PRECISE WORLDWIDE STATION SYNCHRONIZATION VIA THE NAVSTAR GPS, NAVIGATION TECHNOLOGY SATELLITE (NTS-1)

James Buisson, Thomas McCaskill, U. S. Naval Research Laboratory, Washington, D. C., Humphry Smith, The Royal Greenwich Observatory, England, Peter Morgan, John Woodger, Department of National Mapping, Canberra, Australia

ABSTRACT

The NTS-1 satellite is currently being employed as a precursor to the phase I concept validation program of NAVSTAR GPS. The assigned tasks include measurement of components of the GPS error budget related to the performance of precise satellite clocks and orbital accuracy obtainable in an eight hour orbit.

Station Synchronization results are presented using stations located in the United States, England and Australia. Results show a time difference noise level of 3 ns. These single frequency measurements, collected over the past year, have been processed to produce station synchronization values between cesium clocks located at each station. A one month data span, using a zero satellite clock update time, produced a noise level of 43 ns, with a systematic bias of 9 ns. The synchronization noise level gradually increased as the satellite clock update time increased. The largest value measured is on the order of 250-500 ns, when comparing clocks located at the Australia station with clocks located at the central U.S.A. station. The method employed in precise station synchronization is sensitive to two components of satellite position error. The results show that long term predictions, on the order of 2-3 months, are possible with only a small increase in station synchronization error.

INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is a DOD program (1) designed to provide precise navigation to a wide variety of military and civil users via a constellation of 24 satellites deployed in sub-synchronous circular orbits of near 12 hr period (2). The Navigation Technology Segment (NTS) of GPS has been assigned the task of validating key concepts and hardware, with special emphasis on space-borne clocks and atomic frequency standards. Phase 1 of GPS employs time difference measurements between four of the spacecraft clocks and the user's clock (Fig. 1).

Navigation Technology Segment (NTS) Results

The NTS-1 satellite (Fig. 2), launched in 1974, has 11 onboard experiments. Results have been reported (3) on the frequency standards performance, which included two Efratom Atomic Rubidium Oscillators, and a Frequency Electronics quartz oscillator. Following this effort, a change was made in the NTS tracking network to check the spacecraft clock performance, orbital accuracy employing only time difference measurements and prepare for the forthcoming NTS-2 launch. Previous NTS-1 satellite clock comparison between USNO and RGO have been reported (4) employing doppler observations to determine the NTS-1 satellite ephemeris.

Through the cooperation of the Royal Greenwich Observatory (RGO) and the Division of National Mapping (DNM) in Australia, NTS permanent ground stations have been located at the respective countries. Inputs to the NTS time difference receivers (5) are obtained from clocks that are part of cesium clock ensembles. These clock ensembles are periodically compared with the USNO UTC time scale via portable clocks and other means. Hence these stations can be used to assess the station synchronization accuracy.

Other operational ground stations are located at the NRL annex (Chesapeake Bay Division) and in the Panama Canal Zone. The NTS control center is located at NRL.

For a one month system closure test an NTS time difference receiver was located at the U. S. Naval Observatory. The receiver was driven with clock inputs from the USNO Master Clock #1. The NTS-1 measurements are collected using a Datapoint 2200 minicomputer; these measurements are subsequently entered into the General Electric International time sharing system. Time comparisons may be routinely calculated through the use of a software program named "International Time Transfer and Station Synchronization" (ITTAS), developed at the Naval Research Laboratory.

Station Synchronization Equations

$$\text{EQ(1)} \quad (\text{USNO-REMOTE}) = (\text{T-0})_{\text{REMOTE}} - [(\text{T-0})_{\text{CENTRAL}} + \frac{d}{dt}(\text{T-0})\Delta t] + (\text{USNO-CENTRAL}) + \text{CAL}$$

Equation (1) gives the start minus stop value, denoted by (USNO-REMOTE), obtained by combining the information from (A) the ground link from the central station clock to the USNO master clock, (B) the satellite link from the central NTS station to the NTS satellite, (C) the satellite clock and orbital trajectory update of the NTS satellite to the remote station and (D) the satellite link to the remote station at the time of measurement. It should be noted that the algebraic sign convention for (USNO-REMOTE) conforms with the recommended Naval Observatory procedure (6). In Eq(1) the (T-0) remote value (3) is obtained by combining the theoretical time difference "T" computed from a measurement model (Fig. 3), which accounts for all known factors except the clock offset, with an observed value "0" (Fig. 4) obtained from the remote time difference receiver, which measures the time difference with respect to the NTS-1 spacecraft. A similar procedure is followed whenever NTS-1 is over the central site to obtain (T-0) Central. The term $\frac{d}{dt}$ (T-0) denotes the frequency of the NTS satellite with respect to the central station clock. Δt is the difference between the time of observation for the NTS-1 satellite as observed from each station. This procedure is illustrated in Fig. 5. The quantity (USNO-CENTRAL) is the measured (or interpolated) value of the central station clock offset with respect to the USNO master clock. The "CAL" value is obtained by measuring the delay through the antenna and receiver systems. Eq (1) may be evaluated at any time that an observation is available, however the time of closest approach (TCA) of the satellite is the preferred time of observation (Fig. 6) for reasons that will be discussed in the sequel. The (USNO-REMOTE) value obtained by the preceeding technique can then be used to set a remote clock, calculate an updated value of the remote clock frequency or incorporate with other time difference measurements to obtain a navigation solution (7).

The (USNO-REMOTE) value may then be combined to produce a value of (USNO-ENSEMBLE), if the offset of the remote clock is known with respect to the ensemble, using Eq (2).

Eq (2) (USNO-ENSEMBLE)=(USNO-REMOTE)+(REMOTE-ENSEMBLE)

Through the use of Eq (2) for a collection of measurements, the variance of (USNO-ENSEMBLE) may be calculated. Hence a sigma value can be obtained to estimate the weight to be assigned the NTS-1 station synchronization values when incorporating remote clock ensembles in a master clock ensemble or in a time scale.

Time Transfer Geometry at TCA

A typical pass (Fig. 4) of NTS-1 yields time difference measurements with respect to the NTS-1 satellite clock for a 2.5 hour span. Hence these measurements can be combined with the satellite clock information, satellite ephemeris and central station measurements to yield the offset (USNO-REMOTE) values for a 2.5 hour data span.

Assuming the satellite link and central link information is available, Eq (1) may be evaluated for any of these measurements to produce a value of (USNO-REMOTE). For PTTI applications involving long term comparisons of time scales it is computationally efficient to produce a single value of (USNO-REMOTE), with an associated variance, that is subsequently processed in a time scale algorithm. Previous experience has indicated that the evaluation of a single number for clock offset at the time of closest approach (TCA) to the remote station is a good choice. The reasons for choosing TCA are as follows: (1) uncertainties in the ionospheric and tropospheric delays are minimum because the satellite is at a maximum elevation angle with respect to the station, (2) the data is symmetric about TCA, and (3) the contribution of the satellite position error along the satellite velocity vector is minimized because, at TCA, the range rate is zero (Fig. 6).

USNO System Closure Results

A three week system closure test was conducted at the U.S. Naval Observatory (USNO) commencing on day 89, 1976. This test is a special case of the usual procedure depicted by Fig. 7. The normal use of NTS-1 entails use of the satellite clock to transmit a time signal to a remote location, thereby requiring a satellite clock and ephemeris update to the time of the remote observation. For the USNO test, a time difference receiver was physically located at

USNO, using a 5 MHz signal and a 1PPS derived from the USNO master clock #1. Because of the proximity of USNO to NRL and the NRL central station located at the NRL annex (CBD), simultaneous observations were possible from three stations. The use of simultaneous observations of the NTS-1 signal allowed time to be transferred with a zero satellite clock update time.

