TIME TRANSFER VIA SATELLITE-LINK RADIO INTERFEROMETRY

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ABSTRACT

Very long baseline interferometry using natural radio sources has been shown to be an excellent time transfer method. Our group has linked antennas using a synchronous communications satellite instead of the customary independent frequency standards and tape recorders. We have performed a successful preliminary time transfer using a wide-band data link that was accurate at the 100 nanosecond level, and have compared frequency standards to a part in 10^{-13} over a 24-hour period using a phase coherent satellite link. The narrow-band phase coherent link method is potentially capable of timing accuracy of 10 picoseconds, and frequency comparison accuracy of 10^{-16}, and is in addition economical of spectrum usage. We plan to continue development of this latter method using the newly-launched ANIK-B satellite.

Our group's use of a synchronous satellite link between widely separated radio telescopes has demonstrated the feasibility of two related but separate approaches to accurate time transfer and frequency standards comparison. The first of these methods, reported by us previously[1], involves the use of the satellite as a wide-band data link to transfer the video signal used to crosscorrelate and thus determine the differential delay between radio source signals received at two separated stations. In our published work, we used the CTS or Hermes satellite to transfer a 20 megabit data stream between antennas in Greenbank,W.Va. and Lake Traverse, Ont. and to obtain differential clock measurements accurate to the 100 nanosecond level in real time. A joint M.I.T.-U.S.N.O. group has obtained results accurate to 20 nanoseconds[2]. A similar accuracy should certainly be available via satellite link if a similar use of bandwidth synthesis and accurate equipment delay calibration is made. For any operational use, the simplicity of use of a real-time time indication is a significant advantage.

Our time data-link experiment used two large radio astronomy antennas and a wide-band (80 megahertz) satellite data channel. Either of these requirements can be considerably eased, however. The signal-to-noise ratio in a one-minute integration was considerably greater than 100 to 1 for either of the two strong radio sources (3C84 and 3C273) we used. Since the signal-to-noise ratio for a wide-band radio source is proportional to the square root of the signal bandwidth, it is possible to reduce the data rate to a low enough value to enable transmission via a telephone line (4 kilobits per second). This is in fact done as an equipment monitor by radio astronomy groups. The full (less than 10 nanoseconds) timing accuracy should be available by using the bandwidth synthesis technique even with a narrow signal bandwidth, although a greater number of programmed local oscillator settings would be necessary to compensate for the more severe ambiguity problem. An alternative possibility is the use of a portable antenna. For example, the diameter of one antenna could be reduced to a meter or two if used together with a large master antenna.

The delay-calibration method, then, is a relatively well-proven method with a potential for time comparisons to several nanoseconds accuracy. Another method we are presently developing has the ultimate potential for time measurements between separated stations accurate to 10 picoseconds. This is the two-way transfer of a phase-coherent carrier between stations. Although this concept may seem unfamiliar, it is in fact an extension of the coherent doppler tracking used on deep-space probes. In the simplest theoretical realization a signal at frequency f_0 is transmitted from station A via the satellite to station B and compared with the station B standard. Similarly the signal from B is transmitted to A and compared. In this case, we have at either station:

$$\begin{aligned} \Phi_{mB} &= \Phi_{sB} - \Phi_{sA} \\ \Phi_{mA} &= \Phi_{sA} - \Phi_{sB} \end{aligned} \qquad (1)$$

where Φ_{mA}, Φ_{mB} are the measured comparison phases and Φ_{sA}, Φ_{sB} are the phases of the frequency standards. If we now allow the satellite to move, we have:

$$\begin{aligned} \Phi_{mB} &= \Phi_{sB} - \Phi_{sA} - \frac{2\Delta d}{c} \cdot f_0 \\ \Phi_{mA} &= \Phi_{sA} - \Phi_{sB} - \frac{2\Delta d}{c} \cdot f_0 \end{aligned} \qquad (2)$$

where Δd is the component of the satellite's motion along the link path, so that $\Phi_{mB} - \Phi_{mA} = 2(\Phi_{sB} - \Phi_{sA})$ and the satellite's motion cancels out to give a direct measure of the phase difference between the two standards that should be precise to within a fraction of a cycle at the transmission frequency (typically 15 GHz); this corresponds to a timing accuracy of 7 picoseconds for 0.1 turn (1 turn= 360 degrees) phase measurement accuracy. The phase measurement made at B is of course transmitted as data to A via telephone line, satellite link or other convenient means. The satellite's motion in theory cancels completely if measurements are made in such a manner that they transit the satellite at exactly the same time. The satellite used does not have to be synchronous, although our first experiments have used such because of the lesser (although non-zero) motion and the simplified tracking problem.

