0.25103077342	1.02107E-06
15:49:20	0.25103281648	0.251030774	1.02124E-06
15:49:21	0.25103281777	0.25103077648	1.02065E-06
15:49:22	0.25103281973	0.25103077697	1.02138E-06
15:49:23	0.25103282057	0.25103077754	1.02151E-06
15:49:24	0.25103282162	0.25103077922	1.0212E-06
15:49:25	0.25103282285	0.25103078064	1.0211E-06
15:49:26	0.25103282324	0.25103078221	1.02051E-06
15:49:27	0.25103282449	0.25103078348	1.0205E-06
15:49:28	0.25103282682	0.25103078521	1.02081E-06
15:49:29	0.25103282732	0.25103078568	1.02082E-06

NUMBER OF MEASUREMENTS = 30

$$\text{MEAN} = \sum_{i=1}^{30} x_i/n = 1021.01 \text{ ns}$$

$$\sigma = [\ 1/(n-1) \sum_{i=1}^{10} (x_i - x)^2\ ]^{1/2} = 0.32 \text{ ns}$$

maximum = 1021.51 ns

minimum = 1020.47 ns

90% confidence level is 0.1 ns

30 measurements gives the mean as 1021.01 ns (± 0.1 ns for 90% confidence) and a standard deviation of 0.32 ns. All 30 data points are within ± 0.5 ns of the mean. This is a data set selected at random to illustrate the simplicity of the data analysis.

Summary

Two-way time transfer used with geostationary communication satellites can be a practical technique for the comparison or synchronization of clocks at the highest levels of precision and accuracy at reasonable costs. High accuracy is possible because (a) the use of a transfer or calibration earth station, provides the required measure of earth station delays, (b) the relativistic (Sagnac) effect may be accurately calculated with relatively imprecise information on the locations of the satellite and user's clocks, and (c) satellite and propagation path delays cancel to a large extent due to a high degree of path reciprocity.

Commercially available, low cost equipment and an abundance of satellite channels available for lease make implementation of the technique relatively simple. Reduction of data requires very little effort or special procedures. The technique has been used operationally in the United States for more than one year and has shown itself to be simple to operate and maintain. Space segment costs have been approximately $100 (U.S.) per week with enough excess capacity to support the synchronization of a network of at least ten clocks rather than the present two.

The only real barriers to further expansion involves the organization of participants and approval/licensing procedures for the earth stations.

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