Ku-BAND SATELLITE TWO-WAY TIMING
USING A VERY SMALL APERTURE TERMINAL (VSAT)*

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Summary

The NBS Boulder Laboratory has recently completed
installation of a 6.1 meter Ku-band (14/12 GHz)
satellite earth station and has acquired two 1.8
meter portable earth terminals and commercial spread-
spectrum modems. This equipment was procured for the
purpose of doing two-way time transfer experiments in
collaboration with other timekeeping laboratories.
Each portable earth terminal, often called VSAT for
"very small aperture terminal" when the dish diameter
is 1.8 meters or less, is a complete Ku-band earth
station. The VSAT can provide full duplex capability
to transmit to and receive from a geostationary
satellite of the Fixed Satellite Service (FSS).
Thus, two-way time comparisons can be done directly
between NBS and a portable VSAT through a Ku-band
satellite. Phase measurements have been performed of
earth station and VSAT facilities in various loop-
around schemes using a satellite simulator. Frequency
stability $\sigma_y(\tau)$ at various carrier-to-noise density
(C/N_o) ratios will be reported. Stability plots have
shown that performance is $4 \times 10^{-10}\tau^{-1}$ for a C/N_o
ratio of 65 dB-Hz and that this white noise behavior
continues to a few days where σ_y is 3×10^{-15}.
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. Preliminary results of loop tests
through a satellite will be reported.

This paper describes a measurement method which
determines the principle time delay constant
affecting the accuracy of time synchronization using
the two-way technique. The method does not rely on
traditional injection and timing of an RF pulse but
is an in situ determination having fewer measurement
uncertainties.

Introduction

Continuing growth in satellite telecommunications
opens up new opportunities for doing accurate
transfers of time between suitably equipped
laboratories. Wideband Ku-band satellite
transponders in the 14/12 GHz band permit the use of
small, low-cost earth stations with minimal
terrestrial interference and relatively
straightforward licensing. The short wavelength of
the 12 GHz downlink frequency along with the high
power of the satellite transponders yields adequate
signal levels even when using only a small 1.8m dish
on location. These small earth stations are portable
and can be conveniently placed for connection to time
standard outputs. When the dish diameter is 1.8m or

less, the earth station is referred to as a "very
small aperture terminal" or VSAT. The VSAT can
provide full duplex capability to transmit to and
receive from a geostationary satellite of the fixed
satellite service, or FSS.

Recent time transfer experiments using the two-way
technique through geostationary satellites have been
demonstrated to a level of several nanoseconds [1,2].
The development of a modem specifically designed for
this task creates additional opportunity for doing
research on the two-way time transfer technique via
satellites of the Fixed Satellite Service (FSS) by
simplifying the procedure [3]. The modem uses phase-
shift keying modulation in roughly 4 MHz of bandwidth
and a pseudo-random 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
as discussed later this increase can be small enough
that no interference is caused to other transponder
users.

This paper discusses tests conducted using a Ku-band
portable VSAT having a dish diameter of 1.8m with the
spread-spectrum modem. This equipment is part of a
system directed toward two-way time transfer
experiments with various timekeeping laboratories.
In addition, tests have been conducted with a
satellite earth station facility having a 6.1m dish
at the National Bureau of Standards, Boulder
Laboratories. Finally, actual satellite loop tests
were performed using the VSAT and the NBS earth
station.

Facilities

The central component of the present two-way
satellite work is a Ku-band earth station having a
6.1m 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. A picture of the antenna is shown in
the background of Figure 1 and a picture of the earth
station equipment which is located about 30 meters
away is shown in Figure 2. Figure 3 is a block
diagram of the principal parts of the earth station.
Pointing of the antenna is by motorized positioners
controlled by a microprocessor-based driver. The
6.1m dish has a receive gain of 56 dB and has a low
noise amplifier (LNA) with a 2.5 dB noise figure.
The transmitted output power is +26 dBm maximum
(approximately 0.4 watts) measured near the feed. A
complete description of the hub is given in reference
4.

The VSAT consists of a complete earth station RF
package with 70 MHz input and output intermediate
frequency and attached to a 1.8m dish on a free-

standing pedestal. It is shown in the foreground of Figure 1. The dish uses a J-hook prime-focus-feed system. The mount is a simple elevation-over-azimuth assembly using galvanized steel braces arranged in a triangular geometry designed for resting directly on the ground or, in this case, on the roof. Pointing can be done by one person by physically moving the whole terminal to position and locating the satellite by observing the received signal. Since several satellites might be picked up, a unique identifying signal such as a video (television) transmission is very helpful during this pointing exercise. The 6.1m antenna of the hub can automatically point to a given satellite so the signals from it can be used as a reference. This operation is described later.