Significant complications arise because of the necessity for frequency translation at each pass through the satellite to avoid regeneration. Most importantly, the characteristics of the satellite's translation oscillator enter the picture. An ideal satellite for this purpose would be the synthesiser type (Fig. 1) in which the translation oscillator is phase-locked to a submultiple of the incoming frequency, thus contributing no phase error. This is in fact done on certain deep-space probes; but ordinary communications satellites have not had provision for this.It is possible, however, to make phase-coherent link measurements in spite of the incoherent satellite oscillator under certain common conditions. If the frequency of the path from A to B is translated by exactly the same amount, using the same oscillator, as that from B to A, the satellite crystal will contribute no error if both signals transit the satellite at exactly the same time. Both the CTS and ANIK-B satellites have had this equal-translation property. For small differences in the transit time, an error will be produced in the amount:

$$\Delta\Phi = f_t \cdot \Delta t \cdot \frac{\Delta f}{f} \cdot \frac{f_t}{f_0} \qquad (3)$$

where f_t is the frequency translation, Δt is the timing error, $\frac{\Delta f}{f}$ is the satellite crystal stability and f_0 is the nominal link frequency. For typical values of crystal stability of 10^{-7}, timing error of 10 milliseconds, translation frequency of 3 GHz and link frequency of 15 GHz, the total phase error from this source can be kept to within about 100 turns. There is in addition a method of compensating for the satellite's oscillator, using either a separate beacon signal on the satellite derived from the same oscillator, or, if this is not available, transmission of a second pilot tone at a different frequency. In either case, the use of two signals traversing the same path enables one to solve for the phase change of the satellite oscillator as well as that due to the path, and thus eliminate it; reduced accuracy is expected in the case of two pilot tones transmitted with only limited separation. The first method was used by our CTS experiments, the second method is being used in our current series using the ANIK-B satellite.

Another complication is introduced by the fact that, again to avoid regeneration, the mean frequency of the path from A to B cannot be the same as that from B to A. This difference, typically about 1%, can be allowed for, assuming no dispersive effects, by multiplying the total observed phase count from the lower-frequency path by the appropriate ratio before subtraction.

The earth's atmosphere should, surprisingly, contribute a relatively small error. Dispersive phase shift due to the ionosphere is negligible at the 15 GHz frequencies used by our satellite links, and total excess phase delay due to the troposphere is only several hundred turns, and should be completely cancelled by the two-way link.

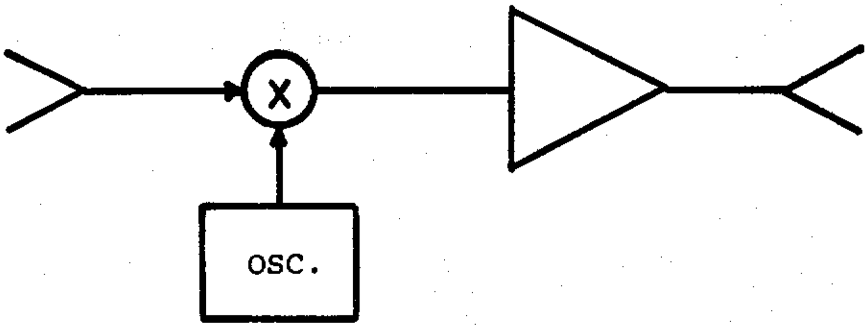
The largest practical error source is expected to be phase wind-up error in the electronics used for transmit and receive. This is similar to the delay error to be calibrated in delay VLBI measurements, but is made more serious here by the higher accuracy required, and by the use of electronics for both transmit and receive functions.

Preliminary experiments using this technique were carried out using the CTS satellite in May 1979. The short-term performance of the link is shown in Fig. 2. Longer-term phase stability is shown in Fig. 3, and a comparison of experimental results with the laboratory stability of different types of frequency standards is shown in Fig. 4. It is clear that short-term phase stability of a small fraction of a turn is attained, but that long-term phase drift with a period of a few hours is present degrading the phase-link measurements. If there were no long-term drifts in the phase-link its frequency measurement accuracy in Fig. 4 would have a 1/t slope. The most likely source of the phase drift that causes the slope of our very limited preliminary data to flatten is phase wind-up in our transmit and receive electronics.

