# High-Accuracy Time Transfer via Geostationary Satellites: Preliminary Results

DAVID A. HOWE

***Abstract*—Signal-delay phase measurements have been performed with Ku-band earth station and VSAT facilities in various loop-around schemes using both a satellite simulator and geostationary satellites. Stability plots show that the standard deviation of pair differences ($\sigma_y$) is $4 \times 10^{-10} \tau^{-1}$ for a C/No ratio of 65 dB · Hz. This white noise behavior continues to a few days where $\sigma_y$ is $3 \times 10^{-15}$ with satellite simulator data. Absolute phase delay measurements show reproducibility to better than 1 ns over a 16 day sample time. This suggests the potential for accuracy to this level given an appropriate calibration. This paper describes a measurement method which determines the principal time delay constant affecting the accuracy of time synchronization using a two-way satellite communications technique.**

## I. Introduction

SATELLITE TELECOMMUNICATIONS advances open up new opportunities for doing accurate transfers of time between suitably equipped laboratories. Ku-band satellite transponders in the 14/12-GHz band permit the use of small, low-cost earth stations. The short wavelength 12-GHz downlink frequency and the high power of the satellite transponders yields adequate signal levels even when using only a small 1.8-m dish referred to as a "very small aperture terminal" or VSAT. The VSAT can transmit to and receive from a geostationary satellite of the fixed satellite service (FSS) in a two-way mode. Time transfer experiments using the two-way mode through geostationary satellites have been demonstrated to a level of six to 30 ns [1]-[7]. A new modem useful for this task creates new research opportunities by simplifying the procedure [6]-[8]. The modem uses phase-shift keying modulation in roughly 4 MHz of bandwidth and a pseudorandom noise (PN) sequence as the signal modulation. Therefore, the signal is indistinguishable from the normal communications link noise. There is, of course, an increase in the noise density over the 4 MHz which the signal occupies, but this increase can be small enough that little or no interference is caused to other transponder users. The central component of the present two-way satellite work is a Ku-band earth station having a 6.1-m dish located on top of the radio building at NBS, Boulder. It is referred to as the "hub" in the sense that other involved earth stations (VSAT's) have less capability and the use of the hub during experiments helps establish initial satellite connections. Fig. 1 is a block diagram of the principal parts of the earth station. The VSAT consists of a complete earth station RF package with 70-MHz input and output intermediate frequency attached to a 1.8-m dish on a free-standing pedestal. Maximum power is 2 W. A complete description of the hub and VSAT is given in [9].

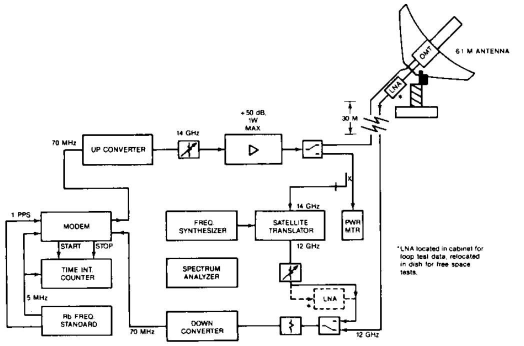

Fig. 1. Block diagram of principal parts of the hub earth station.

## II. In-Cabinet and Free-Space Loop Tests

In order to test the various subsystems comprising the ground equipment, several loop-around schemes were employed which can be divided into two basic categories: 1) in-cabinet tests involving the use of a satellite translator or simulator connected to the transmit and receive (14 and 12 GHz) waveguide ports of the VSAT or earth station, and 2) free-space tests using the translator connected to horn antennas which are located away from and directed at the VSAT with its dish fully operational. Fig. 1 shows the placement of the translator for in-cabinet tests for the hub earth station. The transmit signal from the 1-W power amplifier is switched to a power meter with a sample of the signal routed to the input of the translator. The translator shifts the frequency by 2.3 GHz, and this output is fed to the low noise amplifier (LNA). Fig. 2 is a block diagram of the free-space loop test used with the VSAT. In this test, the VSAT 1.8-m dish is deployed, and horn antennas are used with the translator along with a LNA for gain ahead of it. In-cabinet VSAT loop tests have the antenna removed and satellite translator directly con-

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The author is with the Time and Frequency Division, National Bureau of Standards, Boulder, CO 80303.

