# A Two-Year History of Atomic Frequency Standards Syntonization in the Deep Space Network

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*The NASA-JPL Frequency and Timing System (FTS) of the Deep Space Network (DSN) consists of a collection of three sets of clocks (located in Australia, California, U.S.A., and Spain) driven by independent atomic oscillators. It is the synchronization of the output frequencies (syntonization) of these oscillators (reference frequency standards) that is reported here. Prior to 1980 there was no DSN direct specification of syntonization. However, there was an implied specification of a* $\pm 5.5 \times 10^{12}$ *related to the DSN time synchronization specification of a ±100 microseconds. Both the syntonization within the three sets and the syntonization of the sets to the international standard [International Atomic Time (TAI, UTC (BIH)] are considered.*

## I. Establishing Syntonization

The original calibration was established during the third quarter of calendar 1980 by syntonizing a specially prepared transportable cesium atomic clock (Ref.1) to the standard frequency as maintained by the National Bureau of Standards at Boulder, Colorado. This "calibrated transfer standard" was then transported to each of the three sets of atomic frequency standards, where it was used to measure their frequency offset with respect to the NBS standard (designated as UTC-NBS). In this manner each of the reference frequency standards were syntonized to UTC-NBS and, to a lesser degree, syntonized to each other.

Each atomic reference frequency standard set consists of a Smithsonian Institution Astrophysical Observatory (SAO) model VLG-10B hydrogen maser (H2M) and two Hewlett-Packard model 5061-A option 004 cesium beam frequency standards. The offset of each H2M's output frequency from the hydrogen hyperfine spectral line was established with respect to the transported transfer standard. By means of phase comparators, the H2M calibration is transferred to the two cesium beam standards. Thus, the syntonization between the three sets and between any set and UTC was established (Ref. 2) within less than $\pm 3 \times 10^{-13}$.

## II. Maintaining Syntonization

To make effective use of syntonization it must be maintained on a continual basis; e.g., the tuning of an orchestra to A above middle C is a syntonization maintenance application. The DSN makes use of four resource techniques for maintaining syntonization. They are: LORAN-C, traveling clocks, television vertical sync pulse, Very Long Baseline Interferometry (VLBI/ΔDOR.[1]). Figure 1 illustrates how the DSN is con-

[1] A technique equivalent in accuracy to VLBI that makes use of an extragalactic radio source along with a spacecraft to gather data from which time sync information can be derived.

figured to utilize these resources, making use of a combination of (1) Mediterranean chain LORAN, traveling clocks and VLBI/ΔDOR in Spain, (2) television, microwave links, traveling clocks and VLBI/ΔDOR in Australia, (3) microwave links, West Coast chain LORAN, traveling clocks[2] and VLBI/ΔDOR in California.

Table 1 lists the comparative merits of the resources used for maintaining syntonization. For all comparisons, it has been assumed that the resource has been in use for gathering data for periods longer than one year and that at least two out of three reference frequency standards in a set have been in continual operation over that period.

## III. Syntonization to UTC

Figure 2, a plot of $\Delta f/F$ vs time, presents a two-year history of the syntonization of the DSS 63[3] reference frequency standards with respect to UTC-USNO. The "SPEC wrt UTC (NBS)" annotated dotted lines in the vicinity of UTC (USNO) plus and minus 10E-12 refers to System Functional Requirements Document 821-14.III.B.2. The data were collected through the use of LORAN-C and have been adjusted through the use of USNO Bulletin 4 corrections. With the exception of routine frequency standard maintenance (H2M tuning) periods, 98% of the data presented applies to H2M, SAO VLG-10B serial #07. The data indicate that the reference frequency standards were syntonized to UTC-USNO within less than 1 fractional part in $10^{12}$ over the entire two-year period.