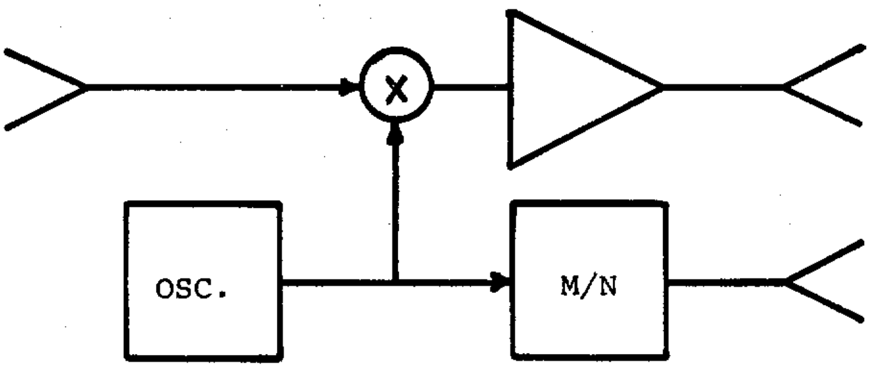
We are presently instrumenting to continue experiments with a coherent link with the new ANIK-B satellite. We expect to obtain at least an order of magnitude better control over the behavior of the link over periods of 6-24 hours, and to obtain data on the performance of the link over periods of many days. This method should have the potential for comparing time bases maintained at different places on the earth to parts in 10^{-16} over periods of a year or greater. Our preliminary measurements correspond to a measurement of timing change with a precision of ±5 nanoseconds over a 24-hour period; a potentially much higher accuracy should be available. For the CTS experiments we made no attempt to resolve our ambiguity interval of 100 picoseconds, and thus were unable to make absolute time comparisons. The transmission of appropriately spaced multiple tones within the typical communications satellite bandwidth of 100 MHz can reduce this problem, however. This method makes very economical use of the spectrum; all that is required is the transmission of a few pilot tones that occupy instantaneous spectral bandwidths of less than one hertz, and long-term bandwidths of less than one kilohertz allowing for satellite doppler. This narrow bandwidth increases signal-to-noise ratio, allowing for the use of small and thus inexpensive ground station antennas. The narrow bandwidth allows simultaneous multi-user use of the satellite (as is occurring on ANIK), unlike satellite pulse-transmission methods. For time- and frequency-standard comparison, it is important to note, radio astronomy antennas play no part and are not required. We hope during the next year or two to investigate and control sources of phase error in this method in order to realize its full potential.

1. S.H.Knowles,W.B.Waltman,W.B.Klepczynski,N.W.Broten,D.H.Fort, K.I.Kellerman,B.Rayhrer,G.W.Swenson and J.L.Yen, "Real-time Accurate Time Transfer and Frequency Standards Evaluation via Satellite Link Long Baseline Interferometry", Proceedings of the 9th Annual PTTI Meeting, p.135, Nov. 29- Dec. 1, 1977, NASA Tech. Memo. 78104

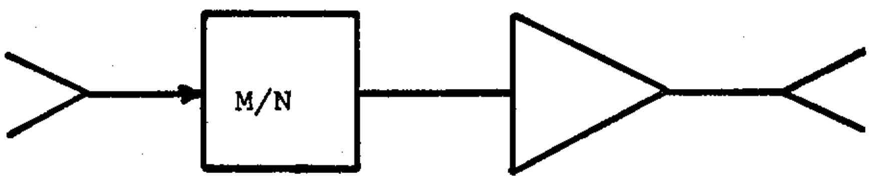
2. A.E.E.Rogers,A.R.Whitney,H.F.Hinteregger,C.A.Knight,T.A.Clark, W.J.Klepczynski,I.I.Shapiro,C.C.Counselman and L.B.Hanson, "Clock Synchronization via Very Long Baseline Interferometry", ibid., p. 127



TRANSLATOR (ANIK-B)



TRANSLATOR WITH COHERENT BEACON (HERMES)



