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STABILITY ANALYSIS OF THE CESIUM FREQUENCY STANDARD ON BOARD NA--ETC(U)

FEB 80　T MCCASKILL, J BUISSON, J WHITE

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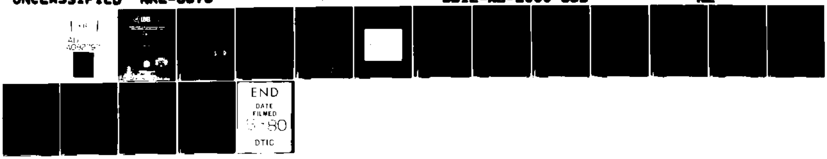

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

NTS-2 was successfully launched on June 23, 1977, and maneuvered into a preassigned constellation position as part of the Phase I demonstration for NAVSTAR GPS. NTS-2 carried two cesium frequency standards. Precise timing signals, derived from one of the cesium frequency standards, were continuously transmitted. Time differences were then measured by the NTS ground stations.

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20. Abstract (Continued)

The NTS-2 time differences were used to fit an orbit to the observations over a (typical) 6-day span. Clock offsets were then obtained using the reference orbit and other measured parameters; these clock offsets were then used to estimate the cesium frequency stability.

Estimates of frequency stability have been obtained for one of the two cesium frequency standards for sample times of from 1 to 9 days. Analysis of the results indicates a white frequency noise of 0.00000000011 divided by the square root of the sample time in days for sample times of 1 to 5 days with a flicker floor of 0.00000000000017 for sample times from 5 to 9 days. For sample times of 10 days or longer an attempt was made to check for cesium aging with respect to the Universal Time Coordinated of Master Clock 1 at the United States Naval Observatory. The value for aging was not significantly different from zero; that is, no cesium aging was found.

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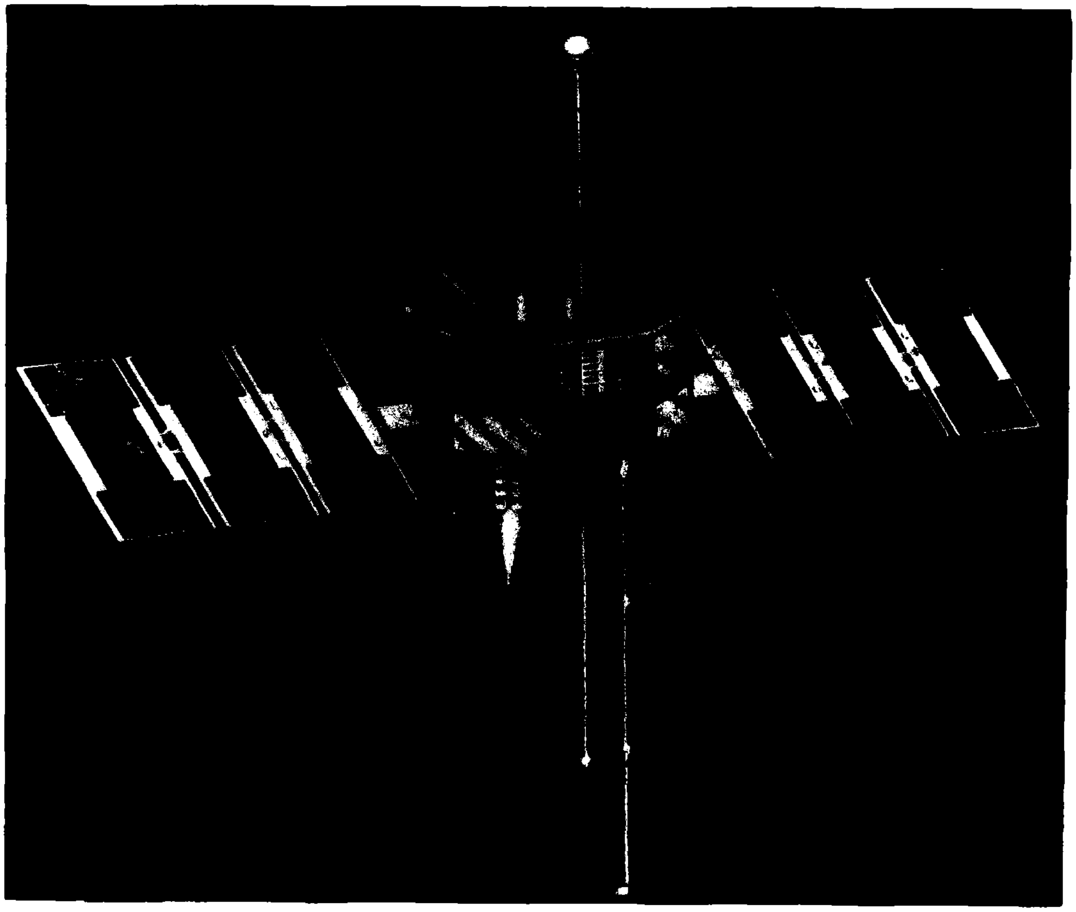