Figure 3, a plot of $\Delta f/F$ vs time, presents a two-year history of the syntonization of the DSS 43[4] reference frequency standards with respect to UTC-AUS[5]. The "SPEC wrt UTC (NBS)" annotated dotted lines in the vicinity of UTC(USNO) plus and minus 10E-12 refers to System Functional Requirements Document 821-14.III.B.2.[4] The data were collected through the daily use of the TV simultaneous view technique. The reference to which syntonization is made is the Department of National Mapping (NATMAP) clock ensemble (four clocks) in the local area custodian of UTC-AUS. It is equivalent to and serves the same function for DSS 43 as the Deep Space Network Master Clock ensemble (NMC) does for DSS 14 at Goldstone, California, U.S.A. The data have been adjusted per published NATMAP Bulletin E corrections. With the exception of the routine frequency standard maintenance (H2M tuning) periods, 83% of the data applies to H2M, SAO VLG-10B serial #06. The data indicate that the reference frequency standards were syntonized to UTC-USNO within a part in $10^{12}$ over the entire two-year period.

Figure 4 presents a two-year history of the syntonization of the DDS 14 reference frequency standards with respect to UTC-NMC[6]. The data were adjusted per weekly NMC clock closure reports. Over this two-year report period there were occasions when UTC-MC and/or UTC-DSN were not available.[7] Continuity of the syntonization history of H2M SAO VLG-10B serial #05 was maintained at those times through the use of output frequency drift data from the hydrogen hyperfine line obtained during tuning maintenance. Greater than 98% of the data presented applies to H2M SAO VLG-10B serial #05, and it indicates that the syntonization of the DSS 14 reference frequency standards was maintained within a part in $10^{12}$ of UTC(NBS) over the entire period. Performance was borderline during April and May 1982.

## IV. Syntonization Within the DSN

Figure 5 presents a plot of $\Delta f/F$ vs time for a two-year history of the syntonization of the DSS 14 reference frequency standard with respect to the DSS 63 reference frequency standard. The data were collected through the use of VLBI and ΔDOR time synchronization operations (Ref. 3). These syntonization data were derived from sets of blunder-free time offset data points, where a set consists of a minimum of three "good" points.[8] Further, where there was a lack of "good" VLBI data, ΔDOR data sets were used. The data indicate that the DSS 63 reference frequency standards remained syntonized to the DSN master at DSS 14 within $\pm 3 \times 10^{-13}$ over the two-year report period.

Figure 6 presents a plot of $\Delta f/F$ vs time for a two-year history of the syntonization of the DSS 14 reference frequency

[2]At Goldstone, California, traveling clocks serve a double role: (1) to synchronize the Network Master Clock (NMC) ensemble of seven cesium clocks to UTC-NBS, and (2) to synchronize the DSS 14 clocks to the NMC ensemble on each VLBI time sync operation.

[3]Deep Space Tracking Station 63 (DSS 63) is located in the Madrid area of Spain (Fig. 1).

[4]DSS 43 is located in the Australian Capitol Territory (A.C.T.) near Canberra.

[5]UTC-AUS is traceable to UTC-USNO within $\pm 5 \times 10^{-13}$ through the use of semiannual traveling clock trips between Canberra, A.C.T., and Washington, D.C.

[6]UTC-NMC is syntonized to UTC-NBS, and to lesser degree to UTC-USNO, within a part in $10^{13}$ through the use of traveling clocks and West Coast LORAN-C. UTC-NMC is syntonized to UTC-DSN within less than a part in $10^{13}$ through the use of weekly traveling clock trips and microwave links. Thus UTC-DSN is syntonized to UTC-NBS within a part in $10^{12}$.

[7]Extended power outages and airconditioning failures in the building housing the NMC ensemble and extensive repair work on the DSS14 antenna caused the loss of UTC-DSN and UTC-NMC.

[8]A point is defined as "good" if it is within less than $3\sigma$ of the average rate computation ($\Delta f/f$), where the number od data points used is greater than 2.

standard with respect to the DSS 43 reference frequency standard. The data were collected through the use of VLBI and ΔDOR time synchronization operations (Refs. 3, 4). These syntonization data were derived from sets of blunder-free time offset data points, where a set consists of a minimum of three "good" points. Further, where there was a lack of "good" VLBI data, ΔDOR data sets were used. The data indicate that the DSS 43 reference frequency standards remained syntonized to the DSN master of DSS 14 within $\pm 3 \times 10^{-13}$ over the two-year report period.