The station synchronization results of the three week USNO test are presented in Fig. 8, using the complete link, with a value of zero for the satellite clock update time. The results show a systematic error and noise level of much less than 1 microsecond, hence an expanded plot of the same results is presented in Fig. 9. A small systematic bias of 9 nanoseconds (ns) with a one sigma noise level of 43 ns was measured. In the plots of Figs. 8 and 9, each point represents the value obtained from one complete 2.5 hr NTS-1 satellite pass as observed from USNO and the central NRL CBD site.

These resultant values are used in Eq (1) where remote = USNO (NTS) to designate the remote receiver located at USNO. This procedure thus allowed a measurement of the NTS-1 systematic error. Analysis of Fig. 9 shows a systematic signal is present in the residuals hence analysis was continued to estimate the random component due to the measurement error. Fig. 10 presents measurements taken with receivers at USNO and CBD for a single 2.5 hr pass. The difference calculations did not include an estimate of the central station offset with respect to USNO, which was about 6.7 μsec (Fig. 10) at the time of the pass.

The very small systematic effect (note: 1 ft ≅ 1 ns) displayed in Fig. 10 is thought to be due to a slight difference in antenna coordinates for each receiver, which would give a different effect depending upon pass geometry. A cubic polynomial was fitted to the data to remove the systematic error and Fig. 11 presents the random time difference measurement error due to both receivers. A one sigma value of 5 ns was measured, which results in 3 ns random error for each receiver.

Royal Greenwich Observatory (RGO) Results

Fig. 12 presents the results from RGO obtained using the NTS-1 satellite and the RGO station clock designated RGO (JP). The data span is the same used for the USNO experiment. The measurements in Fig. 12 exhibit an RMS value of 211 ns. A longer time span (40 days) employing satellite passes is presented in Fig. 13 to obtain better statistical significance on the measurement. The longer time span exhibits a systematic effect that will be discussed later. Fig. 14 depicts the cesium clock ensemble used to obtain UTC (RGO). Outputs from RGO (JP) are used to drive the NTS-1 time difference receiver. Hence the USNO ensemble can be compared to the RGO ensemble via the NTS-1 satellite using the values of (RGO(JP)-UTC(RGO)) as given by Fig. 14. Eq (2) can be used to evaluate this comparison at any convenient epoch. This was done for day 108, 1976 at 00hr and yielded a value given by Eq (3).

Eq (3) $\mathrm{UTC(USNO\ MC\#1)-UTC(RGO)} = -3.578\mu\mathrm{SEC}(-0.0509\mu\mathrm{SEC/D}) * (T-108)$.

The accuracy of this result can be estimated by using interpolated values from portable clock closures. The first of two closures was on MJD42702.3(17 Oct 1975) with a value of $-2.2(\pm)1\mu$SEC. The other closure, given in USNO series 7, #447, on MJD42965.5 (6 July 1976) has a value of $-4.4(\pm)1\mu$SEC. Interpolation to day 108, 1976 yields a value of -3.726μSEC. Comparison with the NTS-1 determination gives a difference of -148 nanoseconds, with respect to NTS-1.

The (USNO-RGO(JP)) measurements exhibited a noise level of 211 ns., which is considerably larger than the value obtained with zero satellite clock update. Further analysis of the data indicated that a small equipment problem was present during this data span which effectively increased the measurement noise from a nominal value of 3 ns up to 10-20 ns. This increase accounts for only a small part of the 211 ns. The additional factors include the satellite clock and ephemeris update, and the use of a single frequency time difference measurements at a nominal frequency of 335 MHz. Previous analysis (3) indicates that the use of single frequency measurements, which prevent accurate measurement of ionospheric delay, is the dominating factor for the 211 ns. noise level.

The (RGO-RGO(JP)) measurements exhibited a one sigma noise level of 12 ns for the 30 day time span from day 90 to day 120, 1976. (Fig. 15) The (RGO-RGO(JP)) noise level is small as compared to the (USNO-RGO(JP)) noise level, therefore, the approximate value of the (USNO-RGO) one sigma value is 211 ns. Hence the (USNO-RGO) time comparisons are to be assigned a weight of 211 ns when incorporating the individual measurements in a time scale algorithm.

Australia Division of National Mapping (DNM) Results

Previous satellite time comparisons between USNO and DNM have been reported (8) employing the low-altitude TIMATION-II satellite. Fig. 16 presents a comparison between USNO and the DNM clock designated as AUS(205) for a time span that overlaps the three week span at USNO. Fig. 17 presents a composite plot of 60 days of (USNO-AUS(205)) measurements. Fig. 18 presents a plot of 40 days of data that used predicted ephemeris with a more recent epoch. The value of (USNO-AUS(205)) to be used for comparison with a remote linkage closure to USNO on day 114, 1976 is an extrapolated value using the (USNO-AUS(205)) measurements given in Fig. 18. The value of (AUS(205)-AUS) was supplied by the Division of National Mapping to be -77.270 μSEC for day 114, 1976. Eq (4) gives the NTS-1 determination for (USNO-UTC(AUS)) for an epoch of day 114, 1976.

EQ (4) $$UTC(USNO\ MC\#1)-UTC(AUS)=-23.112\mu SEC-(0.0717\mu SEC/D)*(T-114)$$

The closure on day 114 gives a value of -23.23 μSEC. This closure was obtained by several links to the DNM/NTS station. Comparison of this value with the NTS-1 determination yields a difference of +118 ns, with respect to NTS-1.

A one sigma noise level of 265 ns was measured for the (USNO-AUS(205)) during the 40 day span given in Fig. 18. Significant statistics on the (AUS(205)-AUS) noise level were not available hence it is assumed that the noise level is small as compared to the (USNO-AUS(205)) sigma value. The approximate (USNO-AUS) noise level for the NTS-1 is 265 ns.

Ephemeris Prediction Results

The comparison of two remote time scales via NTS-1 permits calculation of noise levels for the time scale comparisons, such as one sigma values for (USNO-RGO) and (USNO-AUS). Analysis of the complete link from USNO to a remote site permits link errors to be estimated assuming that the time scales involved are more stable than the satellite link. The technique of calculating comparisons at TCA minimizes the satellite ephemeris contribution along the satellite velocity vector, however the measurement remains sensitive to the two remaining components of ephemeris position. Each individual residual from a collection of time comparisons yields an error along the radial vector

$\bar{\rho}$ given in Fig. 6. Successive observations for different satellite passes occur at different elevation angles with respect to the station, hence successive observations span the plane perpendicular to the velocity vector at TCA. According to Eq (1) evaluated at the times of central and remote observation, differences in the satellite trajectory enter in to (USNO-REMOTE) values. Then using Eq (2) the measurements may be referenced to the difference in the stable time scales.

The satellite ephemeris used to calculate the (USNO-AUS(205)) values given in Fig. 16 was 60 days from epoch (9). The (USNO-AUS(205)) values given by Fig. 18 have a more recent epoch, hence the decrease in one sigma noise level from 689 ns (Fig. 16) to 265 ns (Fig. 18) can be attributed to improved satellite ephemeris. Reference to Fig. 17 shows that combining measurements from the two ephemerides results in a small change in (USNO-AUS(205)). This small difference is further illustrated by comparing the values of (USNO-AUS(205)) calculated from the measurements given by Fig. 18 and Fig. 16 for an epoch of day 129, 1976. A small difference of 440 ns is attributed to the 60 day satellite ephemeris update. This result verifies that long term orbital predictions with small error are possible as indicated by previous NRL analysis (10).

Conclusions

1. The NTS-1 Worldwide station synchronization accuracy, using predicted satellite ephemeris calculated using only 335 MHz time difference observations, is 10 ns for stations near the central station and increases to about 100 ns for stations half-way around the earth.

2. The one sigma synchronization noise level depends on satellite clock update time. A one sigma value of 43 ns was measured with zero satellite clock update; the largest value measured was 265 ns (Fig. 19).

