PRECISE CLOCK SYNCHRONIZATION
VIA VERY-LONG-BASELINE INTERFEROMETRY

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ABSTRACT

Hydrogen-maser clocks at the 37-meter-diameter radio telescope of the Haystack Observatory in Westford, Massachusetts, and the 43-meter-diameter radio telescope of the National Radio Astronomy Observatory in Green Bank, West Virginia, were synchronized by very-long-baseline interferometry on 28 March 1977 and on 23 September 1977. The synchronization was also accomplished independently on each of these occasions by means of traveling Cesium clocks. The clock data, fully analyzed in each case only after the completion of the corresponding VLBI data analysis, confirmed the VLBI results to within 19 and 13 nanoseconds for the first and second experiments, respectively.

Accurate clock synchronization via very-long-baseline interferometry (VLBI) has been possible for several years, and has been a byproduct of many precision astrometric and geodetic experiments (1,2). However, most past synchronization results have been limited in absolute accuracy by certain constant, but poorly known, instrumental delays. Accurate absolute synchronization by VLBI was only recently (3) demonstrated in a short (~1 km) baseline experiment, in which, for the first time, care was taken to estimate or to measure all instrumental delays. Here we report the first absolute synchronization results from relatively long, 845-km, baseline experiments. These experiments are also the first in which the synchronization by interferometry was checked subsequently by an independent agency [the U. S. Naval Observatory (USNO)].

The synchronization experiments involved the hydrogen-maser clocks at the 37-m-diameter radio telescope of the Haystack Observatory in Westford, Massachusetts, and the 43-m-diameter radio telescope of the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia. In the first experiment, on 28 March 1977, the synchronization via VLBI was checked by transporting two Cesium clocks from the USNO in Washington, D.C., one to each of the telescopes, and both back to Washington. In the second experiment, on 23 September 1977, the two Cesium clocks were transported together from the USNO to Haystack, then to NRAO, and finally back to the USNO.

Figure 1 shows a block diagram of the interferometer terminals used in the experiments. A fast rise time (<30 ps) pulse generator was used to calibrate delays in the receiver and recording electronics. The calibration pulse was also returned from the pulse generator, which was located close to the telescope feed, to the control room for easy comparison with the clock which controlled the VLBI recording. A hydrogen-maser frequency standard controlled both the calibration pulse generator and the recording clock both at Haystack and at NRAO.

In our VLBI system the delay of a signal arriving from a distant quasi-stellar radio source is measured using a bandwidth synthesis technique (4) involving the sequential sampling of 360-kHz bands spaced over a much wider spanned bandwidth of 100 MHz, centered at 8441 MHz. The multiband delay measurement has a 1 microsecond ambiguity imposed by a minimum spacing of 1 MHz between the narrow, 360-kHz band samples. However, the ambiguity is eliminated by using the less precise, but unambiguous, delay measurement obtained from the crosscorrelation of signals within a single 360-kHz band.

The difference between the readings of the independent clocks controlling the two interferometer terminals is derived from the analysis of a set of VLBI observations of several radio sources, by simultaneous estimation of baseline vectors, radio source positions, and clock parameters (5). The results from the experiment performed on 28 March 1977 are given in Table 1, where line 16 shows the estimated difference between the VLBI clocks after correction for the instrumental delays. An instrumental delay correction for the antenna geometry (line 1) is needed to correct for the difference in signal delay between the baseline vector termination point (6) and the antenna feed point. Line 21 shows the difference between the VLBI terminal clocks as estimated from the traveling clocks, after correction for the linearly-interpolated relative drift between the portable clocks, based on pre-trip and post-trip comparisons made at the USNO in Washington.

Table 2 shows the results of the experiment performed on 23 September 1977. In this experiment, since Haystack was visited by the traveling clocks approximately seven hours later than NRAO, it was necessary to account for the estimated drifts, over this interval, of the traveling clocks relative to Haystack's clock. (See line 24 of Table 2.) The latter's rate was already accurately known relative to that of the USNO Master Clock, through long-term comparisons via Loran C. The rates of the traveling clocks were determined from direct comparisons with the Master Clock in Washington, before and after the trip.

The accuracy of the VLBI clock synchronization is not limited by the uncertainty of the estimate of the radio signal (group) delay, which is much less than 1 nanosecond, but rather by the accuracy of the determination of the various instrumental delays. The cumulative error arising from these estimates of instrumental delays is thought to be less than ±10 nanoseconds. The error of the synchronization via traveling clocks is limited by clock drifts and is estimated to be under ±20 nanoseconds.