## References


1. Ward, S., "The Operational Performance of Hydrogen Masers in the DSN," *TDA Progress Report 42-63*, pp. 203-218, Jet Propulsion Laboratory, Pasadena, Calif., June 15, 1981.
2. Ward, S., "The Operational Performance of Hydrogen Masers in the DSN," Proceedings of the Twelfth Annual Precision Time and Time Interval (PTTI) Applications and Planning Meeting, pp. 616-617, December 2-4, 1980, Goddard Spaceflight Center, Greenbelt, Md.
3. Roth, M. G., "International Clock Synchronization with the Block I VLBI System," Proceedings of the Thirteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, pp. 489-500, December 1-3, 1981, Goddard Spaceflight Center, Greenbelt, Md.

Table 1. Comparative accuracy of syntonization maintenance resources

| | Osc. to osc. (DSS to DSS)[a] | Osc. to listed Ref.[a] | Osc. to UTC-USNO[a] | Osc. to UTC-NBS[a] |
|---|---|---|---|---|
| LORAN-C (daily meas.) | 1.1E -12 | ±5E -13 LORAN | ±7E -13 | ±7E -13 |
| LORAN-C (simult. view) | 1.0E -12 | ±3.5E -13 LORAN | ±5E -13 | ±6E -13 |
| Traveling clocks (2 trips/yr) | 1.4E -13[b] | ±7.5E -14 Clock[b] | DNA | DNA |
| Traveling clocks (4 trips NBS/yr) | DNA | ±7.8E -14 UTC-NMC | ±2.5E -13 | ±1.3E -14 |
| Television (daily meas.) | 1.05E -12 | ±2.3E -13 UTC-AUS | ±5.5E -13 | ±7.4E -13 |
| VLBI X-band (7 to 10 day) | 5.4E -15 | ±3.8E -15 UTC-DSN | DNA | DNA |
| VLBI S-band (7 to 10 day) | 1.4E -14 | ±9.9E -15 UTC-DSN | DNA | DNA |
| Microwave (3 meas./day) | 2.46E -12 | ±2.2E -15 UTC-NMC (1) | DNA | DNA |

[a]The number following E designates the exponent or power of 10: e.g., ±7.5E -14 is $\pm 7.5 \times 10^{-14}$.
[b]These are frequency or phase measurements. All others are time measurements.