3. Time difference measurements exhibit a one sigma value of 3 ns.

4. Long term (60 day) satellite ephemeris predictions have been verified for two components of satellite position.

5. Work is continuing on this project and further improved accuracy and precision is expected to be obtained with the launch of the NTS-2 spacecraft (Fig. 20) in 1977.

Acknowledgements

The authors acknowledge the technical support of Mr. D. W Lynch, NRL, Mr. Dick Anderle, NSWC and the guidance of Mr. R. L. Easton, NRL NAVSTAR GPS Program Manager.

Further acknowledgement is given to the personnel from NRL, USNO, RGO and DNM who assisted with their efforts in data collection and processing. Special recognition is given to Mr. Hugh Warren and his colleagues from the Bendix field engineering.

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Figure 19 NTS-1 Synchronization Noise Level versus Satellite Clock Update Time

Figure 20 NTS-2

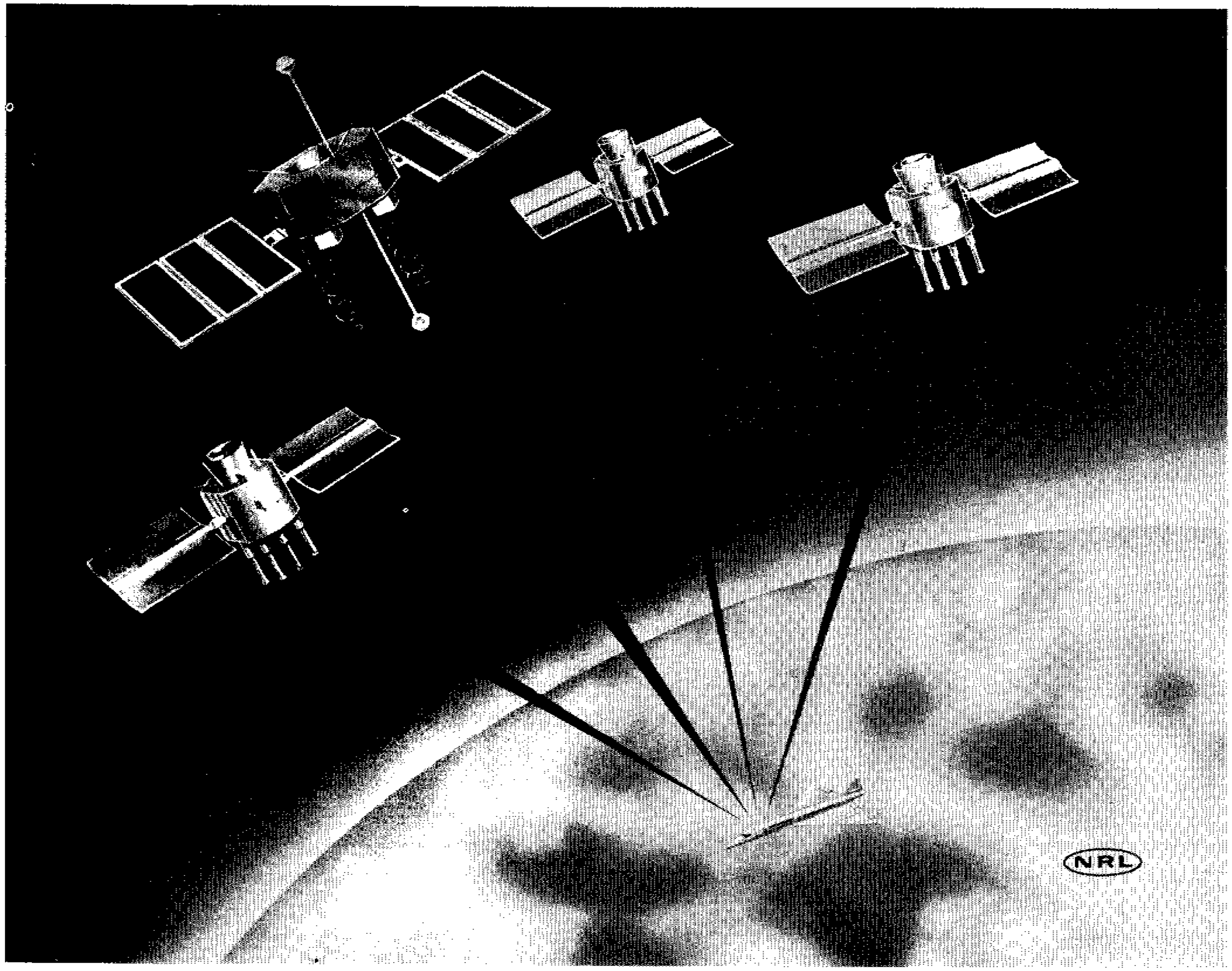

Figure 1. Four GPS Satellites

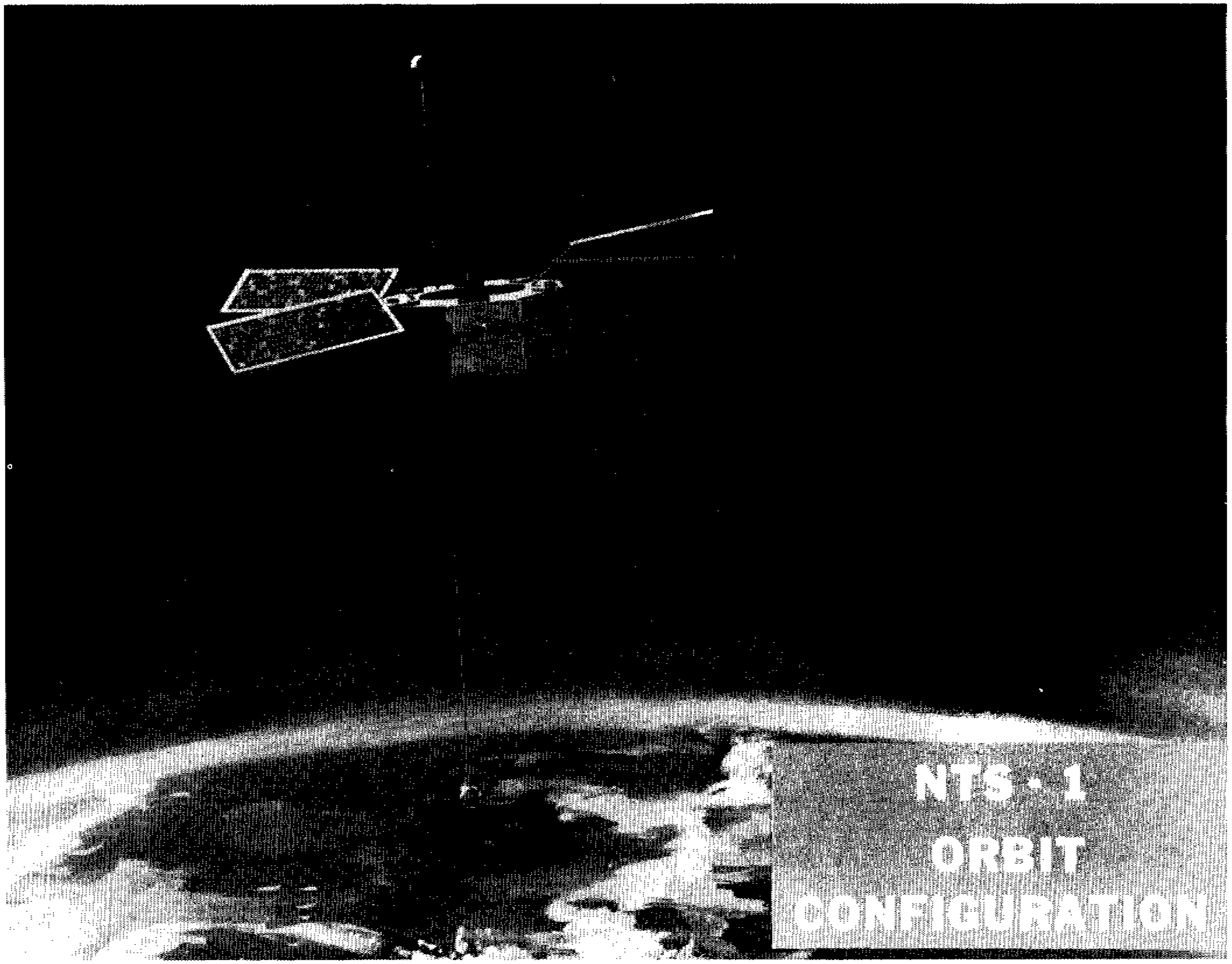

Figure 2. Navigation Technology Satellite 1 (NTS-1)