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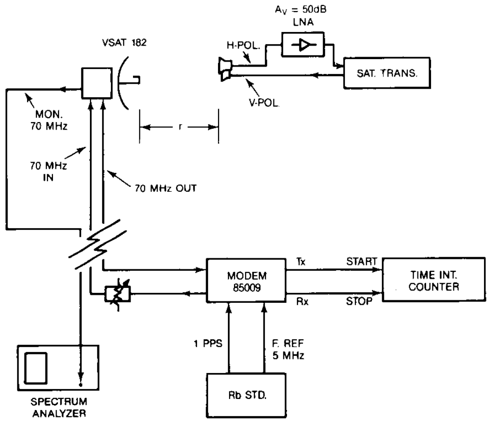

Fig. 2. Block diagram of VSAT free-space loop-around test.

nected to the waveguide ports of the VSAT transceiver.

With the modem sending and receiving PN spread-spectrum modulation in loop tests, one can analyze the phase stability of the 1 pps sent round trip through the ground equipment. This sets an upper limit on the expected stability using this equipment. Stability measurements are performed using the two-sample (pairs of data) Allan variance of the phase readings from a time-interval counter (TIC) [10]. Frequency stability ($\sigma_y$ versus $\tau$) from 1 s to a few thousand seconds is shown in Fig. 3 for three carrier-to-noise-density (C/No) ratios using the hub equipment with an in-cabinet loop test. Carrier-to-noise-density ratio is a figure of merit parameter for communication links and the measurement technique is described in Appendix I [11]. For a C/No of 65 dB · Hz, $\sigma_y$ is about $4 \times 10^{-10} \tau^{-1}$. Also shown is $\sigma_y$ with the modem in its internal (70 MHz) loop test mode which presumably is a best case condition representing a high C/No ratio. Plotted in Fig. 3 is the calculated two-sample variance from the white phase jitter published with the modem. Daily measurements at 65 dB · Hz show fairly good agreement with extrapolated short-term measurements with actual data taken to 4 days and stability of a few $\times 10^{-15}$. Thus, long-term stability is good. For reference purposes, one voice-grade satellite channel typically represents a C/No of about 55 dB · Hz, and the modem works reasonably well at this level as shown by the stability measurements of Fig. 3.

Fig. 4 shows frequency stability results of in-cabinet loop tests performed on the VSAT transceiver. C/No was 75 dB · Hz taken at the upper signal limit of the modem in order to uncover any noise degradation due to the transceiver. Identical results were obtained in the internal loop tests and in-cabinet transceiver loop tests indicating that no degradation had taken place. As an additional test, three modems were connected in series so the loop-around involved transmission by one modem, reception by a second with retransmission by the second, reception by a third with retransmission by the third through the VSAT transceiver and simulator, and finally reception by the first modem. The frequency stability measurement results in Fig. 4 show virtually no stability degradation compared to single modems, so the apparatus does well even in this situation.

Day-to-day loop-around time delay variations were measured with the VSAT in-cabinet and free-space. These results are plotted in Fig. 5 and show reproducibility to the 1-ns level. These results are excellent and show the potential for synchronization at this level. There is a dis-

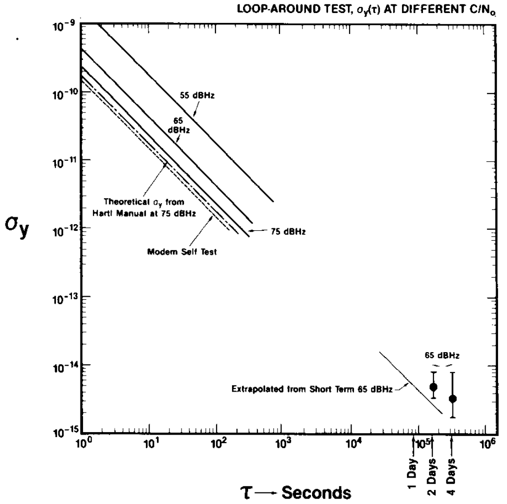

Fig. 3. Frequency stability measurements of hub earth station equipment in an in-cabinet loop test.