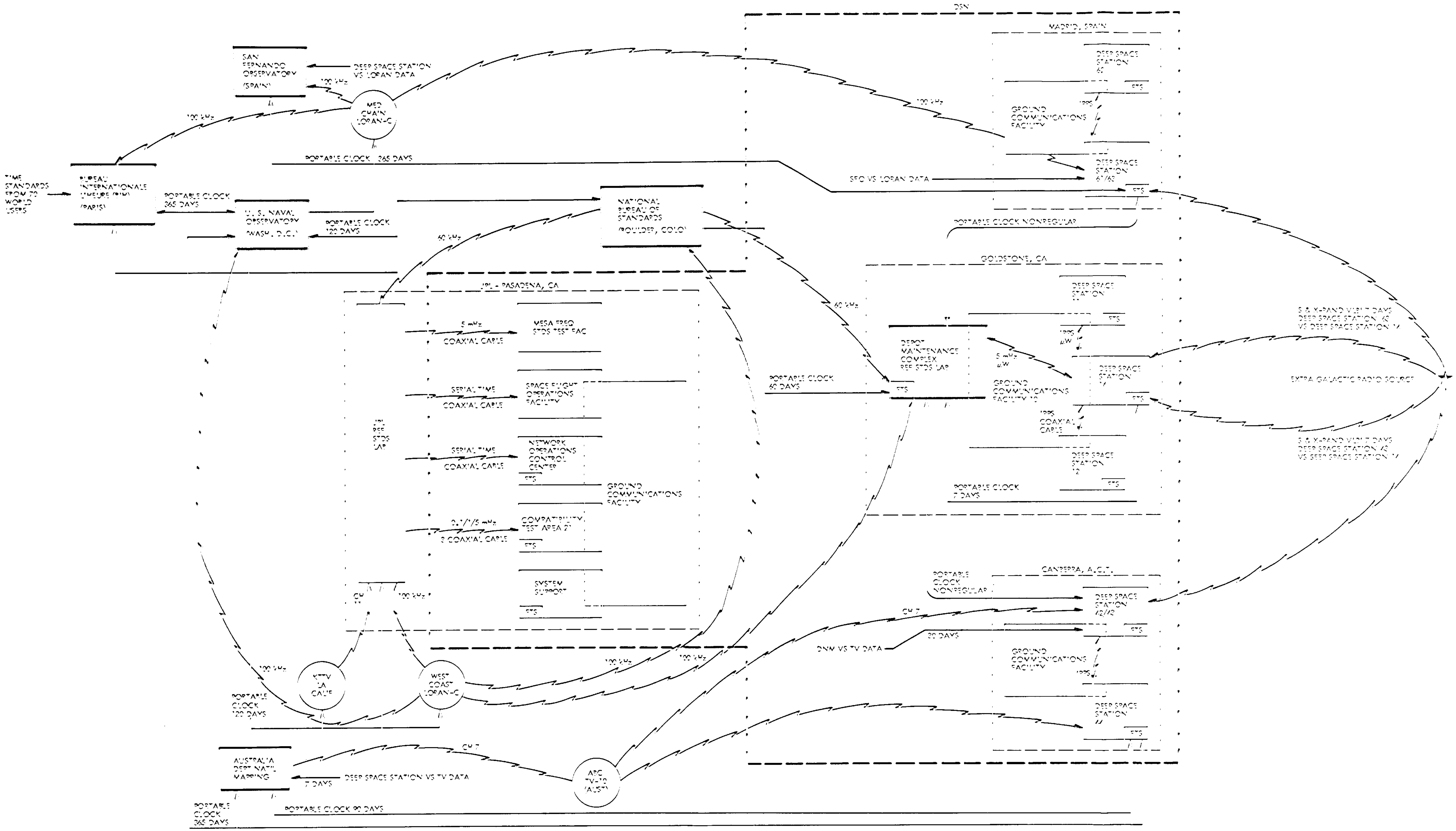


Fig. 1. NASA/JPL intra/extra DSN frequency and time sync system

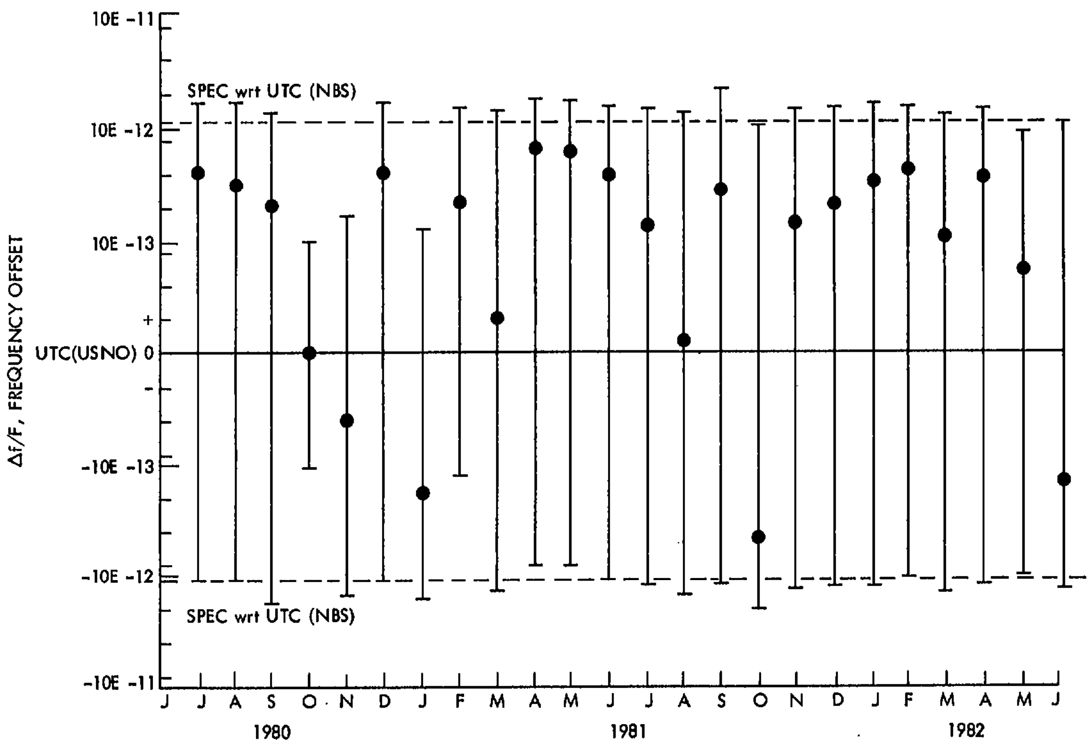