SYNTHESIZER

Figure 1. Types of Satellites

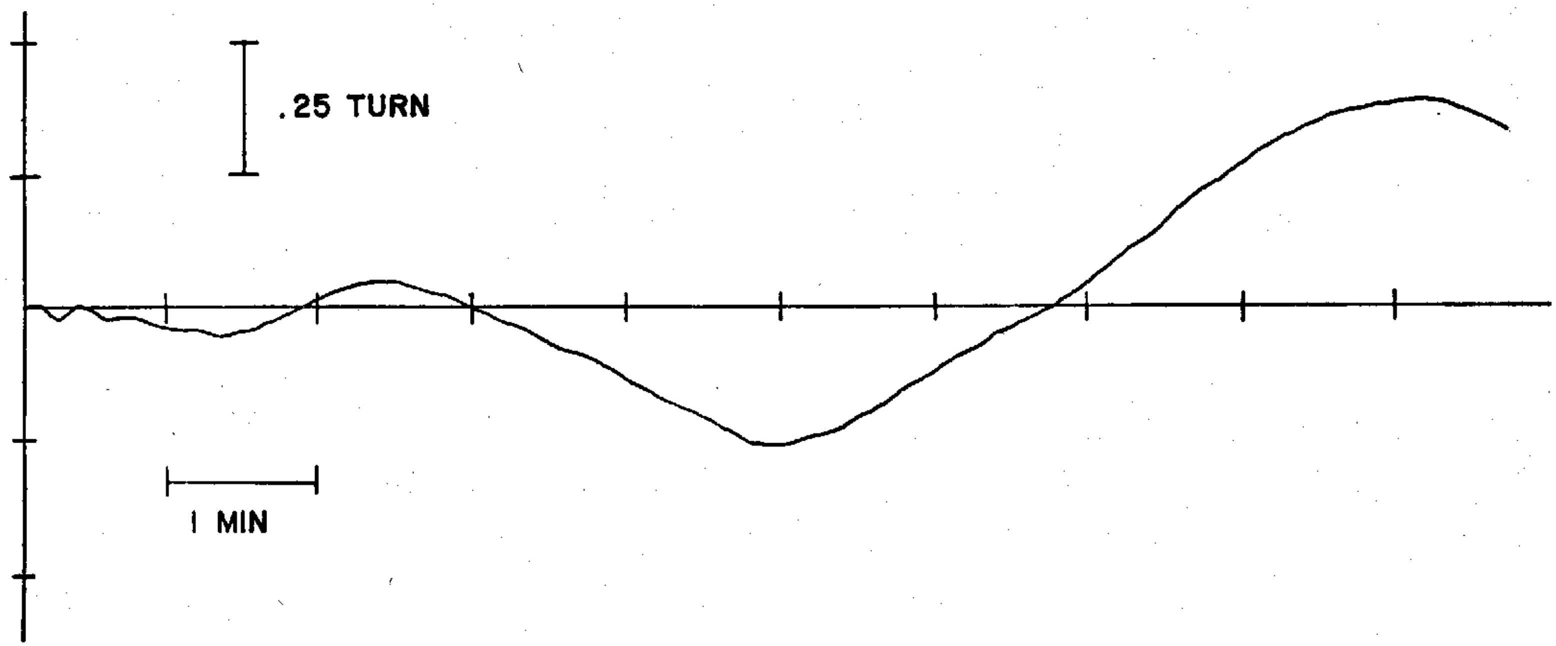


Figure 2. CTS Phase Link Results (Short–Term)