Fig. 1 — Navigation Technology Satellite 2 (NTS-2)

STABILITY ANALYSIS OF THE CESIUM FREQUENCY STANDARD ON BOARD NAVIGATION TECHNOLOGY SATELLITE 2 (NTS-2)

INTRODUCTION

This report presents preliminary frequency-stability results for one of the two cesium frequency standards carried by NTS-2 (figure 1). A relativistic frequency synthesizer is used to correct the cesium frequency so that the Universal-Time-Coordinated (UTC) apparent clock rate of the NTS is near that of the UTC clock rate of Master Clock 1 at the U.S. Naval Observatory (UTC(USNO, MC1)). A C-field tune has been performed to more closely synchronize UTC(NTS) to UTC(USNO, MC1). Frequency-stability values in the region of 1 day to 9 days were estimated using a three-clock cesium ensemble for a reference; for longer sample times UTC(NTS) is related via timing links to UTC(USNO, MC1). These and other procedures similar to actual operations to be used in the Global Positioning System (GPS) are discussed.

NTS-2 is the fourth in a series of NRL technology satellites (table 1) which were launched to qualify frequency standards for space use. NTS-2 was launched on June 23, 1977, and maneuvered [1] into a preassigned constellation position as the first satellite of the Phase I demonstration for NAVSTAR GPS. The Phase I constellation now consists of NTS-2 and NAVSTAR satellites 1 through 4. NAVSTAR satellites 5 and 6, to be launched in January and March 1980, will complete the constellation.

Table 1 — NRL technology satellites

Satellite	Launch Date	Altitude (n.mi.)	Inclination (deg)	Eccentricity	Weight (kg)	Weight [illegible]	Power (W)	Frequency	Oscillator	$\Delta f/f$ per day (pp 10^{13})	Range Error (m/day)
T-I	5-31-67	500	70	0.0008	40	[illegible]	6	UHF	Qtz	300	750
T-II	8-30-69	500	70	0.002	55	[illegible]	18	VHF/UHF	Qtz	100	75
T-III or NTS-1	7-14-74	7,400	125	0.007	295	[illegible]	100	UHF/L band	Qtz/Rb	5-10	12-24
NTS-2	6-23-77	10,900	63	0.0004	430	[illegible]	445*	UHF/L, L_1, L_2	Qtz/Cs	~2	5
NTS-3	1982	10,900	63	0.001	490	[illegible]	475*	UHF/L, L_1, L_2	Cs/H_2	0.1	0.25

*Beginning of life.

PRELAUNCH SYSTEM TESTS

The NTS-2 prelaunch test procedure (figure 2) included a test of the relativistic offset synthesizer, a test of overall system noise, and a check for long-term stability of the system. The relativistic-synthesizer tuning coefficient [2] was verified using an NTS-2 time-difference receiver [3]. The total system noise level was measured using separate (figure 2) frequency standards for NTS-2 and the time-difference receiver. The relativistic synthesizer was then activated, and the noise levels were compared. A standard deviation of less than