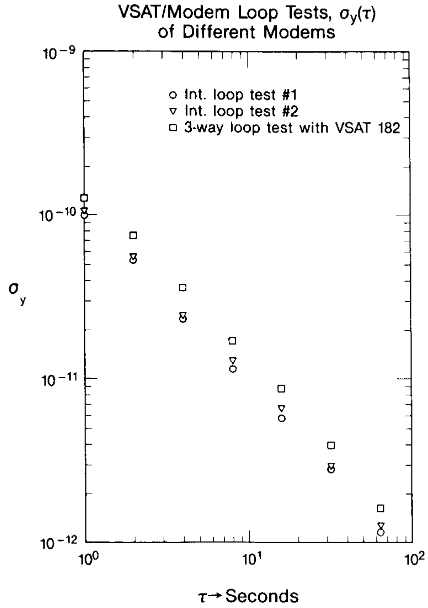

Fig. 4. Frequency stability measurements of VSAT equipment in an in-cabinet loop test and using three different modems for comparison.

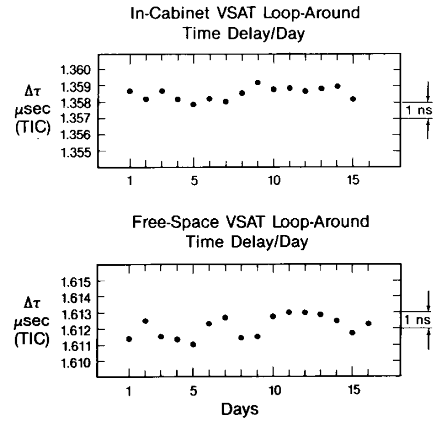

Fig. 5. Day-to-day loop-around time delay using VSAT in-cabinet and free-space showing total in-cabinet and free-space loop-around time delay reproducibility using VSAT.

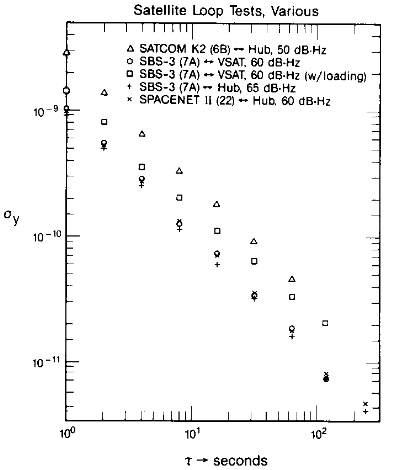

Fig. 6. Frequency stability measurements of loop tests involving hub and VSAT with three satellites.

cernible increase in the noise level of the free-space data. Its cause is unknown but may be due to translator environmental sensitivity. Nevertheless, the results are encouraging since the measurement is "round trip" and represents accumulated phase noise.

## III. Satellite Loop Tests

The configuration for doing satellite loop tests is essentially identical to the free-space tests involving the translator except that the dish antenna is directed at the satellite transponder. Which satellites make suitable candidates for tests depends on the receiver $G/T$ and transmit EIRP of the ground facility, the satellites in view and their $G/T$ and EIRP for a given connection, the minimum acceptable C/No, and (in this case) the available bandwidth [11]. Tests were done on three satellites: SATCOM K2 (81 W), SBS 3 (95 W), and SPACENET II (69 W). A description of the experimental procedure is given in [12].

First loop tests were conducted using the hub earth station and SATCOM K2 located at 81 W. A 4-MHz segment at the high-frequency edge of transponder number six, which is used for in-house voice communications by satellite operators, was used for the test. A potential timing-related problem with use of the edge of a transponder is frequency-response rolloff which creates 1) amplitude-to-phase conversion and 2) decoding errors by the modem. This rolloff, as it turned out, was not significant in this test and hence was not a problem.