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 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 satellite simulator connected to horn antennas which are located away from and directed at the VSAT with its dish fully operational. Figure 3 shows the placement of the simulator for in-cabinet tests for the hub earth station. The transmit signal from the 1 watt power amplifier is switched to a power meter with a sample of the signal routed to the input of the simulator. The simulator shifts the frequency by 2.3 GHz and this output is fed to the LNA (low noise amplifier). Figure 4 is a block diagram of the in-cabinet test using the VSAT. The VSAT RF transceiver contains upconverter, power amplifier, LNA, and downconverter all in one package. Connection of the simulator is straightforward. Figure 5 is a block diagram of the free-space loop test used with the VSAT. In this test, the VSAT 1.8m dish is deployed and horn antennas are used with the simulator along with a LNA for gain ahead of the simulator.

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 Allan variance of the phase readings from a time-interval counter (TIC). Frequency stability (σ_y vs. τ) from one second to a few thousand seconds is shown in figure 6 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. For a C/No of 65 dB-Hz, σ_y is about $4 \times 10^{-10} \tau^{-1}$. Also shown is σ_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. Also plotted in figure 6 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 x 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 at this

level as shown by the stability measurements of figure 6.

Figure 7 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 figure 7 show virtually no stability degradation compared to single modems, so the apparatus does well even in this situation.

The VSAT was set up with the 1.8m antenna assembled on its free-standing mount for making range measurements to the translator located up to 26 meters away. Horn antennas and a LNA were added to the translator as shown in the block diagram of figure 5. The distance r is taken from the open end of the feedhorns to the open end (phase center) of the J-hook prime focus feed horn of the 1.8m VSAT dish. This range measurement yields the delay through the VSAT extrapolated to zero distance after removing the translator delay by taking measurements as shown in figure 8. The slope, that is the round trip delay as a function of distance, is determined by the speed of light, and is 14.95 cm/ns. Three measurements were taken and one can see the agreement with this slope in figure 8.

Day-to-day loop-around time delay variations were measured with the VSAT in-cabinet and free-space. These results are plotted in figure 9 and show reproducibility to the 1 ns level. These results are excellent and show the potential for satellite synchronization at this level. There is a discernible 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.

Satellite Loop Tests

After testing this equipment (the ground segment), we proceeded to loop tests involving actual satellites operating in the domestic Ku-band with assigned uplink between 14.0-14.5 GHz and downlink between 11.7-12.2 GHz. The configuration for doing these 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. Before this operation is done, the first consideration is deciding which satellites make suitable candidates for tests. This decision is dependent 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 [5]. Tests were done on three satellites: SATCOM K2 (81 W), SBS 3 (95 W), and SPACENET II (69 W). These transponders are primarily used for video transmissions, and are available on a pre-emptible, partial-transponder, occasional-use basis as long as

no interference is caused to other normal traffic. The spread-spectrum modem requires a minimum C/No of 50-55 dB-Hz, the equivalent of about one voice grade channel, spread across a bandwidth of 2 to 4 MHz. In practice, the modem requires more than 60 dB-Hz in order for the demodulator to acquire initial lock because of the effects of any unknown frequency offset errors in the transponder and because of occasional spurious interference in the roughly 4 MHz bandwidth.

Figure 10a shows a block diagram of key elements of the loop test using the hub and its 6.1m dish. The intermediate frequency used into and out of the upconverter and downconverter equipment is 70 MHz and connections are made to the corresponding transmit and receive ports of the modem. A 1 pps and a 10 MHz reference were provided by a rubidium standard and the transmitted 1 pps identification point used in the modulated PN sequence is approximately synchronized with the external 1 pps reference. The transmitted and received 1 pps as determined by the modem are used as start and stop pulses and are measured using a time interval counter having a resolution of 35 picoseconds (rms) per second. The negative going transitions provide triggering. Figure 10b shows a similar setup but instead using the VSAT with its 1.8m dish. In this case, the upconverter and downconverter are part of the transceiver which is attached to the backside of the dish. About 15 meters of coax cable separates the modem's 70 MHz ports from the input/output of the VSAT.

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 was used for the test. The advantage to this kind of segment is its availability and low-cost since it is useful mainly for in-house voice communications by satellite operators and its marketability is not great due to potential interference problems described here. Figure 11 shows spectrum analyzer displays of signals received from SATCOM K2(6B) using the modem and hub earth station. The center of each display marks the frequency of the loop test signal as a clean carrier (figure 11a) and with PN modulation (figure 11b). Figure 11c represents a wider frequency span. Of the normal video signal which may occupy the upper half of transponder number six (designated 6B), there is usually only a small amount of power that extends to the last 4 MHz. However, video signals are frequency modulated and may extend to 24 MHz wide. A full transponder on SATCOM K2 is 54 MHz wide and can carry two video signals. Allowing for a guard band between two video signals, one sees the possibility of interference even at the transponder edges. An adjacent video signal is clearly seen in the spectrum analyzer displays of figure 11. Another form of interference comes from a second transponder which is operating at nearly the same frequency but has orthogonal antenna polarization. This configuration is called the dual polarization mode. Commonly, horizontal and vertically polarized signals share the same satellite permitting greater utilization of the frequency spectrum. If signals are present on the other polarized transponder, then the interference depends on the signals' frequencies, amplitudes, and the degree to which the orthogonal component can be nulled by the earth station antenna. Cross-polarization interference is evident in figure 11

from video transmissions from the other transponder. Another potential problem with use of the edge of a transponder is frequency-response roll-off which creates (1) amplitude-to-phase conversion and (2) more difficult decoding by the modem. This roll-off, as it turned out, was not significant in this test and hence was not a problem.