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References and Notes

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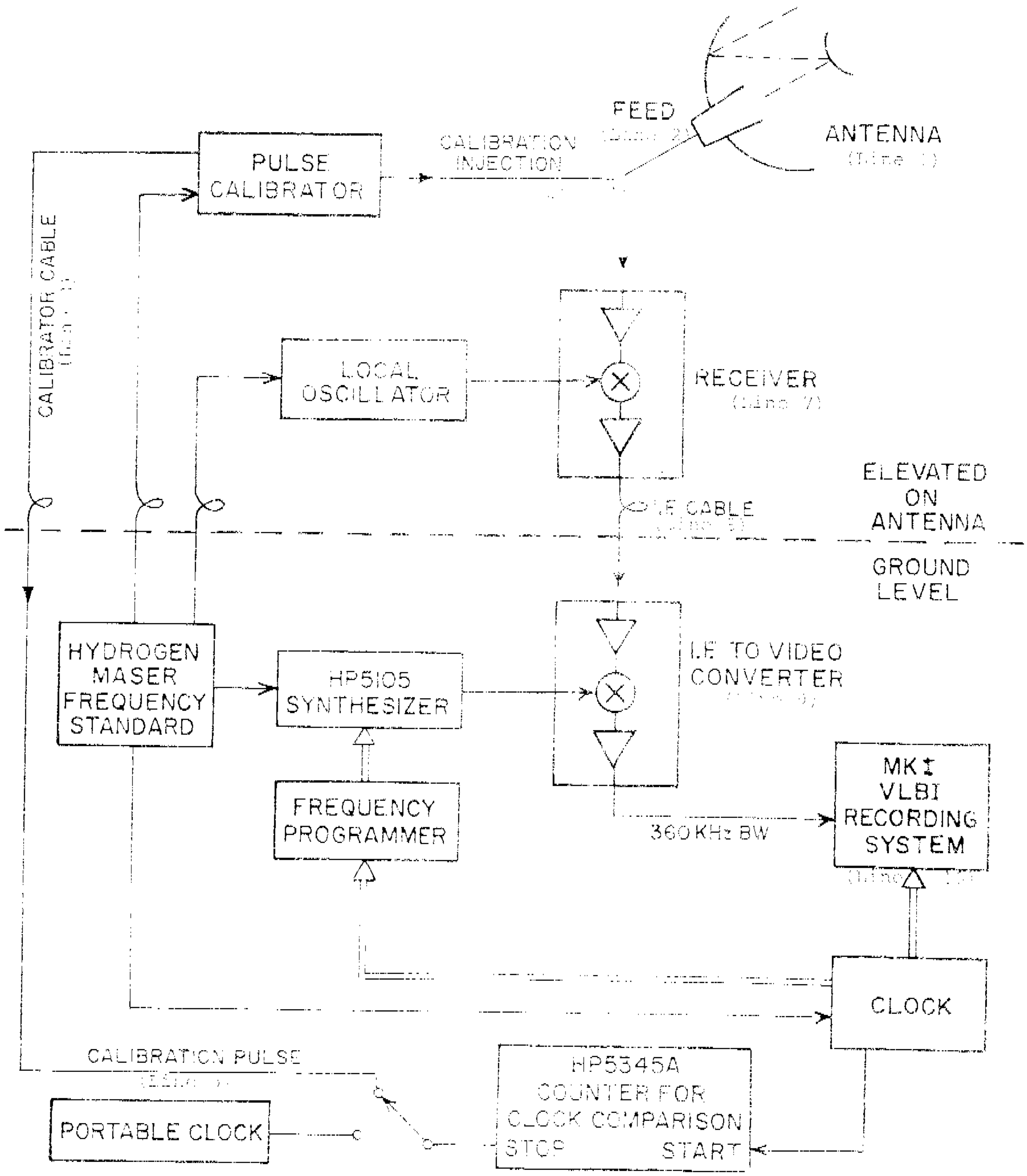
6. The baseline termination point at Haystack is the intersection of azimuth and elevation axes and at NRAO it is the intersection of the polar axis and the perpendicular plane that contains the declination axis.

Table 1 Comparison Between VLBI Clock Synchronization and Traveling Clock Synchronization for the 28 March 1977 Experiment