Satellite loop tests were performed using the VSAT and SBS-3 located at 95 W. A difficulty with using the particular brand of VSAT used here is that the frequency offset between transmitting and receiving is preset at 2.3 GHz and the transponder has an allowable error in its re-transmit offset of ±24 kHz. The signal to the modem should be within ±1 kHz for its best accuracy, but no provision exists for compensating any frequency error. For this test, the frequency error back to the modem was about 12 kHz which yielded an off-scale condition of a frequency discriminator meter located on the panel of the modem. For two-way time transfers between a VSAT and the hub earth station, independent frequency synthesizers are used at the hub for transmit and receive so all frequency errors can be compensated in this configuration.

Time delay through the satellite is about 250 ms in these loop tests. Analysis of the round-trip time (phase measurement) was done again using the two-sample Allan variance and its square-root $\sigma_y$, and typical results are shown in Fig. 6. These results are consistent with in-cabinet and free-space loop tests done on the ground equipment and shown in Fig. 4. In addition to loop tests described thus far, plots are shown in Fig. 6 for hub earth station to SBS-3 and SPACENET II (69 W), transponder 22. The stability plots follow $\tau^{-1}$ behavior as expected for white noise except for the case of VSAT and SBS-3 with transponder loading. Transponder loading is described in Appendix II.

## IV. Two-Way Time Transfer Using a Common Reference Standard

In making estimates of the time transfer accuracy using the two-way technique, signal delays everywhere in the link are of concern. Such delays come from cables, amplifiers, filters, converters, and, of course, the transmission link itself. In doing a time comparison using the two-way time transfer technique, the absolute values of the signal delay are not directly involved; instead, the difference between the transmit path and the receive path is the parameter of interest (the differential delay). Realizing that two transmit/receive facilities are needed for the transfer, it is ultimately the difference of the two differential delays of the involved facilities that is essential (the "offset of the differences"). Appendix III derives this offset of the differences term. The accuracy and stability of this term gives an upper limit on the accuracy and stability of the time comparison.

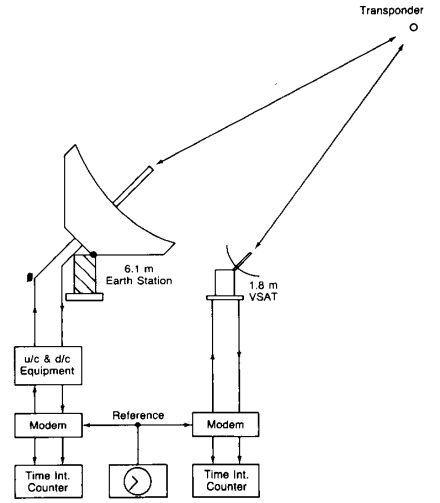

Fig. 7. Common view/common clock scheme for measurement of ground-segment differential delay constant.

Most measurements of ground equipment delays involve the timing of an injection RF pulse and the detection of the same pulse at a point before the antenna for the transmission portion. The delay measurement for the receive portion is done in the same way but with the injection pulse usually at the LNA and the envelope detector after the appropriate receive chain equipment. There are two common difficulties with this approach. The first is that the pulse injection and detection scheme itself introduces a measurement uncertainty since this is not the way the equipment normally operates. A more favorable measurement would be done *in situ*. Second, the measurement does not include the antenna and its associated orthomode transducer and feed system. One cannot assume that the antenna's differential delays are zero.