There are other forms of interference than those stated above, but they were negligible in these tests. Interference analysis is described in reference 5. There is, however, a type of interference that is subtle yet significant when a low C/No signal is shared with video transmissions; its effect is called "loading". The transponder output power amplifier is not linear when operating near saturation; that is, its overall gain becomes a function of its input signal level. When there are no other signals on the transponder, a given signal level is retransmitted back based on the satellite's specifications thus yielding a predictable received C/No. Multiple carrier systems (usually non-video) generally require that the received satellite flux density be several dB less than that required for saturated ouput in order to reduce intermodulation interference. However, 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 PN signal to drop by as much as 6 to 8 dB causing a net reduction in the received C/No by this amount. Since σ_y is increased as C/No is decreased, unexpected characteristics in σ_y may occur if transponder loading is changing during sampled time intervals. A few transponders have an automatic gain step capability that alleviates this problem by adjusting the gain of the transponder so low level data channels are less affected by loading.

Satellite loop tests were performed using the VSAT and SBS-3 located at 95 W. Setting up the VSAT and actually doing the loop around proved to be a formidable task that is greatly simplified with the availability of the hub earth station. The VSAT with its small dish, low power, and fixed 2.3 GHz transmit/receive offset introduces a new set of problems compared to the hub earth station. In addition to making sure that the link calculation with a given satellite (in this case SBS-3) yields at least 60 dB-Hz, one has to consider the problem of pointing at the correct satellite, assuring that the correct frequency and power level is actually transmitted, and verifying that the spread spectrum signal is being received.

Figure 12 shows spectrum analyzer displays of received signals from the VSAT in a loop test with SBS-3. Clean carrier is shown in figure 12a with a 10 MHz scan and 10 kHz analysis bandwidth, figure 12b is the same display but with PN modulation on, and figure 12c is with PN modulation and with an expanded scan of 50 MHz and 1 MHz analysis bandwidth. Scan time is 10 seconds for figures 12a and 12b, and one can see the difficulty in discerning an identifiable spread spectrum signal in the noise. These displays are typical of the kinds of signals obtained using the modem. The modem usually took several minutes to acquire lock of the return signal from the transponder. 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 for 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. A convenient method of remotely incrementing the offset in the VSAT in less than 1 kHz steps would be ideal. As it turns out, two-way time transfers will usually occur between a VSAT and the hub earth station, and frequency synthesizers are used at the hub for transmit and receive independently 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 σ_y, and typical results are shown in figure 13. These results are consistent with in-cabinet and free-space loop tests done on the ground equipment and shown in figure 6. In addition to loop tests described thus far, plots are shown in figure 13 for hub earth station to SBS-3 and SPACENET II (69 W), transponder 22. The stability plots follow τ^{-1} behavior as expected for white noise except for the case of VSAT and SBS-3 with loading. As described earlier, the effect of satellite loading is to change or "modulate" the C/No causing a change in σ_y dependent on when and how much loading occurs during the data sample.

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 II 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.

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.

Figure 14 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 [3]) 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 colocated 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 II. Figure 15 shows a method of directly measuring the offset of the differences with one time interval counter (TIC) and hence establishing a calibration with the use of these earth stations.

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). The VSAT is used in conjunction with precise time transfers via satellite to a central hub facility at NBS, Boulder, with the commensurate differential time offset between VSAT and hub having been directly measured. Tests have also been conducted using a specialized spread spectrum modem designed for two-way time transfer. Short term stability data with this equipment in three different loop-around tests (in cabinet, free space, and via satellite) have been performed under various conditions and various C/No ratios. Satellite loop tests used SATCOM K2 (81 W), SBS 3 (95 W), and SPACENET II (69 W). Loop tests with the hub and with the VSAT were also described. Stability performance is on the order of $4 \times 10^{-10}\tau^{-1}$ for a C/N_0 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 to a few days where σ_y is 3×10^{-15}. Absolute phase delay measurements show reproducibility to better than 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.

Future work will be directed toward analysis of the accuracy and stability of the common-view/common-clock scheme as outlined here. At the present time, the plan is to incorporate more extensive instrument control and automated data analysis to facilitate data reduction and documentation of results. The ground segment and satellite loop tests of frequency stability point to an accuracy capability in the range of a few nanoseconds or better and stability of several x $10^{-10}\tau^{-1}$ for a C/N_o ratio of 65 dB-Hz.