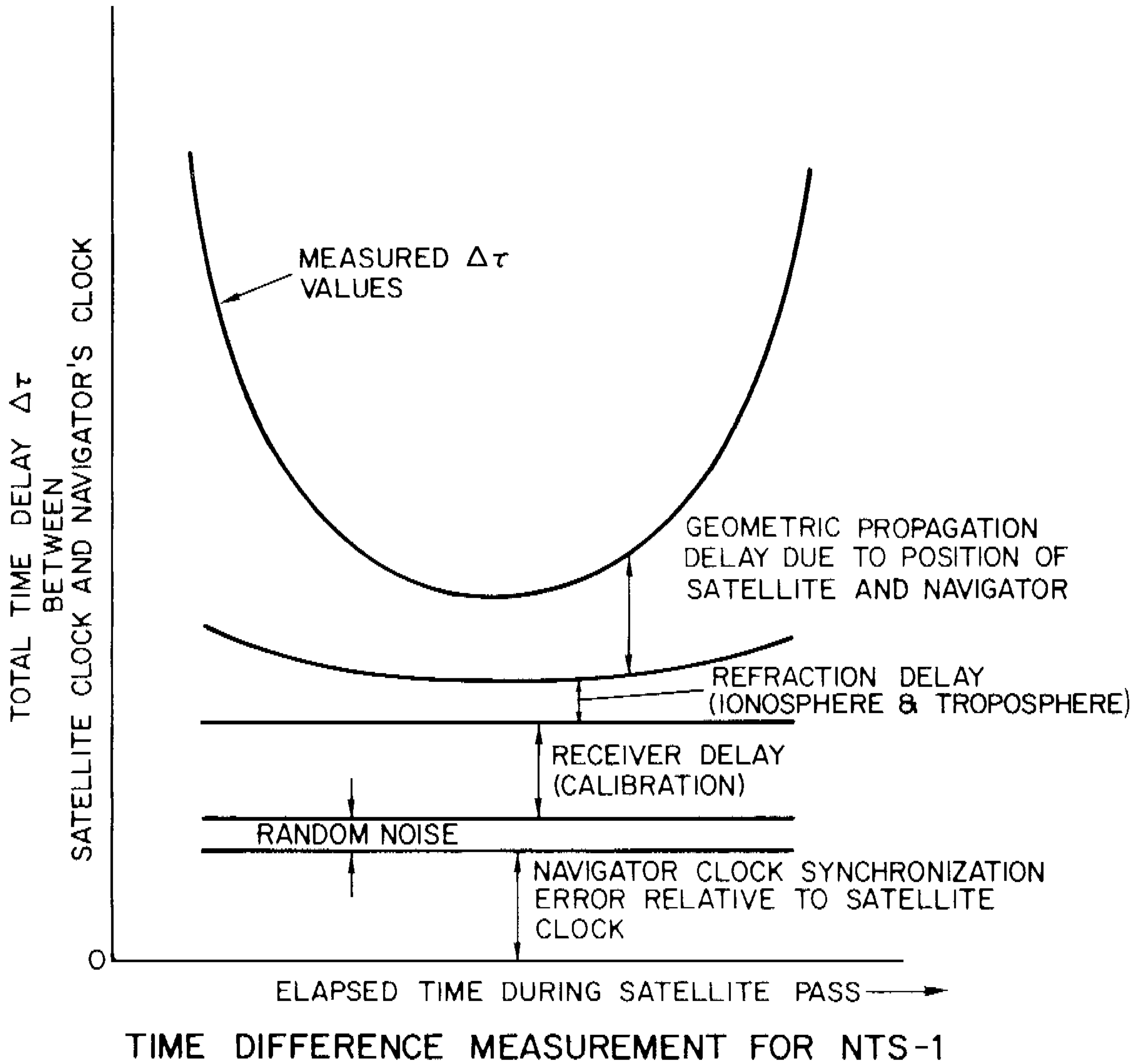

Figure 3. Time Difference Measurements

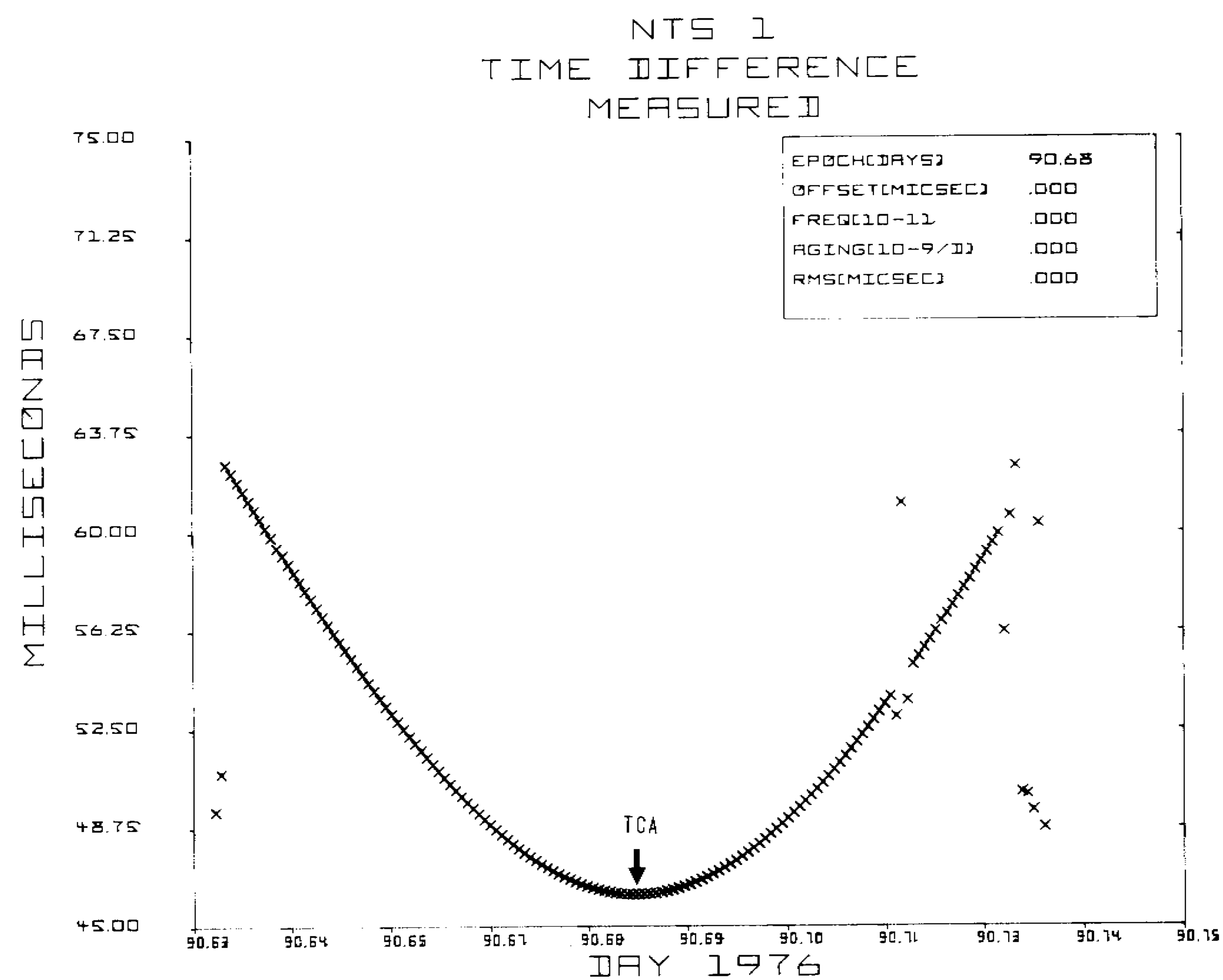

Figure 4. Typical NTS-1 Satellite Pass