**Fig. 2. DSS 63 syntonization to UTC/(USNO) through the use of LORAN-C**

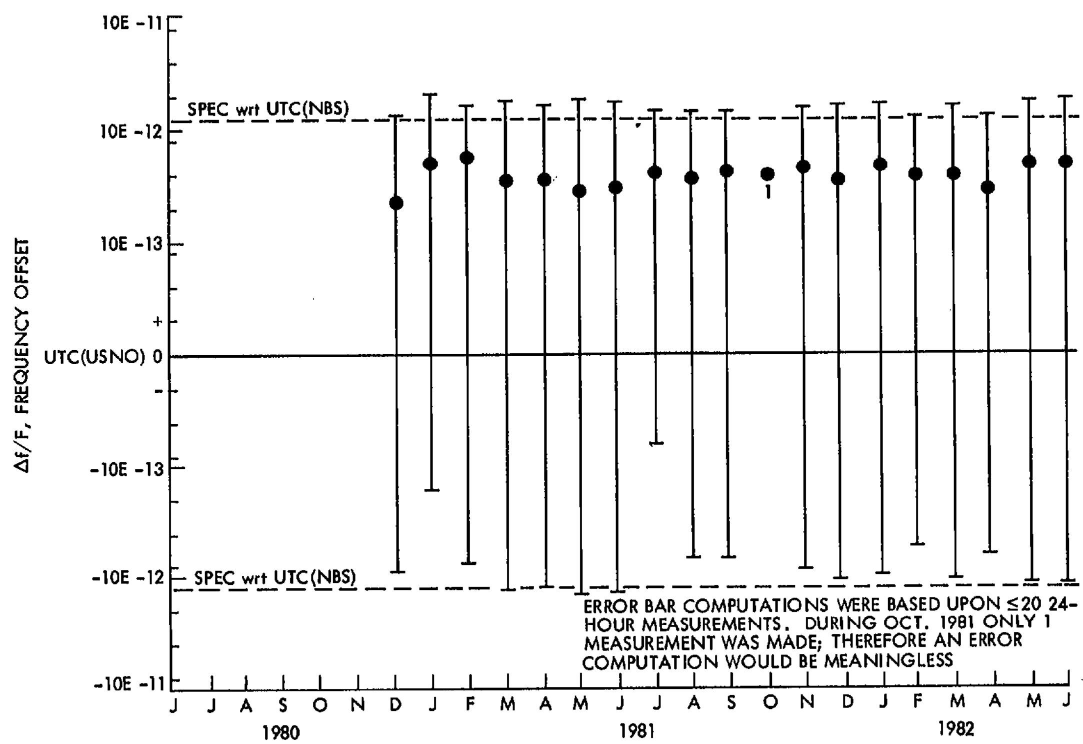


**Fig. 3. DSS 43 syntonization to UTC/(USNO) through the use of television**