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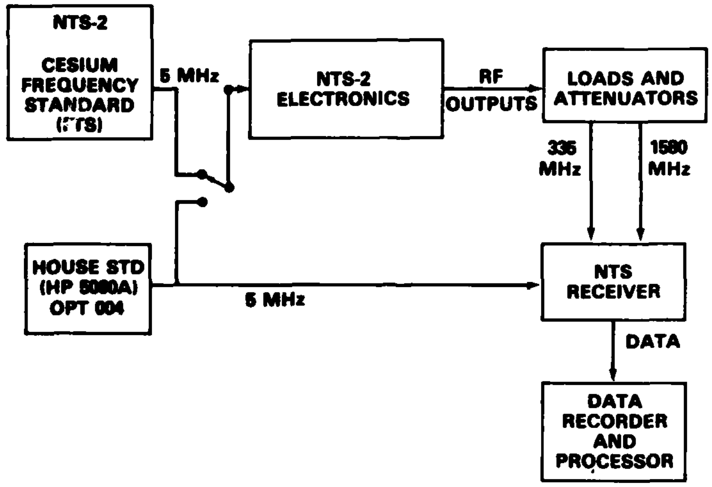

Fig. 2 — NTS-2 prelaunch system configuration

3 nanoseconds was measured with and without the relativistic synthesizer in use. Finally, a long-term drift check was made using the same frequency source for NTS-2 and the time-difference receiver.

Frequency offsets of both NTS-2 cesium frequency standards were determined with respect to UTC(USNO, MC1). The values obtained were within the GPS specifications.

NTS-2 FREQUENCY HISTORY

The quartz-oscillator subsystem of one of the two cesium frequency standards (cesium standard 2) was used during launch and orbit insertion. Before lockup by cesium standard 2, the quartz frequency was tuned to a value near the cesium resonance frequency (figure 3).

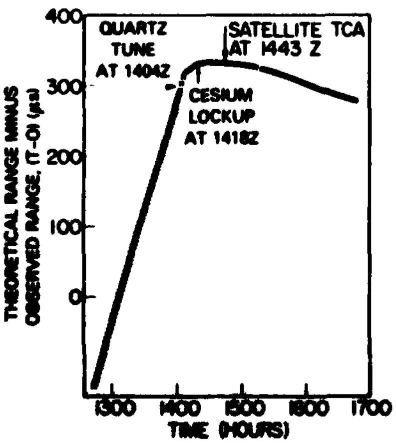

Fig. 3 — Lockup of the cesium frequency standard (cesium standard 2) on July 13, 1977 (day 190). The T - O values measure the offset of the spacecraft clock with respect to the clock at the NTS Panama station. (Also shown is the time of closest approach (TCA) to the station, to be referred to later.)

Cesium standard 2 locked up on the first attempt. The apparent clock rate was then measured by the NTS network to determine the relativistic clock offset. Figure 4 presents the clock rate as measured from the NTS Panama station. After applying the correction for the Panama cesium clock, a difference of -1.9×10^{-12} was measured between the theoretical relativistic offset (445.0×10^{-12}) and the NTS-2 cesium frequency standard. This difference is within the repeatability specification for the cesium standards. These measurements verify the predicted relativistic clock effect to within 1/2 percent.

The relativistic frequency synthesizer was then activated to correct the cesium output frequency close to the UTC rate. Figure 5 presents measurements, taken from the NTS CBD station, that show the immediate change in clock rate corresponding to the relativistic synthesizer, which offset the frequency by a constant amount.

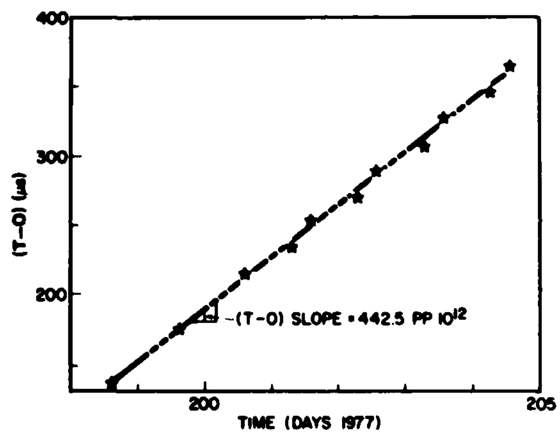

Fig. 4 — The offset of cesium standard 2 with respect to the clock at the NTS Panama station. The offset is within 1/2 percent in value to Einstein's theoretical relativistic frequency determination of 445.0 pp 10^{12}.