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 one second to a few thousand seconds were performed for various carrier-to-noise-density (C/N_o) 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/N_o 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 is presented in the documentation which accompanies the modem is useful for the analysis of frequency stability presented here.

Figure 6 shows a plot from data of the white noise phase jitter versus carrier-to-noise density ratio [2]. A value for σ_y can be computed and the value for 75 dB-Hz is included with the data. If we assume that modem data is the classical variance about the mean of the phase jitter (σ_x^2) then the relationship to the Allan variance is [6,7]

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

Appendix II

"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) = ΔT + u/c(2) + sat.path(2 to 1) + d/c(1)

and TI(2) = -ΔT + u/c(1) + sat.path(1 to 2) + d/c(2).

ΔT is the time difference of the clocks at 1 and 2, u/c denotes time delay through the up-conversion at locations 1 or 2, and d/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 delays due to the earth's rotation. ΔT can be calculated as

ΔT = ½{[TI(1)-TI(2)] + [u/c(1)-d/c(1)]
        - [u/c(2)-d/c(2)] + sat.path(1 to 2)
        - sat.path(2 to 1)}.

If we assume sat.path time delays are reciprocal, except for the time difference term due to the earth's rotation, then sat.path(1 to 2) = sat.path(2 to 1) + δT(rotation) and we have

ΔT = ½{[TI(1)-TI(2)] + [u/c(1)-d/c(1)]
        - [u/c(2)-d/c(2)] + δT(rotation)}.

Now with the two earth stations co-located and using a common clock, δT(rotation) = 0 and ΔT = 0 and the difference in the u/c's and d/c's is explicitly the difference in the time interval counters. We have

TI(2)-TI(1) = [u/c(1)-d/c(1)] - [u/c(2)-d/c(2)]
            = 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 non-reciprocity 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 [8]. Certainly the ionospheric dispersion and the effects of water vapor dispersion are small (below 100 ps) [9]. 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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Fig. 1.   6.1 meter antenna used as a hub (shown in background) and 1.8 meter VSAT (shown in foreground).
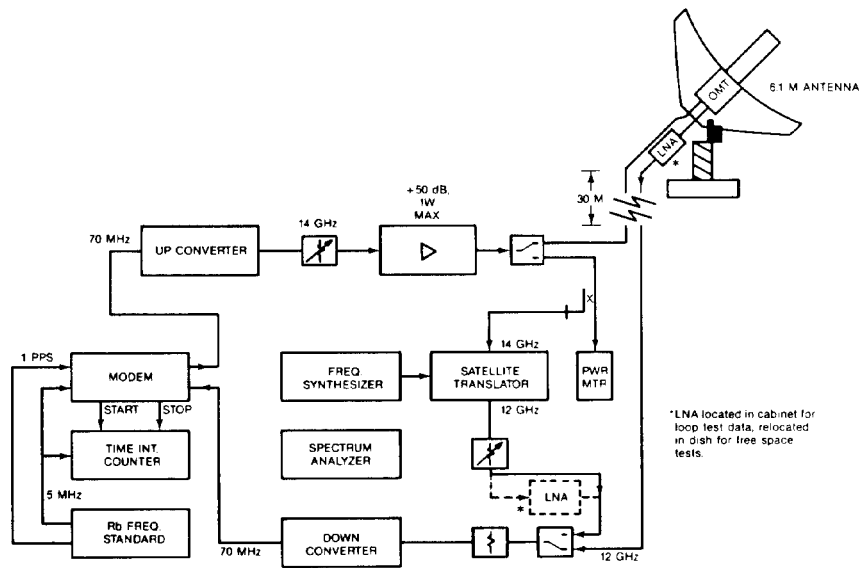
Fig. 2.   Earth station equipment.

Fig. 3.   Block diagram of principal parts of the hub
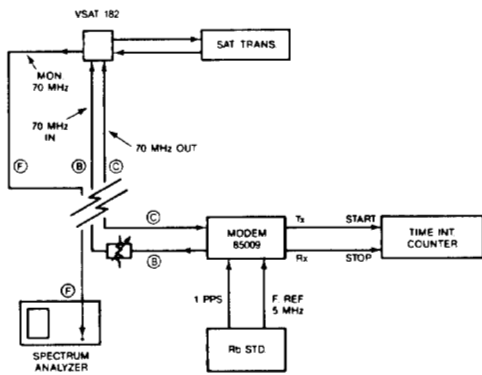earth station.

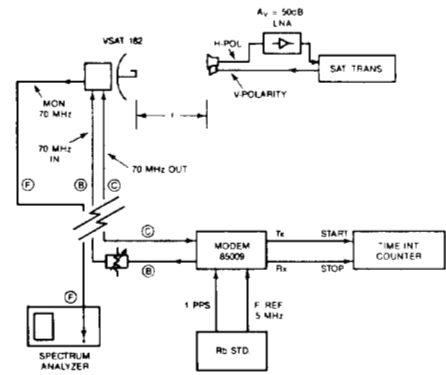Fig. 4. Block diagram of VSAT in-cabinet loop-around test.