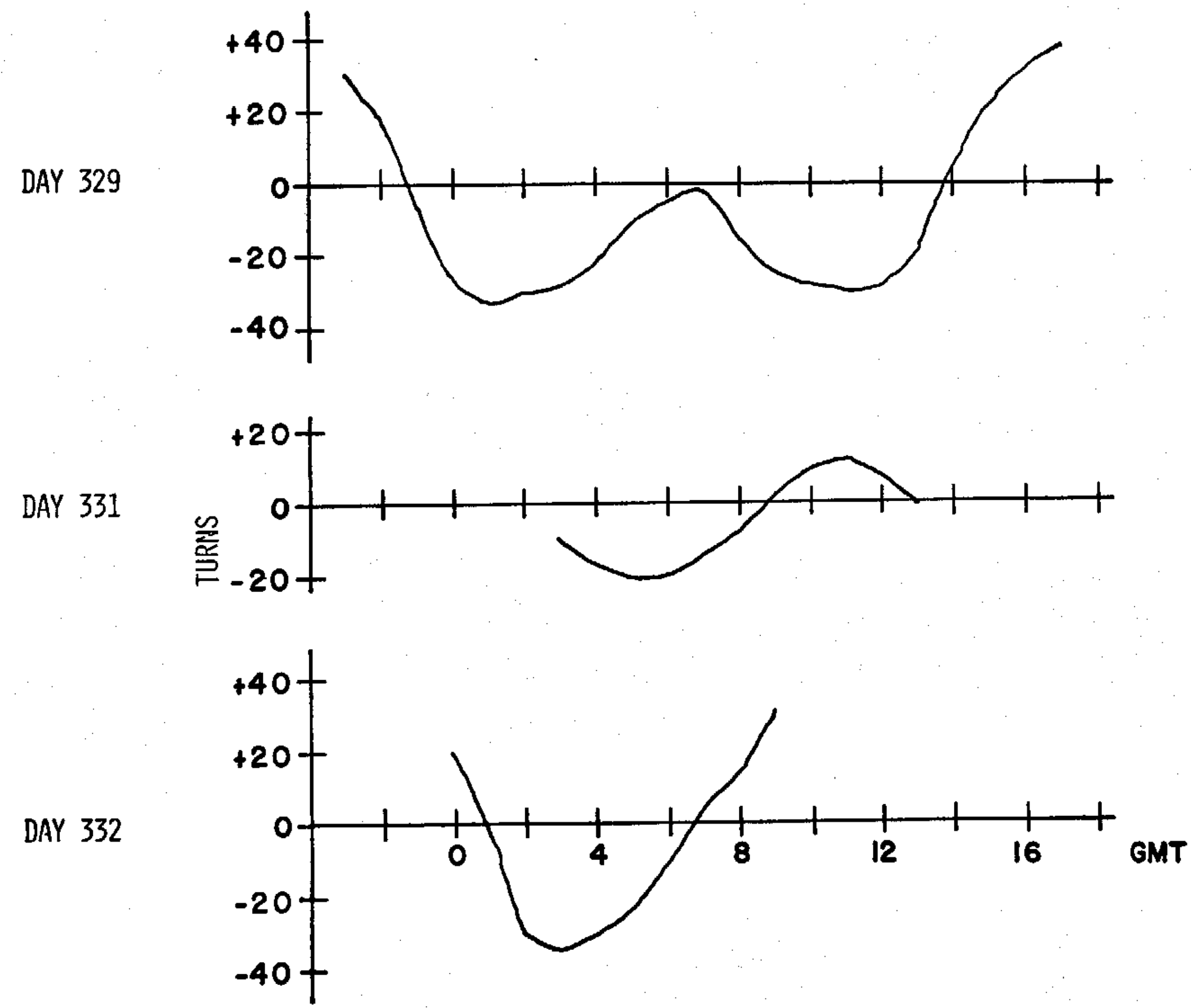


Figure 3. CTS Phase Link Results (Long-Term)