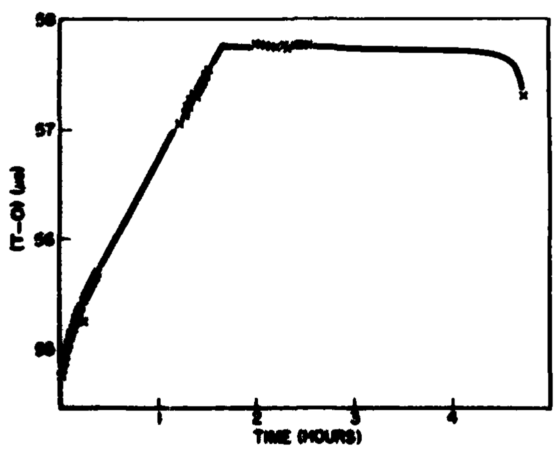

Fig. 5 — Effectiveness of the relativistic frequency synthesizer in making the relativity correction, on day 215, 1977, as measured with respect to the Chesapeake Bay Division (CBD) clock

Closer frequency synchronization to UTC was attempted through the use of cesium C-field tuning. A frequency tune of -7.8 pp 10^{13} was applied to the UTC(NTS) rate, which resulted in a slight overcorrection.

Figure 6 summarizes the frequency offset from UTC(USNO, MC1) from launch to the end of the year.

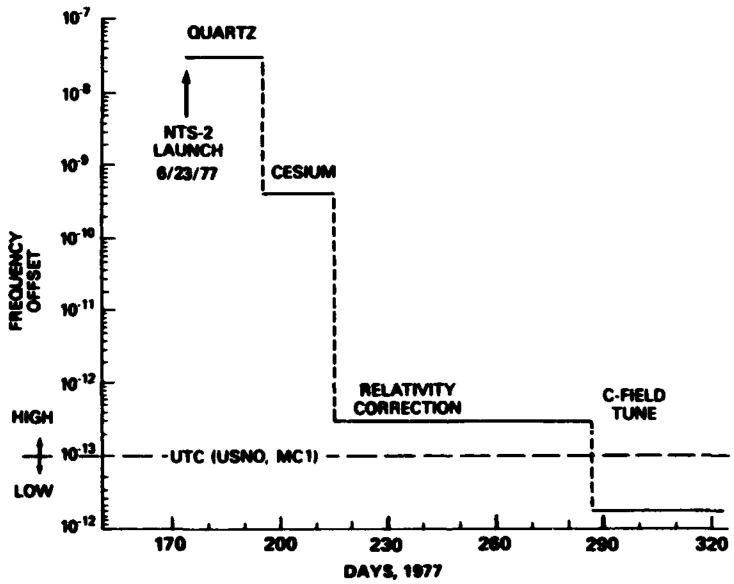

Fig. 6 — History of the NTS-2 frequency offset, plotted in 1977 with respect to days

PERFORMANCE DATA FOR THE CESIUM-STANDARD-2 QUARTZ SUBSYSTEM

Approximately 270 days of aging data are available for the crystal oscillator in cesium standard 2. The crystal aging is derived from the control-voltage changes in the servo loop. Figure 7a shows the initial crystal tuning curve for cesium standard 2, figure 7b shows the control-voltage telemetry versus time from July 1977 through April 1978, and figure 7c shows the relative frequency shift of the crystal for the same time period. The apparent aging rate ranges from 1×10^{-10} per day just after launch to approximately zero for the most recent 100 days. Since the telemetry resolution is about 2×10^{-9} per bit, the rate would be 2×10^{-11} per day. This apparent aging is due to at least two sources: natural aging of the resonator, and natural radiation at the NTS-2 orbit altitude.