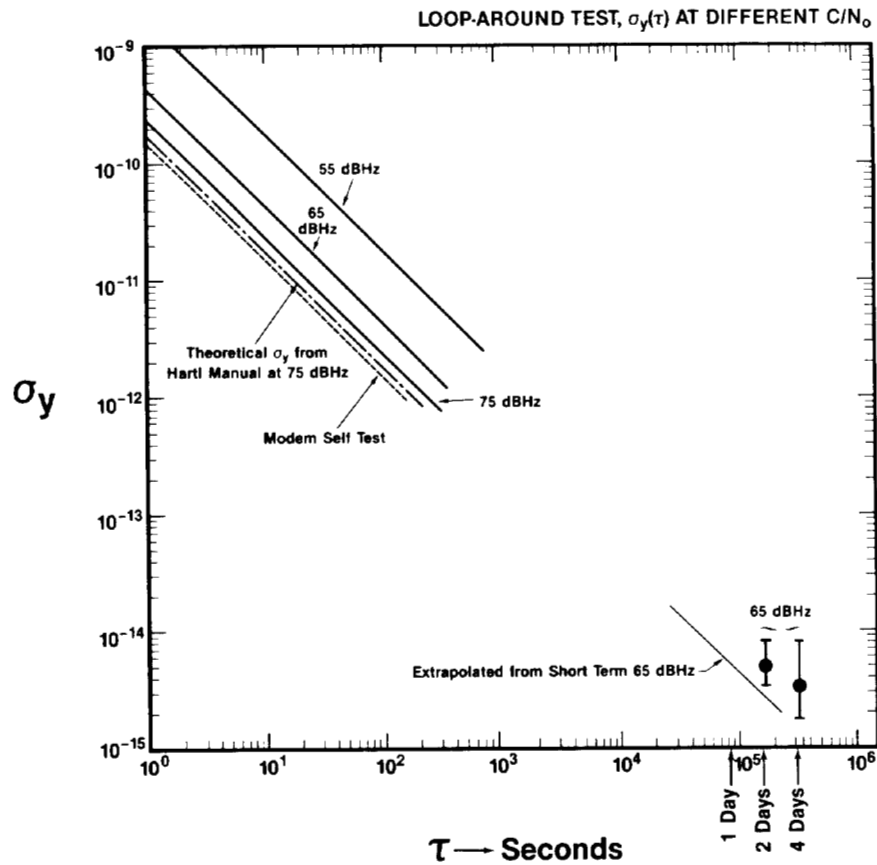Fig. 5. Block diagram of VSAT free-space loop-around test.

Fig. 6. Frequency stability measurements of hub earth station equipment in an in-cabinet loop test.
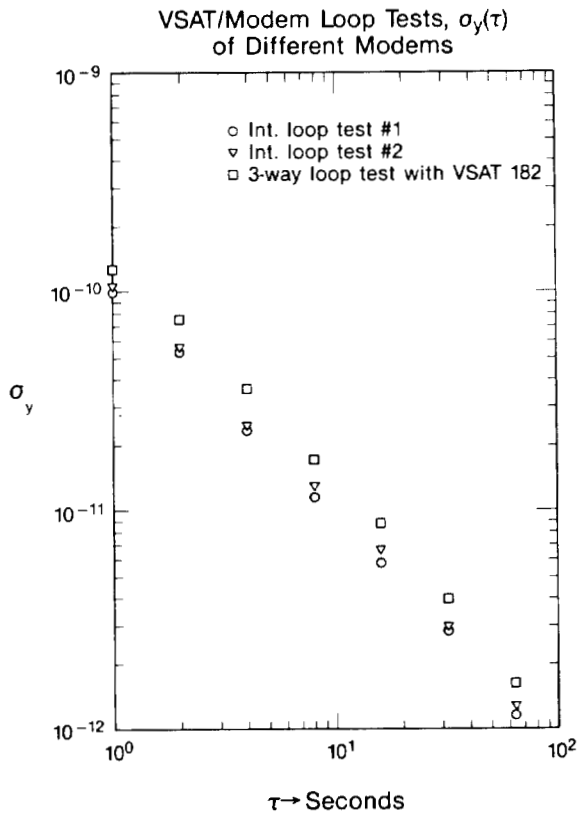
VSAT/Modem Loop Tests, $\sigma_y(\tau)$ of Different Modems

o Int. loop test #1
▽ Int. loop test #2
□ 3-way loop test with VSAT 182

σ_y

$\tau \rightarrow$ Seconds

Fig. 7. Frequency stability measurements of VSAT equipment in an in-cabinet loop test and using three different modems for comparison.