Fig. 7 is a diagram showing the basic scheme in which the hub earth station and VSAT simultaneously use a common transponder with two separate spread spectrum sequences (near orthogonal [8]) timed by a common 1-pps reference. A modem is used at the hub and another is used at the VSAT and the transmit sequence ($Tx$) is indicated as "0" for the hub and "1" for the VSAT. The receive sequence ($Rx$) is "1" for the hub and "0" for the VSAT so each earth station receives the sequence from the other one and not itself. This is the basic configuration used between separate locations doing a simultaneous two-way time transfer. In the case here, the two earth stations are collocated with a common 1-pps reference thus allowing a direct measurement of differential timing errors. Furthermore, this approach allows a direct measurement of system accuracy and stability [1]. Although no data has been analyzed at this time, the concept has been demonstrated using the hub and VSAT equipment operating simultaneously through SBS-3 using two separate spreading sequences. Time interval counter measurements need to be taken and the results compared as described in Appendix III.

## V. Conclusions

A number of tests have been performed on commercially available Ku-band satellite telecommunications equipment and, in particular, on a small, self-contained earth terminal (VSAT). Satellite loop tests used SATCOM K2 (81 W), SBS 3 (95 W), and SPACENET II (69 W). Stability performance is on the order of $4 \times 10^{-10} \tau^{-1}$ for a C/No ratio of 65 dB · Hz. Long-term stability data in a satellite loop test has not yet been obtained, but in-cabinet and free-space loop tests of the ground equipment using a satellite simulator show that this white noise behavior continues for a few days where $\sigma_y$ is $3 \times 10^{-15}$. Absolute phase delay measurements show reproducibility to about 1 ns over a 16 day sample time. Future tests will be done to gather long-term stability measurements and long-term reproducibility in loop tests involving actual satellites.

This paper described a direct measurement technique for determining the differential offset term for two satellite earth stations (one, a portable VSAT) in close proximity to each other using a common satellite and a common reference clock. Usually, the differential offset constant has been determined in satellite time comparisons by measuring delays of injected RF pulses, a method which has certain inaccuracies. The method used here provides a direct measurement of the delay for two earth stations under actual operating conditions. The direct measurement makes the fewest assumptions regarding the uncertainty in the determination of the differential offset constant.

## Appendix I

## Measurement Methods

Of interest in this paper is a relationship between standard frequency stability measurement techniques and standard satellite, signal-to-noise ratio parameters. In the case of frequency stability the measurement performed is the two-sample Allan variance of the phase noise of the ground segment in both in-cabinet and free-space, loop-around schemes. Frequency stability measurements from 1 s to a few thousand seconds were performed for various carrier-to-noise-density (C/No) ratios. Carrier-to-noise density ratio is a general figure of merit parameter for a satellite communications link. Frequency stability data also was taken at one day intervals to look at long-term stability and its agreement with extrapolated short-term stability results. The actual C/No measurement is made using a spectrum analyzer sampling the unmodulated pure RF carrier of the modem compared to the density of noise in a 1-Hz bandwidth. The spectrum analyzer had a minimum resolution bandwidth of 10 Hz but the noise component was white and allowed straightforward calculation to 1-Hz bandwidth. The analyzer incorporated a correction for doing noise bandwidth measurements at various analyzer settings. These corrections were found to be accurate to the rated specification of 1 dB by scanning the shape of the response curve and scaling the bandwidth as high as 100 kHz and (again assuming white noise) seeing correct closure of the equivalent noise bandwidth at 1 Hz. At low $(C + N)/N$ ratios, it is difficult to accurately measure the signal level because of the presence of the noise component. To overcome this difficulty the carrier signal was introduced at a higher level, accurately measured by the analyzer, and then a precision attenuator was applied to only the carrier in order to reduce its level to a known value.

Some data which are presented in the documentation which accompanies the modem are useful for the analysis of frequency stability presented here. Fig. 3 shows a plot from data of the white noise phase jitter versus carrier-to-noise density ratio [8]. A value for $\sigma_y$ can be computed and the value for 75 dB · Hz is included with the data. If we assume that modem data are the classical variance about the mean of the phase jitter ($\sigma_x^2$) then the relationship to the Allan variance is [10], [13]

$$\sigma_x^2(\tau_0) = \frac{\tau^2 \sigma_y^2(\tau)}{3}$$

where $\tau_0$ is the sample time between phase measurements.