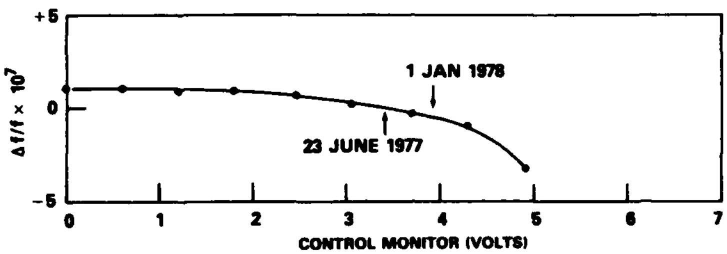

Fig. 7a — Initial tuning curve for the crystal oscillator in cesium standard 2 carried by NTS-2

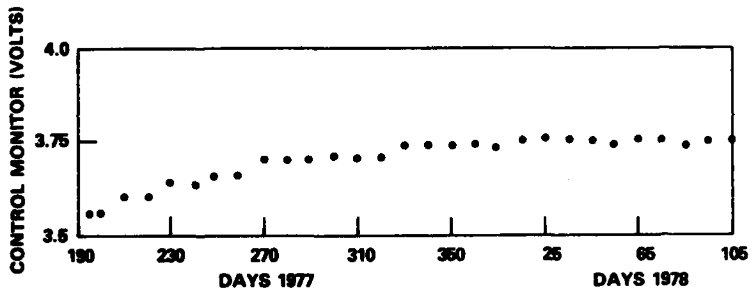

Fig. 7b — Control-voltage telemetry from cesium standard 2

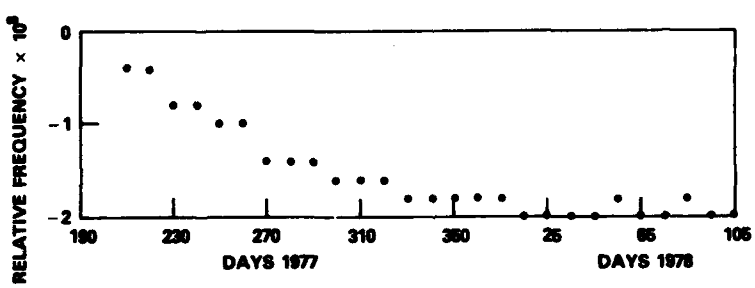

Fig. 7c — Relative frequency shift of the crystal oscillator

ORBITAL CONSIDERATIONS

Figure 8 depicts the NTS network coverage for the NTS-2 spacecraft. NTS-2 follows a repeating ground-track orbit of two revolutions per sidereal day. Curves for the limits of visibility from each station are also shown in figure 8. Figure 9, which again shows the coverage from Panama, illustrates that NTS-2 may be tracked from Panama for nearly one complete orbit every day.

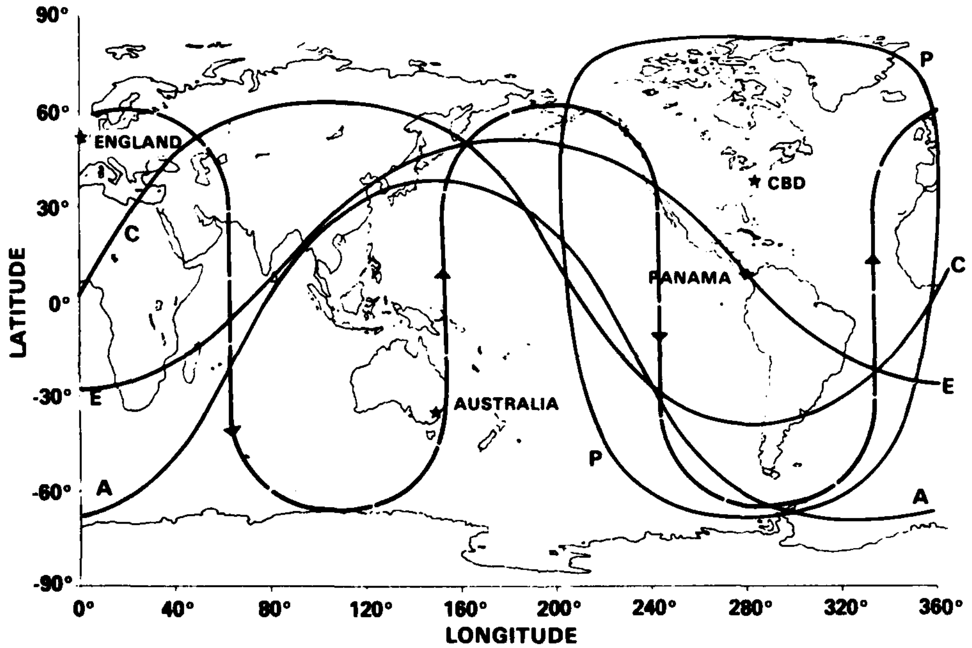

Fig. 8 — Network coverage for the NTS-2 satellite. The dashed curve is the NTS-2 ground track, and curves P, C, E, and A are the limits of visibility from the Panama, CBD, England, and Australia NTS stations