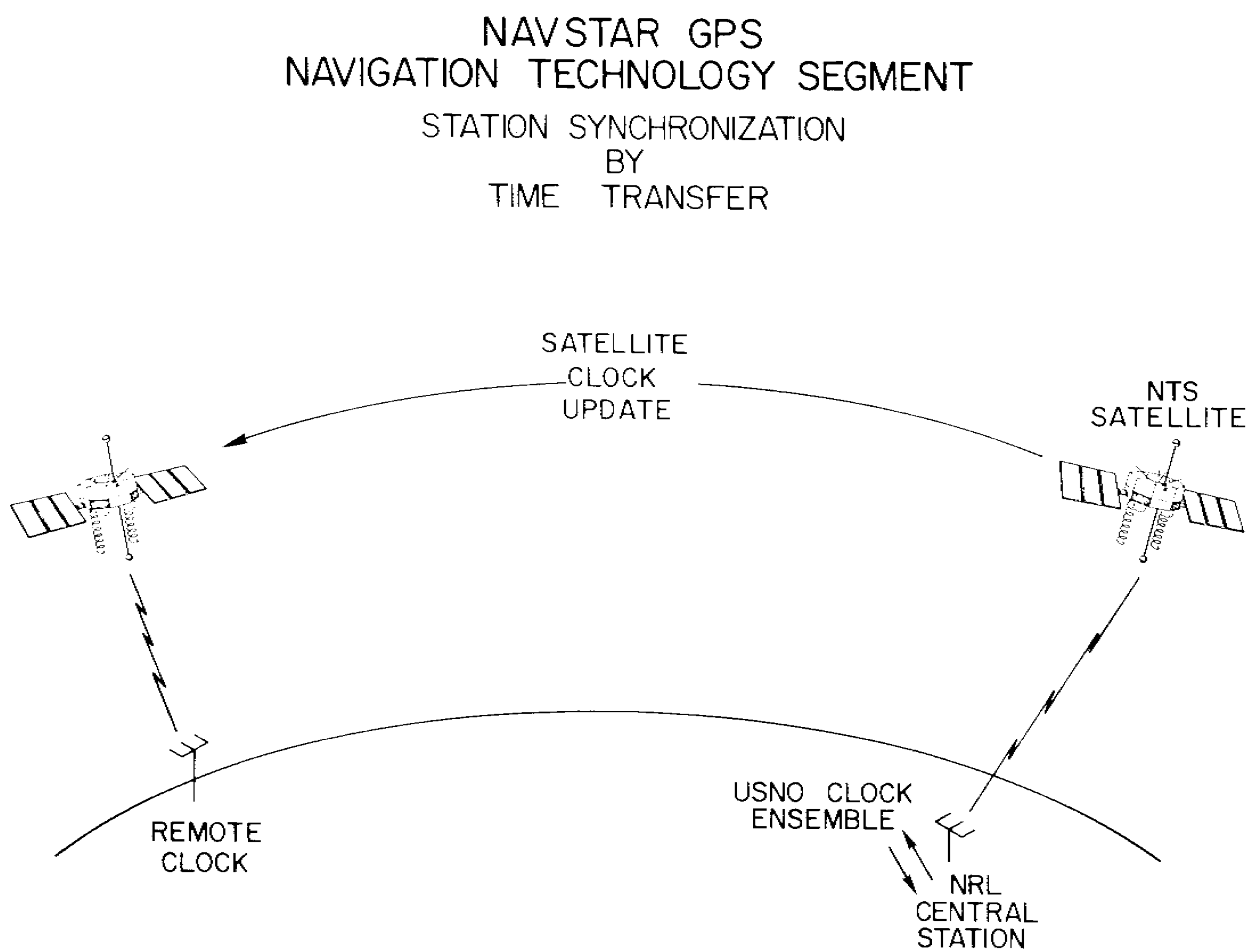

Figure 5. Station Synchronization by NTS

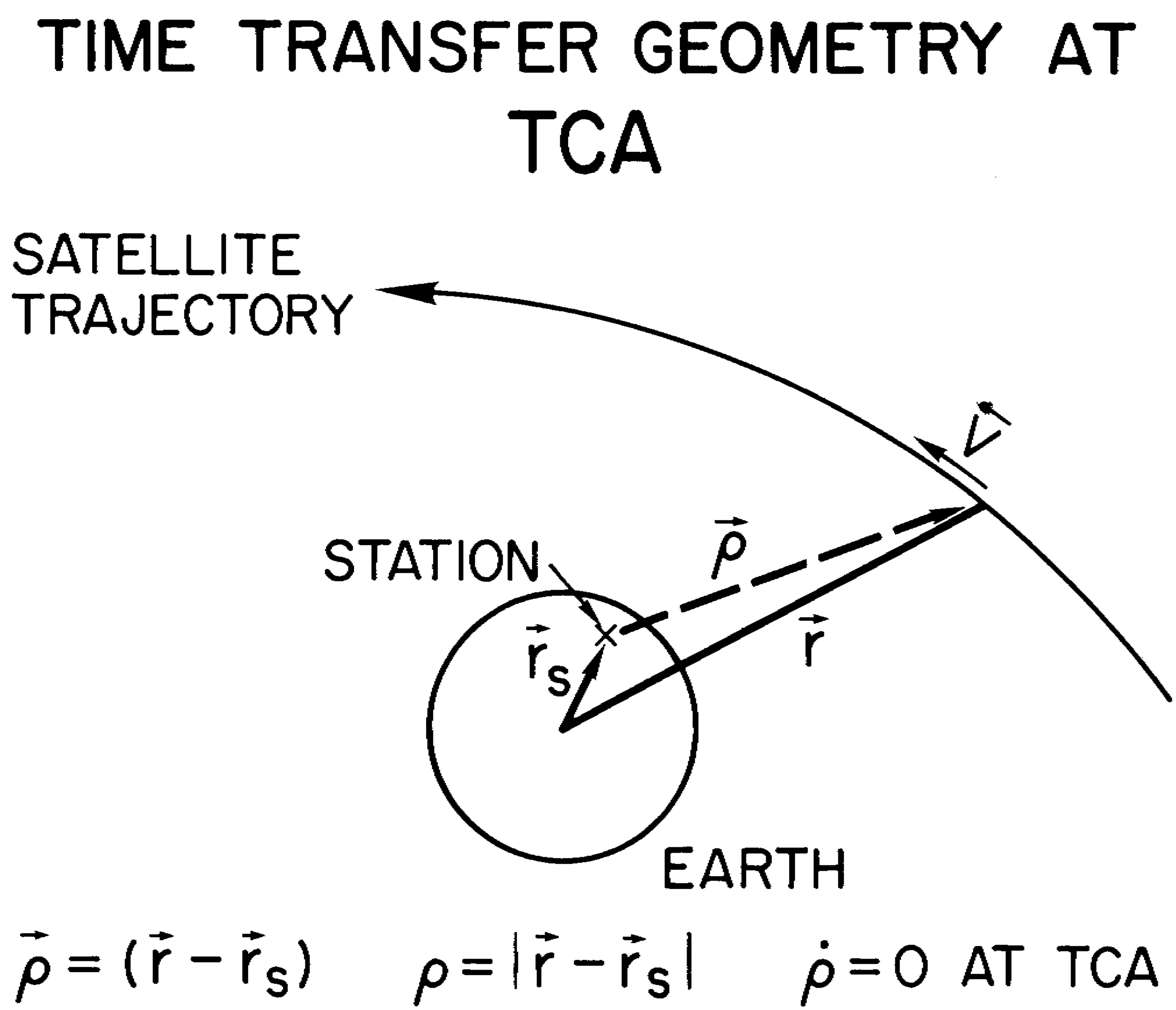

Figure 6. Time Transfer Geometry at TCA

