# TRAVELING CLOCK VERIFICATION OF VLBI CLOCK SYNCHRONIZATION

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## ABSTRACT

Four experiments are described which involved measurements of clock offsets at two DSN stations. Both VLBI and traveling clock measurements were performed and the agreement between the two methods was within about 6 ns for all four comparisons.

## INTRODUCTION

The Deep Space Network (DSN) plans to initiate a periodic program of very long baseline interferometry (VLBI) experiments in order to monitor the performance of the frequency standards used at its radio telescopes. In order to demonstrate the capability of accurate measurement of epoch offsets between DSN station clocks using VLBI, as well as to develop procedures to be used in the operational program, four VLBI experiments were performed from June 1979 to September 1979. During each VLBI experiment, a traveling clock was used to check the accuracy of the VLBI clock synchronization. In order to achieve a high degree of accuracy in the traveling clock measurement, a pair of DSN stations separated by a relatively short baseline was used. A previous short baseline VLBI/traveling clock experiment has been reported by C. C. Counselman III et al.[1] That experiment gave a reported difference of 9 ns ± 11 ns in the clock offset obtained with the two methods, and it was suggested that a more accurate measurement would be desirable.

## VLBI Experiment

The radio telescopes used were DSS 13 and DSS 14, with dish diameters

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[1] C.C. Counselman III, I. I. Shapiro, A. E. E. Rogers, H. F. Hinteregger, C. A. Knight, A. R. Whitney, and T. A. Clark, Proceedings of the IEEE, Vol. 65, No. II, p. 1622 (1977).

of 26 and 64 meters, respectively. Both DSS 13 and DSS 14 are situated within the DSN complex at Goldstone, Ca., and are separated by approximately 22 kilometers. Each station used a Hydrogen maser as its frequency standard. The VLBI experiments were typically 5 hours long, incorporating some 40 observations of about 25 extra galactic radio sources.

Figure 1 illustrates the VLBI experiment in a schematic way. The plane wave represents an incoming burst of radio noise. Some incremental delay above that for free space is added by the media. Because of the proximity of the two radio telescopes used, and because the experiments were conducted during local nighttime, when media effects are at a minimum, the media delay is assumed to be the same at each site.

The wave front reaches the two antennas at times separated by the geometric delay, $\tau_g$. At each station, phase calibrator tones derived from the frequency standard were injected into the data stream near the beginning of the receiver assembly. From this injection point on, the phase calibrator tones were imbedded in the data, and indicated the instrumental delays and phase shifts added to the data as it was down converted and recorded into three time multiplexed s-band frequency channels along with time tags from the station clock. These channels were later combined to synthesize a measured delay.

Each 2 MHz channel of data contained three phase calibrator tones. In order to use the unambiguous delay resulting from the correlation of a single 2 MHz channel at each station to remove the cycle ambiguities inherent in the delays determined via the bandwidth synthesis technique, it is necessary to know the instrumental delay characteristics of that single channel. The instrumental delay can be measured as a separate experiment, but this can prove difficult for a complex receiving system and must be re-done after station hardware changes which affect instrumental delay. In the interest of avoiding the need for extensive calibration measurements, the system of phase calibration used by the DSN allows a variable spacing of tones, with the narrowest spacing corresponding to an ambiguity of 19.8 μs in the instrumental delay. As this is much larger than the 2 or 3 μs delay typical for DSN radio telescopes, somewhat wider spacing can be used. In these experiments, for instance, a tone spacing of 0.5 MHz was used. With this system the instrumental delays added below the phase calibrator injection point never need to be measured separately, and the VLBI clock synchronization is not jeopardized if these delays change between experiments. Another advantage of the presence of multiple phase calibrator tones per channel was that it allowed a continuous monitor of the phase versus frequency response of each channel.

When the video tapes from each station were brought together and correlated, the geometric delay, $\tau_g$, known A priori, was removed analytically. The phase calibration correction was made, resulting in the following VLBI delay:

$$(1) \quad \tau_{VLBI} \simeq (\tau_a^{14} - \tau_a^{13}) - (\tau_u^{14} - \tau_u^{13}) + (t_c^{14} - t_c^{13})$$

Portions of the antenna delays, $\tau_a^i$, were measured and the rest were calculated from the physical dimensions of antennas and waveguides. The results were $\tau_a^{14} = 119.2 \pm 1.0$ ns and $\tau_a^{13} = 53.4 \pm 2.0$ ns. The uplink delays, $\tau_u^i$, consisted largely of a stabilized cable whose delay was held constant with the use of a phase locked loop controlling a phase shifter in series with the cable. In addition to the fixed portion of the uplink delay, there was a 200 ns ambiguity in the timing generator.

$\tau_u^{14}$ and $\tau_u^{13}$ were $1321.0 \pm 4.2$ ns and $2015.2 \pm 4.2$ ns, respectively. The remaining term in formula 1 is the clock offset term, which was solved for. The errors in the determination of the clock offset using VLBI were dominated by the estimated error of 6 ns in the determination of antenna and uplink delays. These errors were systematic, in the sense that they were not expected to vary among the four experiments. The errors in the determination of $\tau_{VLBI}$ were $\simeq 0.1$ ns.