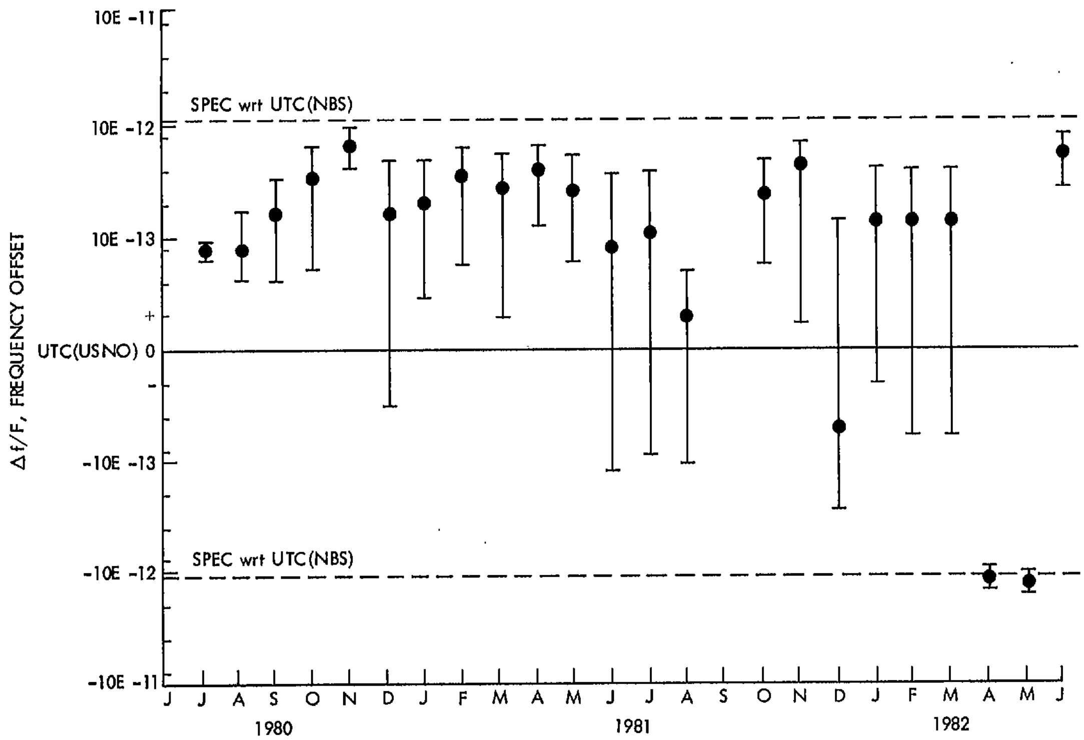


**Fig. 4. DSS 14 syntonization to UTC/(USNO/NBS) through the use of microwave and traveling clocks**

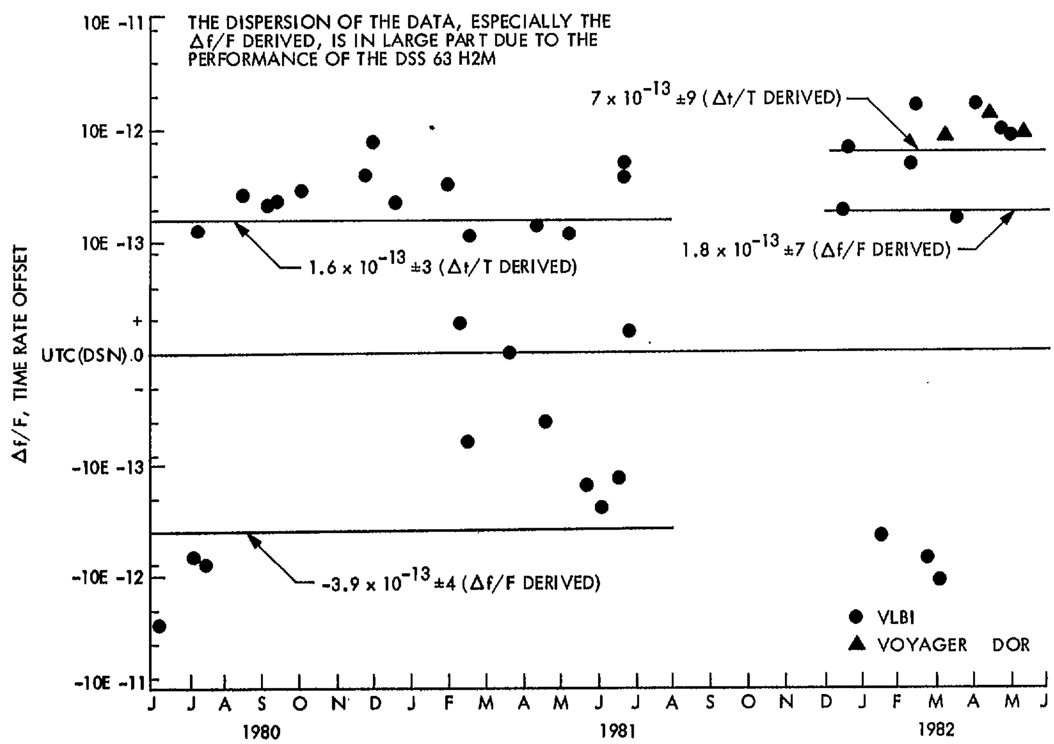