## APPENDIX II
## TRANSPONDER LOADING AND ITS EFFECT

The transponder output power amplifier is not linear when operating near saturation; that is, overall gain becomes a function of its input signal level. This is called "loading." When one or two video signals share the transponder, the system is usually operated near saturation. If only one video signal occupies the entire transponder, it may be operated at or even above saturation. This can cause the shared low-level timing signal to drop by as much as 6 to 8 dB causing a net reduction in its received C/No by this amount. Since $\sigma_y$ is increased as C/No is decreased, unexpected characteristics in $\sigma_y$ may occur if transponder loading is changing during sampled time intervals.

## APPENDIX III
## "OFFSET OF THE DIFFERENCES" MEASUREMENT

For measurement of the differential delay terms which show up in the two-way transfer scheme, one can use the portable dish in conjunction with a fixed ground station. With a common clock, one can calibrate out these differential delay terms. This is shown in the following analysis in which $TI(1)$ and $TI(2)$ are the time interval counter readings at locations 1 and 2, respectively, in a two-way time transfer involving locations 1 and 2.

$$TI(1) = \Delta T + \mathrm{Up}C(2) + \text{sat.path}(2 \text{ to } 1) + \mathrm{Dn}C(1)$$

and

$$TI(2) = -\Delta T + \mathrm{Up}C(1) + \text{sat.path}(1 \text{ to } 2) + \mathrm{Dn}C(2).$$

$\Delta T$ is the time difference of the clocks at 1 and 2, Up$C$ denotes time delay through the up-conversion at locations 1 or 2, and Dn$C$ denotes the down-conversions. Sat.path represents the total signal path delays up to and through the satellite and down for signals going from location 1 to 2 and vice versa. Sat.path includes any additional delays due to the satellite-earth system rotation during the propagation time of the signal [14].

$\Delta T$ can be calculated as

$$\Delta T = \tfrac{1}{2}\big\{[TI(1) - TI(2)] + [\mathrm{Up}C(1) - \mathrm{Dn}C(1)] - [\mathrm{Up}C(2) - \mathrm{Dn}C(2)] + \text{sat.path}(1 \text{ to } 2) - \text{sat.path}(2 \text{ to } 1)\big\}.$$

If we assume sat.path time delays are reciprocal, except for the time difference term due to the rotation of the satellite-earth system, then sat.path(1 to 2) = sat.path(2 to 1) + $\delta T$(rotation) and we have

$$\Delta T = \tfrac{1}{2}\big\{[TI(1) - TI(2)] + [\mathrm{Up}C(1) - \mathrm{Dn}C(1)] - [\mathrm{Up}C(2) - \mathrm{Dn}C(2)] + \delta T(\text{rotation})\big\}.$$

Now with the two earth stations co-located and using a common clock, $\delta T(\text{rotation}) = 0$ and $\Delta T = 0$ and the difference in the Up$C$'s and Dn$C$'s is explicitly the difference in the time interval counters. We have

$$TI(2) - TI(1) = [\mathrm{Up}C(1) - \mathrm{Dn}C(1)] - [\mathrm{Up}C(2) - \mathrm{Dn}C(2)] = \text{constant}.$$

This constant which is the offset of the differences can be used for subsequent two-way time transfers using the earth stations, one of which is a portable VSAT which can be located with another earth station to yield a "calibration" of that earth station.

In doing two-way time transfer experiments through geostationary satellites, there exists a limit on the knowledge of the time delay difference between the outgoing signal and the received signal. This nonreciprocity is due to the difference of paths and the difference of equipment between the uplink and the downlink. Using spread spectrum modulation with different pseudorandom codes for the two directions of time transfer, it is common to assume the difference in the transmission paths to and from the satellite as well as through the satellite transponder to be zero and the earth's rotation correction can be computed [14]. Certainly the ionospheric dispersion and the effects of water vapor dispersion are small (below 100 ps) [15]. The most significant time delay difference error enters in the ground segment. The use of cables, interconnects, conversions, and test points for instruments creates the most significant absolute delays and thus the opportunity for significant differential delays.

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