## Traveling Clock

During each VLBI experiment the traveling clock comparisons were made at station A, station B, back to station A, and finally back to station B. Each comparison involved about five offset measurements between the traveling clock and station clock over a 45 minute period. For each offset measurement, a Hewlett Packard 5360A computing counter with time interval plug-in was used to measure the offset between the 1 pps signal from the traveling clock and the zero crossing of a 5 MHz signal from the station clock. In order to remove the 200 ns ambiguity inherent in this measurement, the traveling clock 1 pps was also compared with a 1 pps signal from the station clock. In all these measurements, a digital voltmeter was used to insure the appropriate and repeatable setting of trigger levels. As a result, the error attributed to the setting of trigger levels was less than 1 ns.

The error in the synchronization of station clocks by the use of a traveling clock was estimated by noting that the fit of a straight line to the approximately 10 offsets measured between each station clock and the traveling clock gave a RMS residual of about 1 ns. While the behavior of these residuals ruled out the existence of large unobserved jumps in the Rubidium clock during travel times, jumps of up to 3 ns could not be excluded. Therefore, the accuracy of the offset determined between the two station clocks was estimated to be ± 3 ns, which is expected to be a random error among the four experiments.

## Results

The results of the independent measurements of clock offset, $t_c^{14} - t_c^{13}$, using the traveling clock and using VLBI are shown in table 1 for the four experiments. The frequency offsets between the two stations, $2 \times \frac{f_c^{14} - f_c^{13}}{f_c^{14} + f_c^{13}}$ are also shown. The epoch offset measurements did agree within about 6 ns in all four cases. In fact, there was a systematic deviation of 4.6 ns between the two techniques, with a R.M.S. scatter of 1.4 ns about the average. The systematic deviation originates from the measurements of the antenna and uplink delays. The 1.4 ns scatter is primarily due to the traveling clock measurements. The fact that the scatter is less than the estimated value of 3 ns implies that there were no undetected clock jumps of this magnitude while the Rubidium Clock was in transit.

## Acknowledgements

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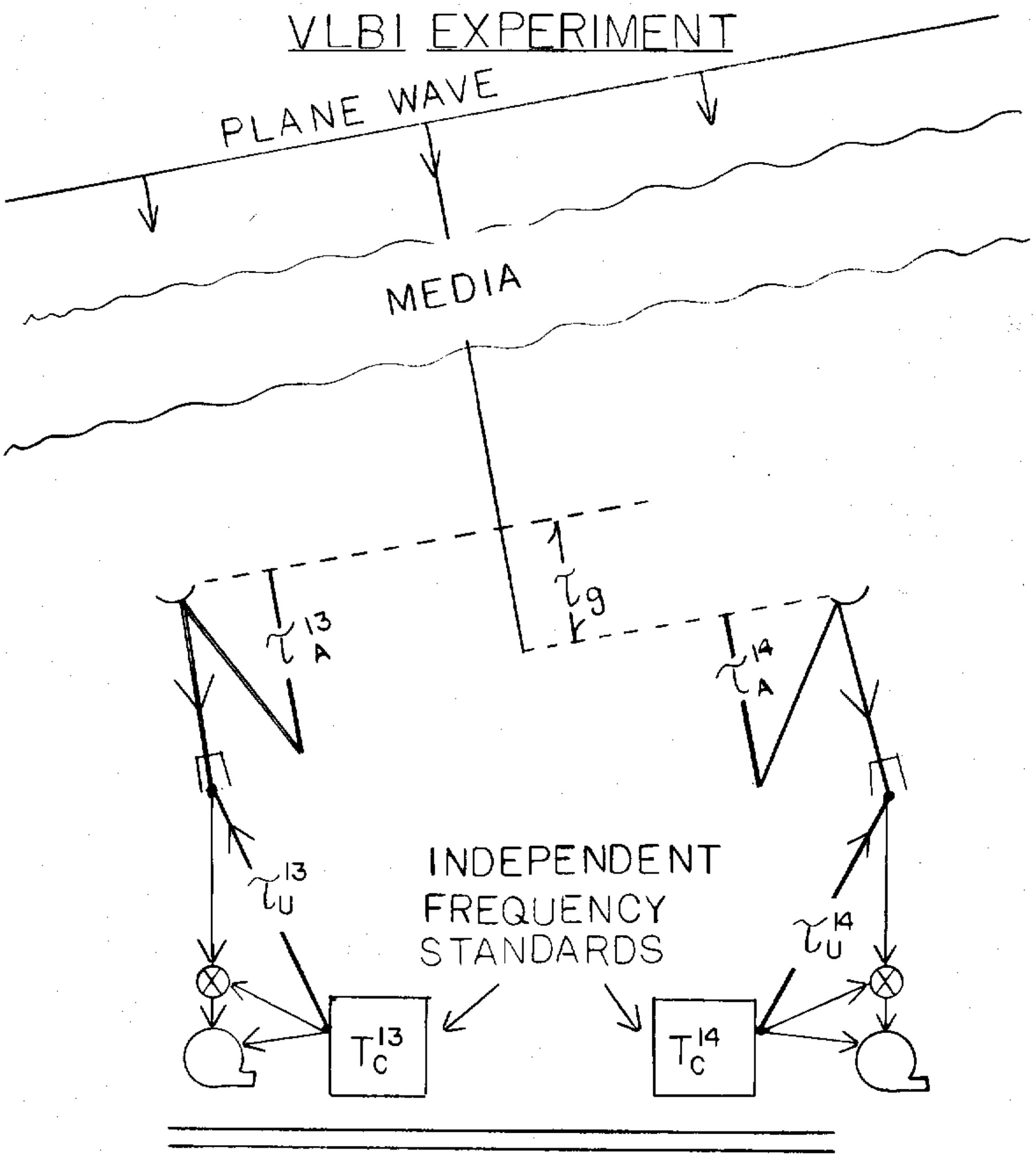