VSAT Free-Space Range Measurements

$\Delta\tau$ μsec (TIC)

14.95 cm/ns

Range r, meters
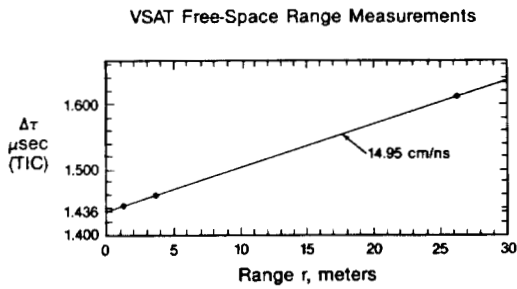
Fig. 8. Three VSAT free-space range measurements can be extrapolated to zero distance to determine delay with the dish. Time interval counter (TIC) readings are a function of range r. Slope is exactly expected result and extrapolation to zero is straightforward.

In-Cabinet VSAT Loop-Around Time Delay/Day

$\Delta\tau$ μsec (TIC)

1 ns

Free-Space VSAT Loop-Around Time Delay/Day

$\Delta\tau$ μsec (TIC)

1 ns

Days
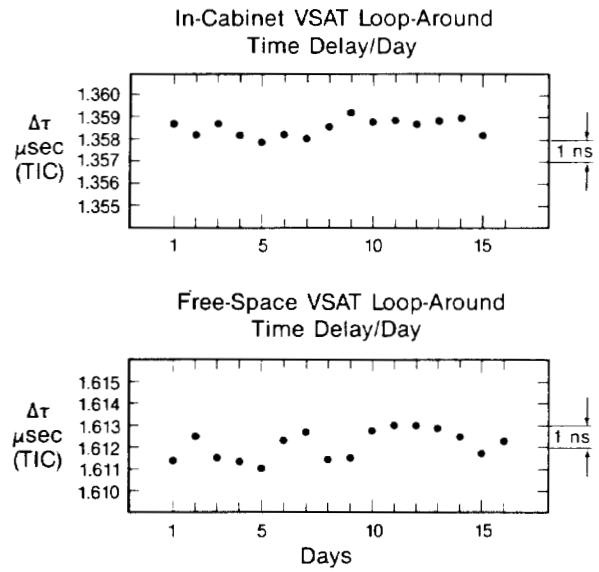
Fig. 9. Day-to-day loop-around time delay using VSAT in-cabinet and free-space showing total in-cabinet and free-space loop-around time delay reproducibility using VSAT.

Transponder

Satellite/HUB Loop Test

Satellite/VSAT Loop Test

Transponder

6.1 m Earth Station

U/C & D/C Equipment

1 PPS and 10 MHz Reference

Modem

10 MHz

Time Int Counter

1.8 m VSAT

1 PPS and 10 MHz Reference

Modem

Time Int Counter

10 MHz

a

b
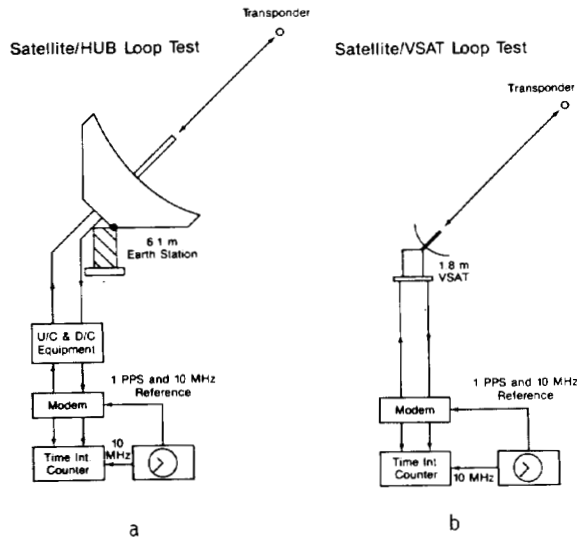
Fig. 10a. Block diagram of principal part of satellite loop tests with hub.