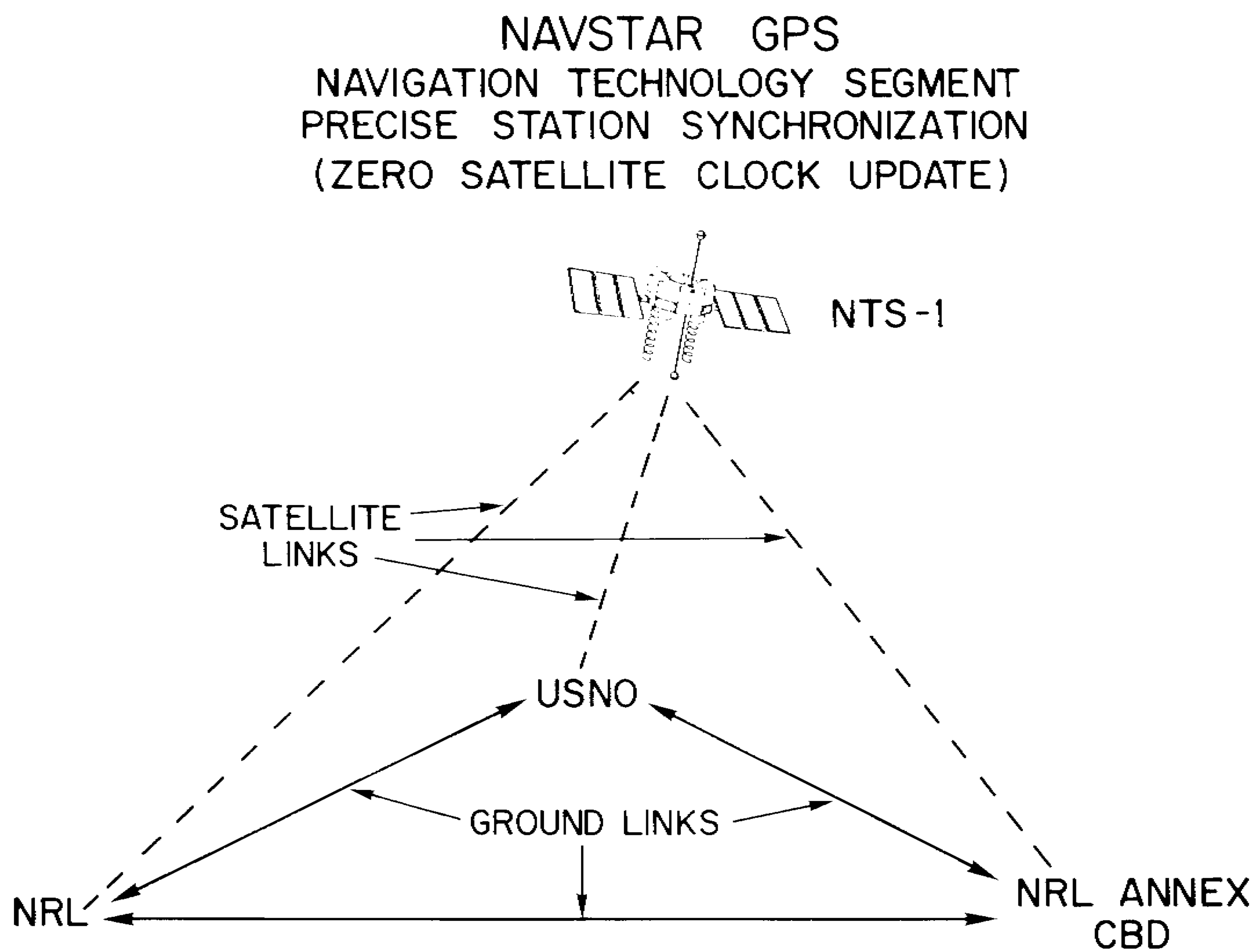

Figure 7. Station Synchronization with Zero Clock Update

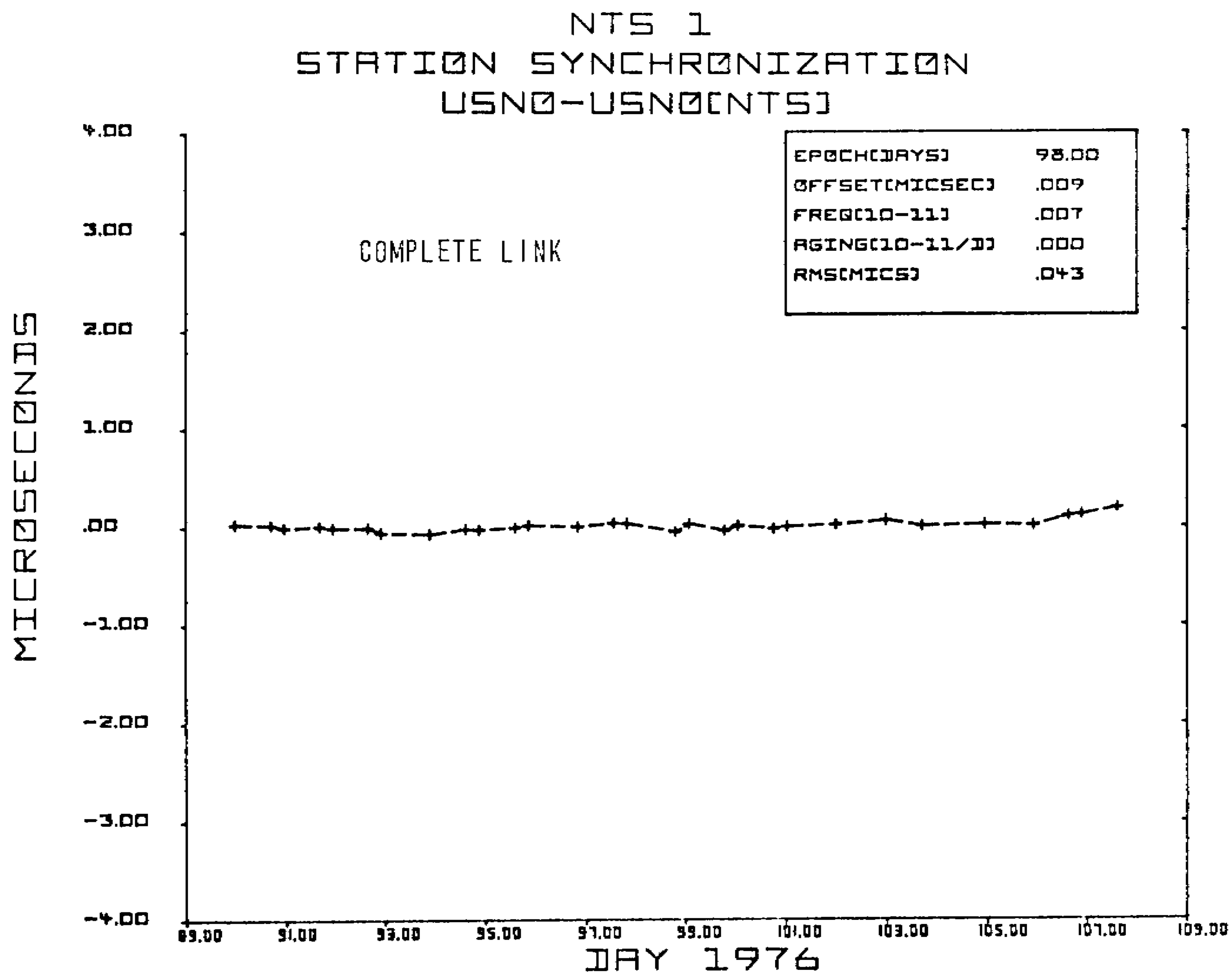

Figure 8. USNO-USNO (NTS)