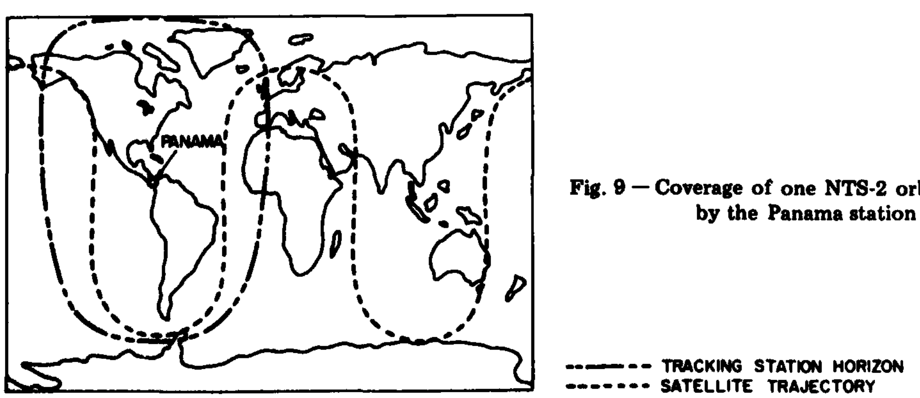

Fig. 9 — Coverage of one NTS-2 orbit per day by the Panama station

THREE-CLOCK ENSEMBLE

Because the expected frequency stability [2] of the spacecraft's cesium frequency standards is near the performance of many commercial standards, a three-clock ensemble was employed at the NTS Panama station. The resultant time scale formed from this ensemble is denoted by UTC(PMA, mean). An ARIMA (0, 1, 1) model [4] was used to process the observations. Figure 10 presents the time difference between each clock in the ensemble and UTC(PMA, mean). Table 2 details the ARIMA parameters for UTC(PMA, mean). In this solution the θ_0 parameter was set to zero. It is expected that the three-cesium-clock time scale will be more stable than a single clock for sampling times in the region of 1 to 10 days.

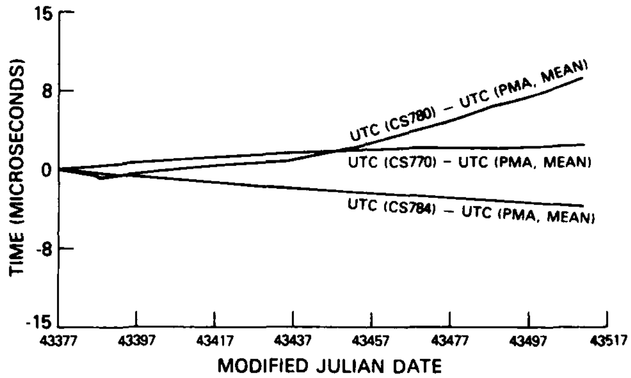

Fig. 10 — Time difference between each clock in the three-clock ensemble at the NTS Panama station and the resultant time scale denoted UTC(PMA, mean)

Table 2 — ARIMA model (0, 1, 1) parameters for the NTS-2 Panama time scale UTC(PMS, mean) (analysis by D. B. Percival, U.S. Naval Observatory)

Clock	Weight (%)	$\hat{\theta}_1$	$\hat{\sigma}_a$
CS770	52	0.64	1.33×10^{-13}
CS780	5	0.58	4.28×10^{-13}
CS784	43	0.84	1.45×10^{-13}

CLOCK-OFFSET ESTIMATION

The measured time difference contains clock-offset information plus other factors that must be measured, modeled, and estimated. The clock offset is evaluated at the time of closest approach (TCA) of the spacecraft to the tracking station. The orbit is determined using the Naval Surface Weapons Center (NSWC) CELEST [5] program. CELEST was primarily designed for processing doppler observations; it has been modified to process time-difference observations. The current procedure employs a maximum satellite pass time of 6-1/2 hours (τ = 23,400 s). The Panama observations for one revolution are split into two segments. These two passes are identified as even revolutions (ascending NTS-2 node) or odd revolutions (descending NTS-2 node). A similar procedure is followed for the other NTS stations. Once a reference orbit has been calculated, a smoothed value of clock offset is made by NRL for the TCA of each satellite pass. These estimates of clock offset are then used to estimate the frequency stability.