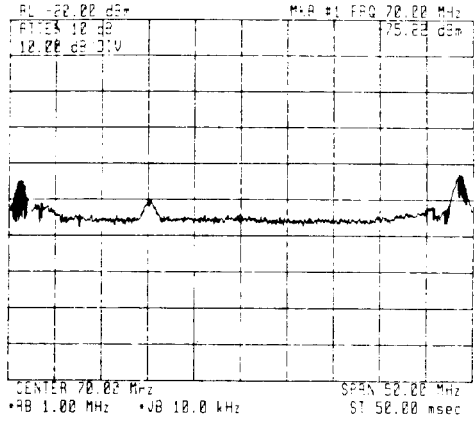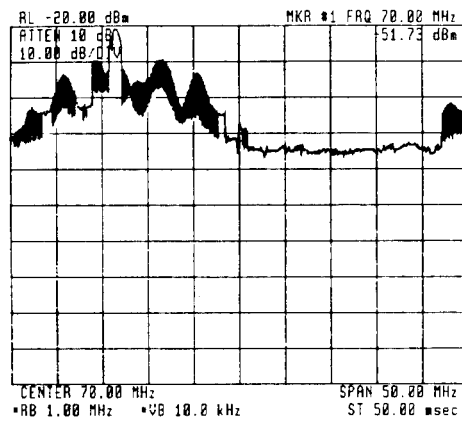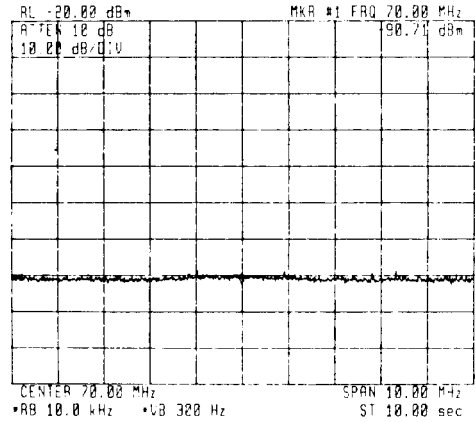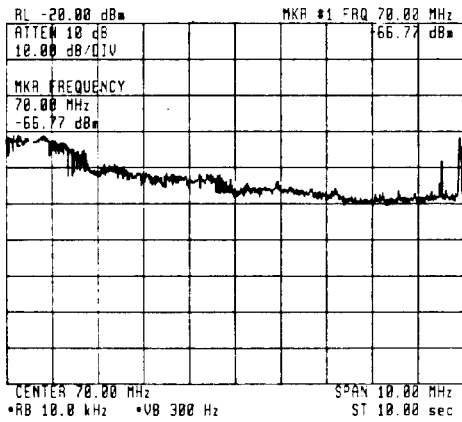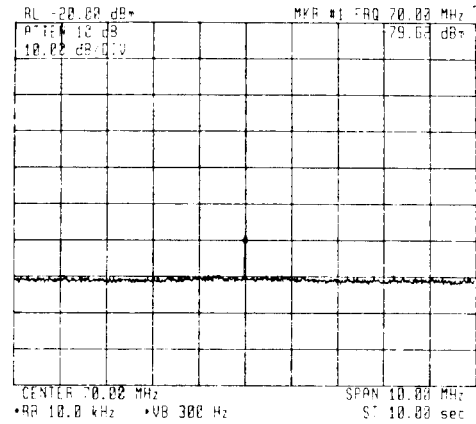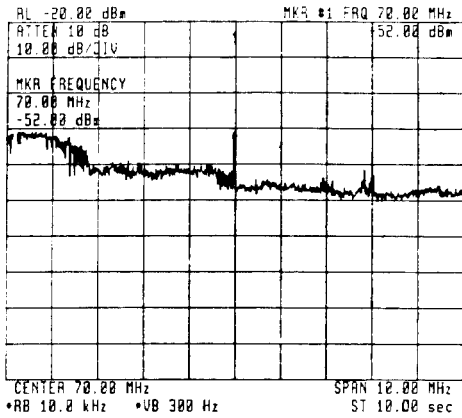Fig. 10b. Block diagram of principal part of satellite loop tests with VSAT.

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Fig. 11. Spectrum analyzer displays of loop tests with hub earth station and SATCOM K2(6B). Adjacent video signal and cross-polarization interference are easily identified.

Fig. 12. Spectrum analyzer displays of loop tests with 1.8 m VSAT and SBS-3(7A).
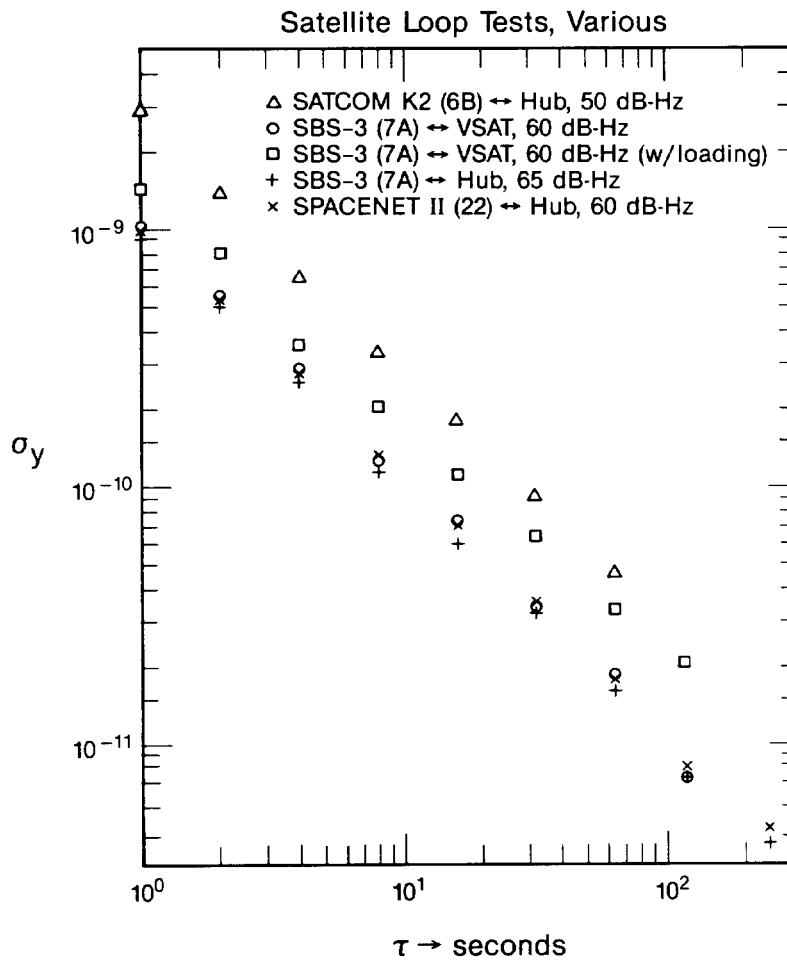
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Satellite Loop Tests, Various