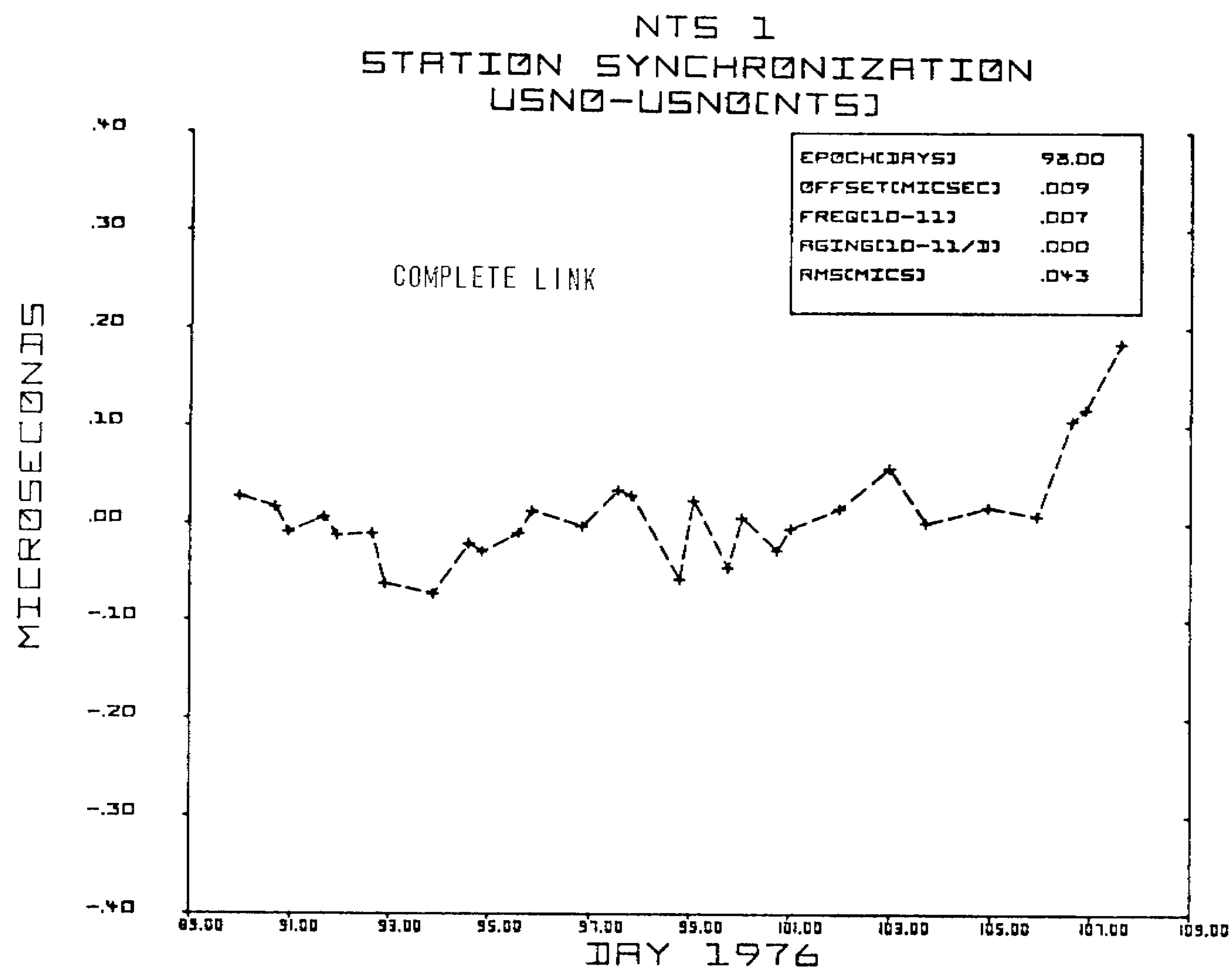

Figure 9. USNO-USNO (NTS)