Line No.		Haystack (μsec)	NRAO (μsec)	Comments
1	Antenna geometrical delay	0.06977	0.05167	Estimated from antenna geometry
2	Feed delay	0.00920	0.00175	Estimated from feed geometry
3	Calibration cable delay	0.60500	0.59090	Measured with a time domain reflectometer
4	Calibration injection delay	0.00800	0.00900	Estimated from cable lengths
5	(Clock-cal. pulse)	0.77800	0.76310	Measured using electronic counter (HP5345A)
6	Instrumental delay	-0.10205	-0.12778	Lines (1)+(2)+(3)-(4)-(5)
7	Receiver delay	[illegible].01	0.01	Estimate
8	IF cable delay	[illegible].61	0.63	Measured with time domain reflectometer
9	IF to video converter delay	5.00	5.00	Estimated from impulse response
10	Recording system delay	-21.01	-22.14	Measured by test signal injection
11	Single band instrumental delay	[illegible]	-16.45	Lines (1)+(2)+(7)+(8)+(9)+(10)
12	Clock solution from single-band VLBI data	[illegible]		Clock solution for an epoch of 1920 UT, 28 March 77
13	Line 12 corrected for single-band instrumental delays	[illegible]		Lines $(12)+(11)_E-(11)_N$
14	Clock solution from multi-band VLBI data	xx.8133		Clock solution for an epoch of 1920 UT, 28 March 77
15	Line 14 corrected for inst. delays	xx.8390		Lines $(14)+(6)_E-(6)_N$
16	(NRAO VLBI Clock-Haystack VLBI Clock)	2[illegible].8390		1 μsec ambiguity resolved by line (13)
17	(USNO P[illegible]-USNO PC1256)	1.813		Measured at 1310 UT, 28 March 77 before departure for each VLBI site
18	(USNO [illegible] USNO PC1253)	[illegible].839		Measured at 0310 UT, 29 March 77 after return of traveling clocks to Washington, D.C.
19	(Haystack VLBI Clock-USNO PC1255)	[illegible]3.120		Measured at 1911 UT, 28 March 1977
20	(NRAO VLBI Clock-USNO PC653)	33.114		Measured at 1928 UT, 28 March 1977
21	(NRAO VLBI Clock-Haystack VLBI Clock)	21.820		Lines (20)-(19)+((17)+(18))/2
22	(VLBI Clock Sync.-Trav. Clock Sync.)	0.019		Difference of results from two methods of clock synchronization Lines (16)-(21)

Table 2 Comparison Between VLBI Clock Synchronization and Traveling Clock Synchronization for the 23 September 1977 Experiment

Line No.		Haystack (μsec)	NRAO (μsec)	Comments
1	Antenna geometrical delay	0.06977	0.05167	Estimated from antenna geometry
2	Feed delay	0.00920	0.00175	Estimated from feed geometry
3	Calibration cable delay	0.60500	0.58740	Measured with a time domain reflectometer
4	Calibration injection delay	0.00800	0.00900	Estimated from cable lengths
5	(Clock-cal. pulse)	0.75800	0.13070	Measured using electronic counter (HP5345A)
6	Instrumental delay	-0.08203	0.50112	Lines (1)+(2)+(3)-(4)-(5)
7	Receiver delay	0.01	0.01	Estimate
8	IF cable delay	0.61	0.63	Measured with time domain reflectometer
9	IF to video converter delay	5.60	5.00	Estimated from impulse response
10	Recording system delay	-21.01	-22.14	Measured by test signal injection
11	Single band instrumental delay	-14.71	-16.45	Lines (1)+(2)+(7)+(8)+(9)+(10)
12	Clock solution from single-band VLBI data	15.530		Clock solution for an epoch of 1520 UT 23 Sept 77
13	Line 12 corrected for single-band inst. delays	17.270		Lines $(12)+(11)_H-(11)_N$
14	Clock solution from multi-band VLBI data	xx.8202		Clock solution for an epoch of 1520 UT 23 Sept 77
15	Line 14 corrected for inst. delays	xx.2370		Lines (14) and $(6)_H-(6)_N$
16	(NRAO VLBI Clock-Haystack VLBI Clock)	17.2370		1 μsec ambiguity resolved by line (13)
17	(Haystack VLBI Clock - Cs 1117)	16.4350		2227 UT, 23 Sept 77 (measured with 48" cable on Cs)
18	(Haystack VLBI Clock - Cs 1368)	17.1890		2227 UT, 23 Sept 77 (measured with 48" cable on Cs)
19	(Haystack VLBI Clock - Mean of Cs)	16.8066		Line ((17)+(18))/2 corrected for 48" of cable
20	(NRAO VLBI Clock - Cs 1117)	33.6580		1519 UT, 23 Sept 1977
21	(NRAO VLBI Clock - Cs 1368)	34.4260		1519 UT, 23 Sept 1977
22	(NRAO VLBI Clock - Mean of Cs)	34.0420		Lines ((20)+(21))/2
23	(NRAO VLBI Clock - Haystack VLBI Clock)	17.2354		Lines (22)-(19)
24	(NRAO VLBI Clock - Haystack VLBI Clock) corrected for drifts over 7 hrs to Haystack	17.2238		Corrected for Cs drift rate of 3.05 ns/hour and for a Haystack maser drift rate of 1.39 ns/hour, both measured relative to USN Master Clock
25	(VLBI Clock Sync. - Trav. Clock Sync.)	0.0132		Difference of results from two methods of clock synchronization, lines (16)-(24)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