CLOCK-DIFFERENCE AND FREQUENCY-STABILITY RESULTS

The clock differences between UTC(NTS) and UTC(PMA, mean) are presented in figure 11. Each point in figure 11 (denoted by X) corresponds to a smoothed estimate for one pass with respect to UTC(PMA, mean). To obtain the offset with respect to the UTC(PMA, mean) time scale, the values with respect to the cesium clock (used as a time and frequency source for the ground-station receiver) were incorporated with its offset from

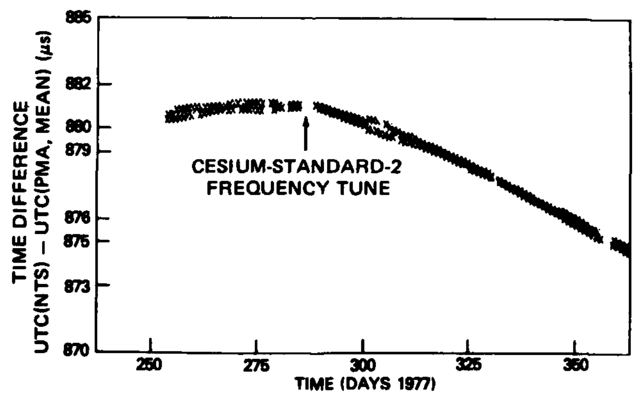

Fig. 11 — Clock differences between UTC(NTS) and UTC(PMA, mean)

the time scale. This procedure employs the stability of an individual cesium clock during a single satellite pass while incorporating the stability of the time scale for sample times of 1 day or more.

A cesium C-field tune of six bits (-7.8×10^{-13}) was applied on day 287, 1977. Figure 12 presents the one-day frequency values with respect to UTC(PMA, mean). In figure 12 the *expected* frequency shift is drawn to scale. The frequency pairs used in calculating the Allan variance (for independent sampling) have been connected as an aid in graphically displaying the results. The results obtained for the even satellite passes (not shown) were similar to the results presented in figure 12. From combining the frequency values for both even and odd revolutions, it was concluded that the C-field tune was unbiased with an uncertainty on the order of the resolution of a one-bit change (1.3×10^{-13}).

The [UTC(NTS) - UTC(PMA, mean)] values were then referred to USNO to obtain values of [UTC(NTS) - UTC(USNO, MC1)]. Figure 13 presents the clock offset for the entire data span. Those values were then used to produce frequency offsets for τ = 4 days

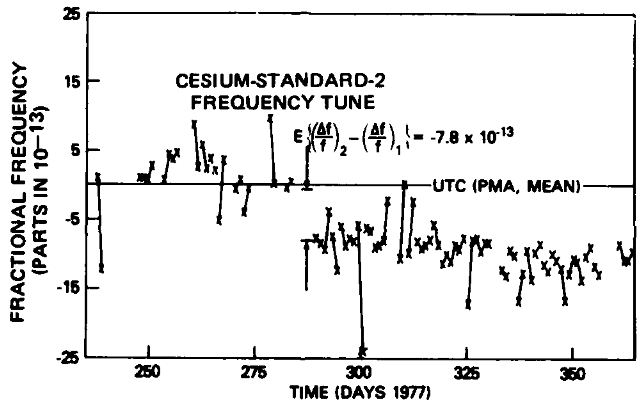

Fig. 12 — One-day frequency offset values (odd revolutions: ascending NTS-2 nodes) with respect to UTC(PMA, mean), showing the effect of the expected frequency shift of -7.8×10^{-13} from a cesium C-field tune of six bits.