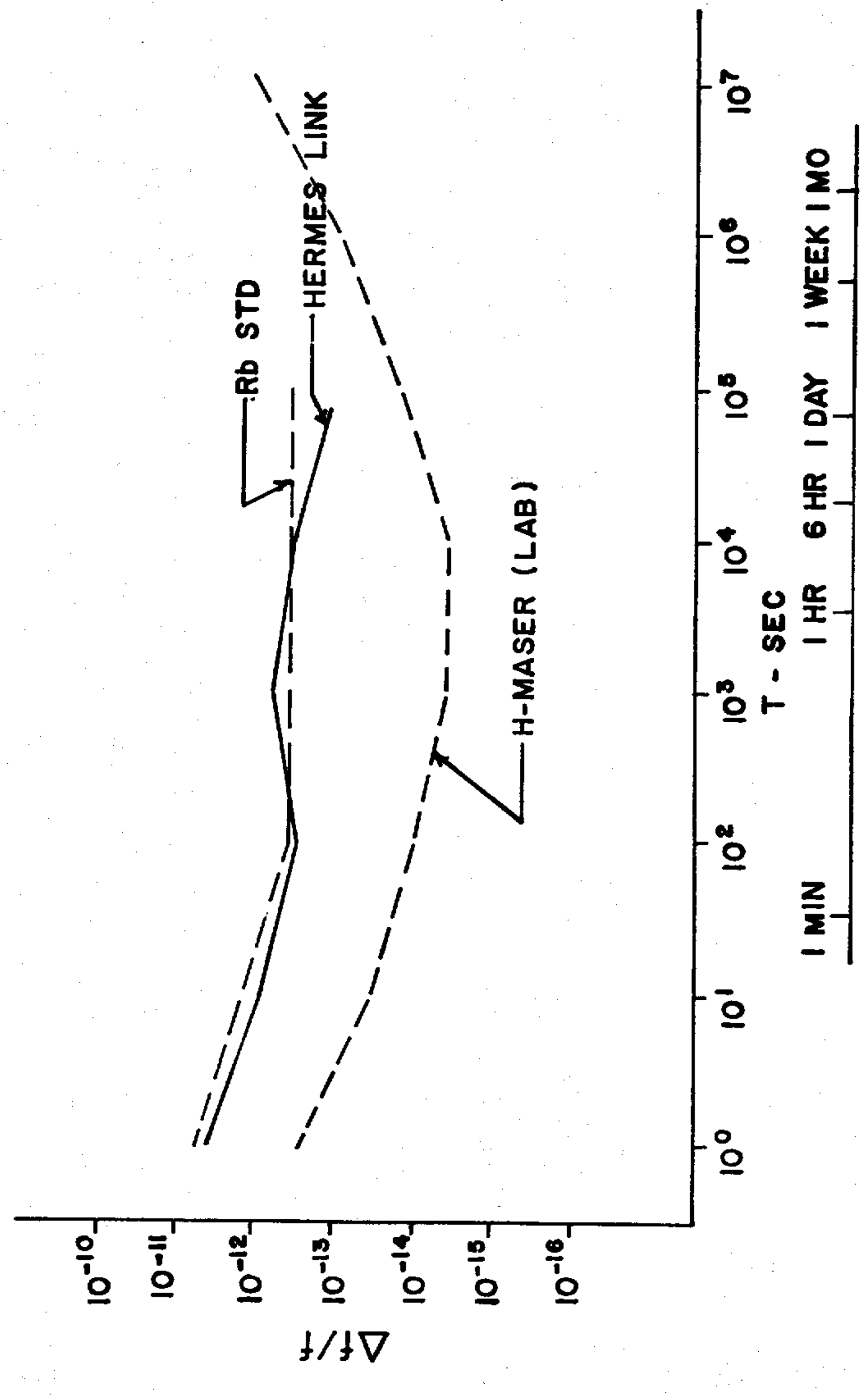


Figure 4. Comparison of Phase Stability

QUESTIONS AND ANSWERS

DR. KEN PUTKOVICH, Naval Observatory

Pardon my ignorance, but could you define the term "turn" for me?

DR. KNOWLES:

Yes. A turn is 360 degrees. I simply used it because it looks more impressive than saying our errors were 17,000 degrees. If you say it was 20 turns, it sounds better and is more appropriate.

DR. JIM JESPERSON, National Bureau of Standards

Really, what I have is more in the way of a comment. As you pointed out at the beginning of your speech, probably VLBI is one of the very best techniques that we know of for clock comparison. And in fact some of the ordinary ways that you can think of for checking these new techniques, such as carrying, say, a portable clock between the two sites as an independent check, perhaps isn't good enough, especially if there is a great separation between the two sites.

The only other system I can think of that might check the kinds of results that seem to be coming out here is the two-way satellite technique. And what I am wondering is that if at some future time you or perhaps some of the people here who are in a position to support a VLBI experiment with a two-way satellite, what about the possibility of doing the two-way satellite and the VLBI experiment simultaneously, because I think the kind of errors that contribute to the two systems are rather different. For example, the two-way satellite, the errors due to propagation effects, atmospheric delays and so forth cancel out, whereas in VLBI you have to make some assumptions, some guesses about what is going on now.

DR. KNOWLES:

In actual fact, we will do this routinely as part of the ANIK program because the major objectives of the ANIK program are to measure UT and polar motion, and for those purposes we do need to measure the position of a radio source using VLBI and we will completely reduce it according to the standard methods using the Canadian VLBI system and we will attempt to solve for several parameters. In the first place, we have to see to what extent our link works and measure UT, but we will have that comparison.

I do want to mention one thing, one slight point that I forgot to mention. The phase link for ANIK, I had no mention of avoiding the ambiguity problem. We haven't been concerned with that. In actual fact, if one is, the actual bandwidth of the ANIK transmitting band is 60 megahertz so one could think of transmitting multiple tones and alleviating the ambiguity problem from it so you could indeed lock in on the signal precisely.

DR. ROBERT KAARLS, Van Swinden Laboratory in the Netherlands

With respect to the question put by Dr. Jesperson, I can tell that we have some possibilities in our country because VLBI stations and stations which have possibility for two-way satellite links are very close to each other and we are looking into the possibilities to set up such an experiment. Thank you.

DR. KNOWLES:

Yes. I have talked to some of the people in the Netherlands, Dick Skilutsee in particular and I know there is an active effort to set up such a network in Europe. I think it is very commendable and I think you are ahead of current efforts in this country.