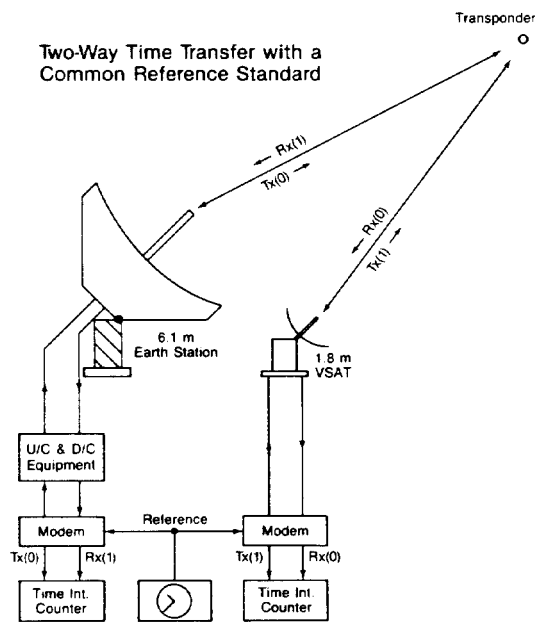Fig. 13. Frequency stability measurements of loop tests involving hub and VSAT with three satellites.

Fig. 14. Common view/common clock scheme for measurement of ground-segment differential delay constant.

"Offset of the Differences"
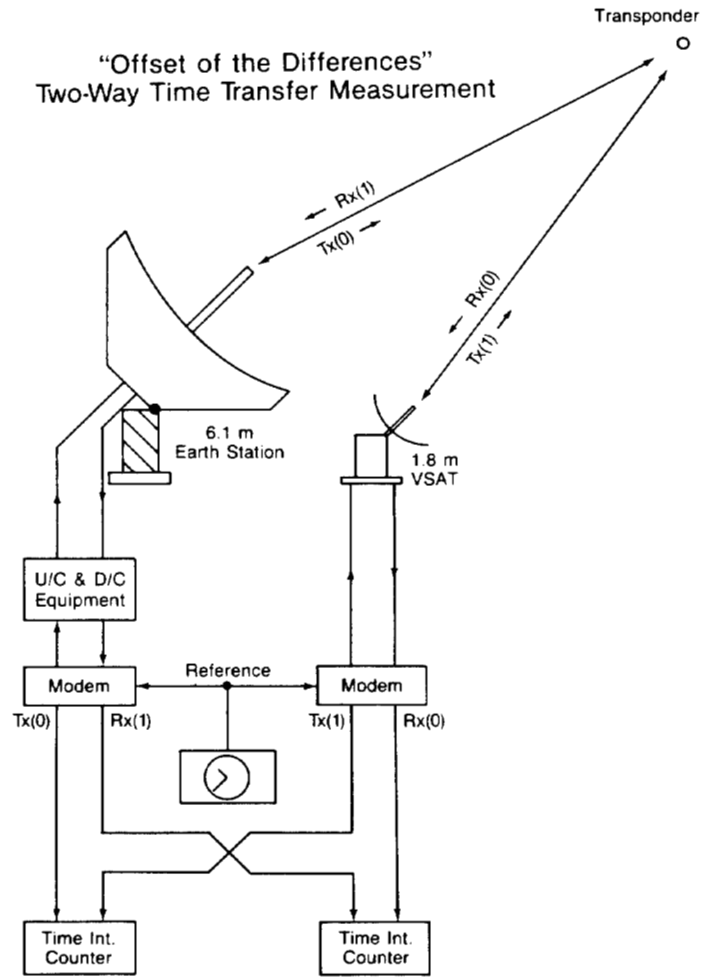Two-Way Time Transfer Measurement

Fig. 15. Technique for direct measurement of offset
of the differences. If the left time
interval counter (TIC) is zero
(representing identical on-time
transmission of 1 pps from hub and VSAT),
then right TIC is exactly the offset term.