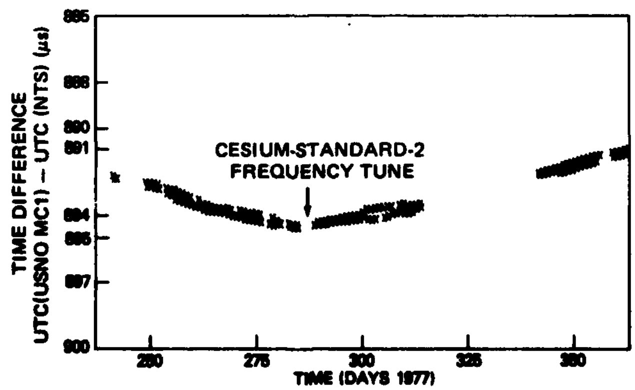

Fig. 13 — Clock differences between UTC(NTS) via the Panama station and UTC(USNO, MC1)

(*figure* 14). Figure 14 indicates either no cesium aging or an extremely small value ($<1 \times 10^{-14}$ per day). Future analysis should result in smoother estimates for the UTC(USNO, MC1) link.

The values of [UTC(NTS) - UTC(PMA, mean)] were then used to calculate $\sigma_y(2, \tau)$ values for $\tau = 1$ day to $\tau = 9$ days (figure 15). Analysis of these results indicates a white-noise value of $(1 \times 10^{-10})/\sqrt{\tau}$ with a flicker floor of 1.7×10^{-13} for $\tau \geq 5$ days.

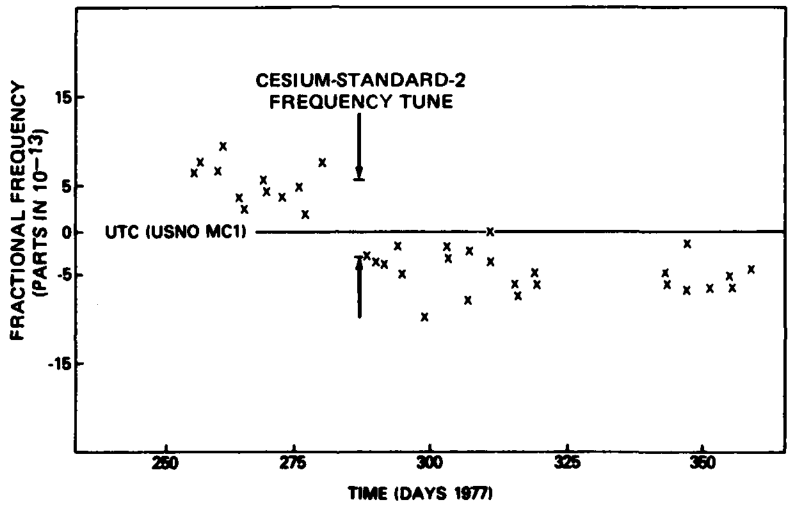

Fig. 14 — Frequency-offset values obtained from Fig. 13 for $\tau = 4$ days

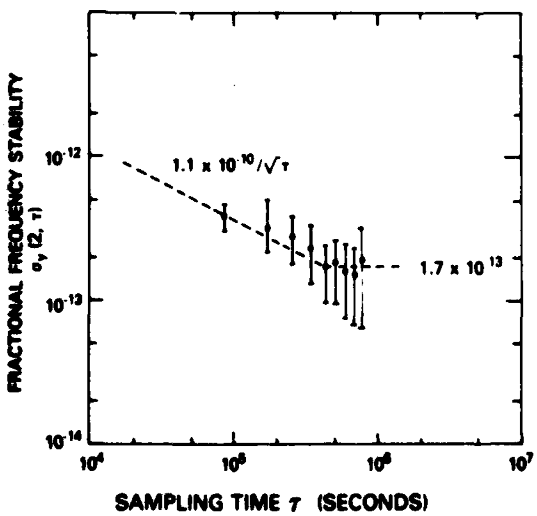

Fig. 15 — Analysis of the stability of the NTS-2 cesium-standard-2 frequency with respect to the time scale determined by the three-clock ensemble at the Panama station. The stability is expressed using the measure $\sigma_y(2, \tau)$ for $\tau = 1$ day to $\tau = 9$ days, which measure is the square root of the Allan variance

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