**Fig. 5. DSS 63 vs DSS 14 syntonization through the use of VLBI**

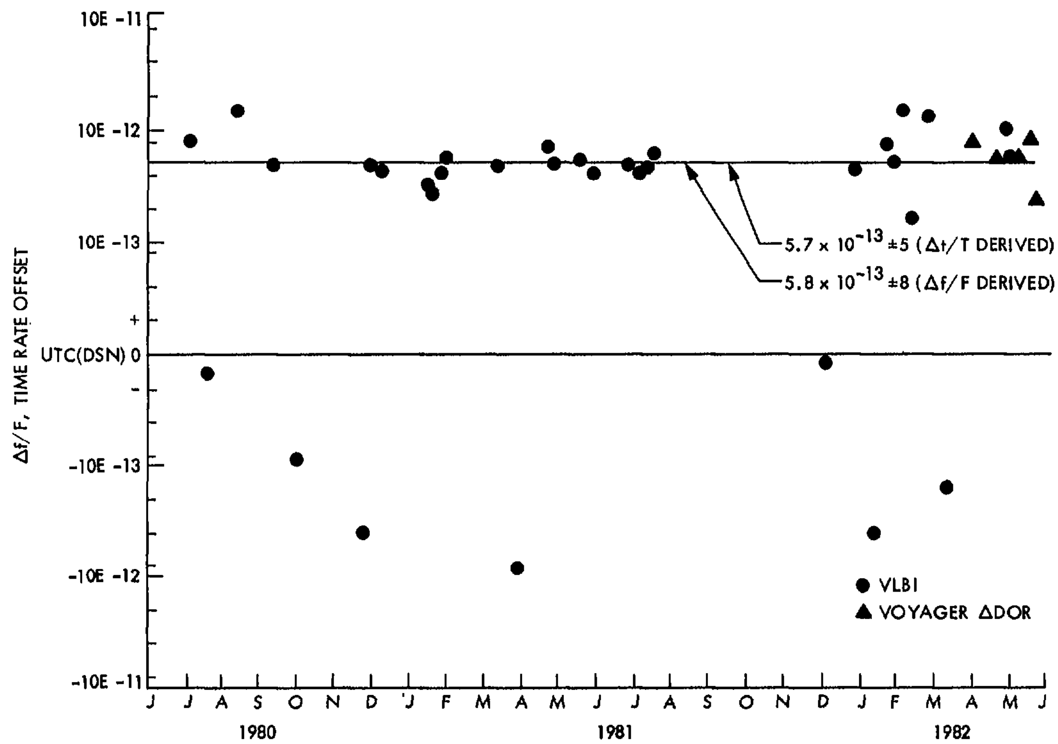


Fig. 6. DSS 43 vs DSS 14 syntonization through the use of VLBI