$$\tau_{VLBI} \approx (\tau_A^{14} - \tau_A^{13}) - (\tau_U^{14} - \tau_U^{13}) + (T_C^{14} - T_C^{13})$$

(AFTER REMOVAL OF $\tau_g$)

Figure 1. This figure illustrates the instrumental delays, $\tau_a$ and $\tau_u$, which must be measured at each station in order to use a VLBI experiment to synchronize station clocks. The use of phase calibration with multiple tones per channel eliminates the need for measurements of the receiver and downlink delays. It should be noted that, in practice, $\tau_a$, and $\tau_u$ are defined relative to the intersection of the antenna axes.

## Table 2

This table shows the results of four VLBI measurements of clock offset along with the results of concurrently performed traveling clock experiments. For each experiment, the clock offsets are given for a certain epoch chosen within that experiment.

RESULTS

| | Traveling Clock | VLBI | VLBI - T.C. |
|---|---|---|---|
| 6-6-79<br>Clock Offset<br>$\frac{\Delta f}{f}$ Offset | <br>+733.9 ±3. ns<br>$+2.3\text{x}10^{-12} \pm 1.5\text{x}10^{-12}$ | <br>+740.1 ±6. ns<br>$+1.00\text{x}10^{-12} \pm 0.03\text{x}10^{-12}$ | <br>+6.2 ±7. ns<br>$-1.3\text{x}10^{-12} \pm 1.5\text{x}10^{-12}$ |
| 7-21-79<br>Clock Offset<br>$\frac{\Delta f}{f}$ Offset | <br>+874.2 ±3. ns<br>$+2.1\text{x}10^{-12} \pm 0.6\text{x}10^{-12}$ | <br>+879.7 ±6. ns<br>$+2.31\text{x}10^{-12} \pm 0.01\text{x}10^{-12}$ | <br>+5.5 ±7. ns<br>$+0.2\text{x}10^{-12} \pm 0.6\text{x}10^{-12}$ |
| 8-26-79<br>Clock Offset<br>$\frac{\Delta f}{f}$ Offset | <br>-302.1 ±3. ns<br>$+0.4\text{x}10^{-12} \pm 1.5\text{x}10^{-12}$ | <br>-299.7 ±6. ns<br>$+1.00\text{x}10^{-12} \pm 0.01\text{x}10^{-12}$ | <br>+2.4 ±7. ns<br>$+0.6\text{x}10^{12} \pm 1.5\text{x}10^{-12}$ |
| 9-18-79<br>Clock Offset<br>$\frac{\Delta f}{f}$ Offset | <br>-1135.5 ±3. ns<br>$+2.9\text{x}10^{-12} \pm 0.6\text{x}10^{-12}$ | <br>-1131.1 ±6. ns<br>$+2.04\text{x}10^{-12} \pm 0.01\text{x}10^{-12}$ | <br>+4.4 ±7. ns<br>$-0.9\text{x}10^{-12} +0.6\text{x}10^{-12}$ |

Mean difference between two methods VLBI - T.C. = +4.6 ns

RMS Scatter = 1.4 ns

## QUESTIONS AND ANSWERS

MR. CHI:

Are there any questions? Yes?

DR. KAARLS, Van Swinden Laboratory

You use in your system a cable of several hundreds of meters, do you know if there is any influence of temperature on the delay? I assume the cable is in the open air.

DR. YOUNG:

Yes. The cable is in the open air and is in the sun in some cases. However, the cable has a delay compensation network, in which, the total delay through the cable is held constant by a voltage controlled phase shifter, so that if the cable were to stretch, the voltage controlled phase shifter would have its delay diminished in such a way as to hold the total delay constant through this uplink.

MR. RUEGER:

In making your differential measurements of your traveling clock, did you use the same counter at both ends?

DR. YOUNG:

Yes. The same equipment.

MR. RUEGER:

Was the counter turned off in-between?

DR. YOUNG:

Yes. The counter was turned off in-between.

MR. RUEGER:

We found some problems in some of our work by having that counter stabilizing thermally between measurements.

DR. YOUNG:

Well, I have seen those problems too. And we have thrown away some data at the beginning of the measurements, during the warm-up time of the computing counter.