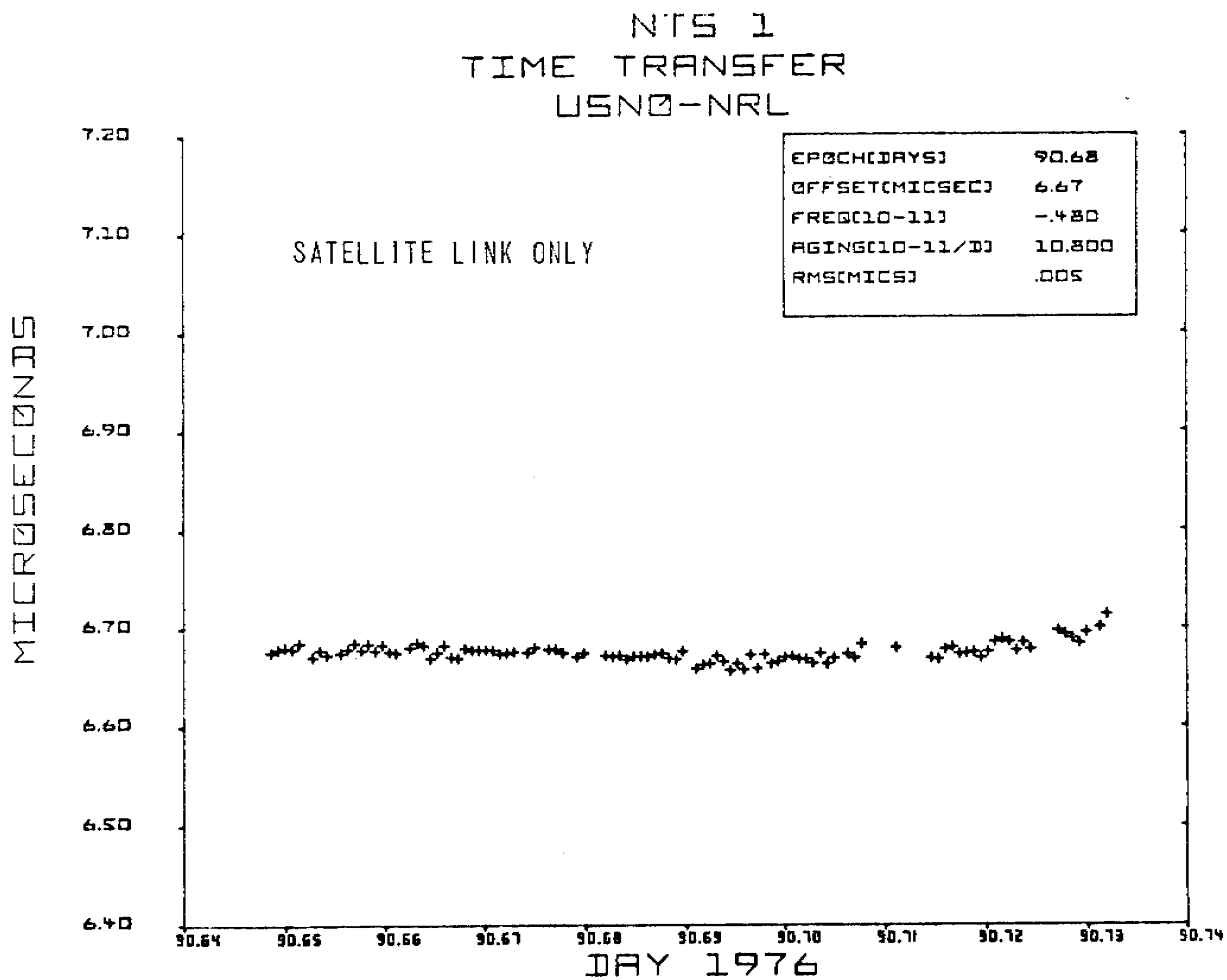

Figure 10. USNO-NRL

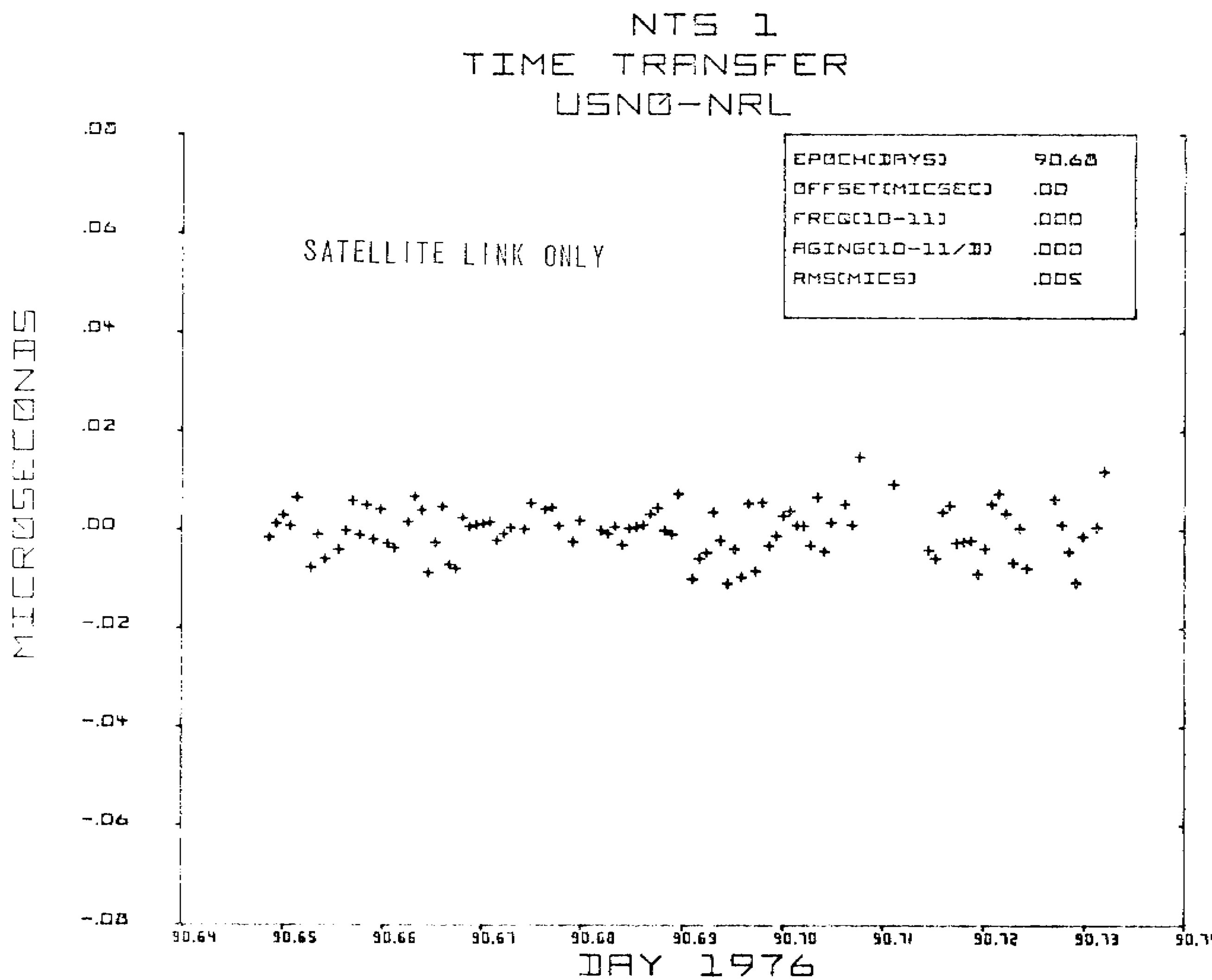

Figure 11. (USNO-NRL) Residuals

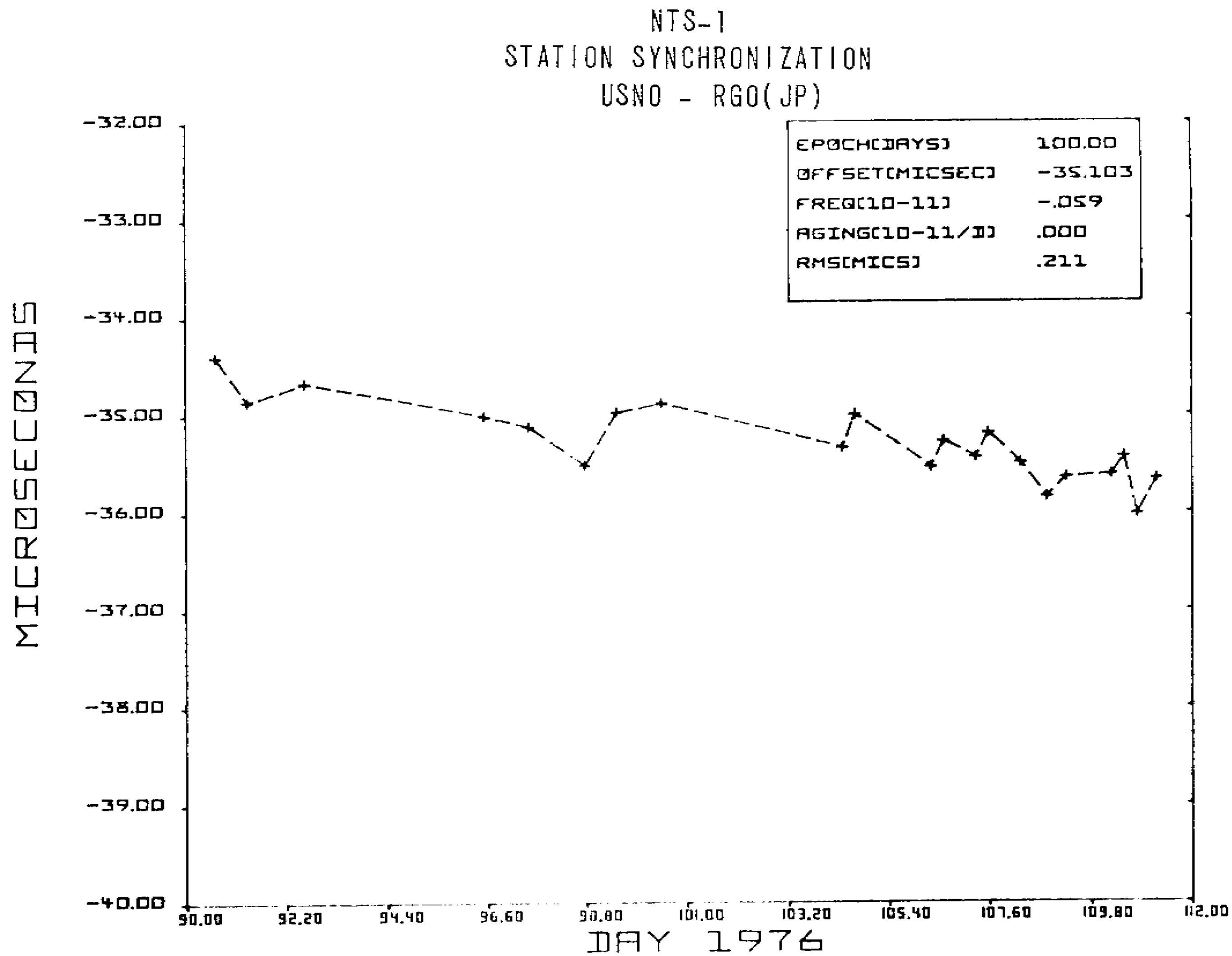

Figure 12. USNO-RGO (JP) Day 90-112, 1976

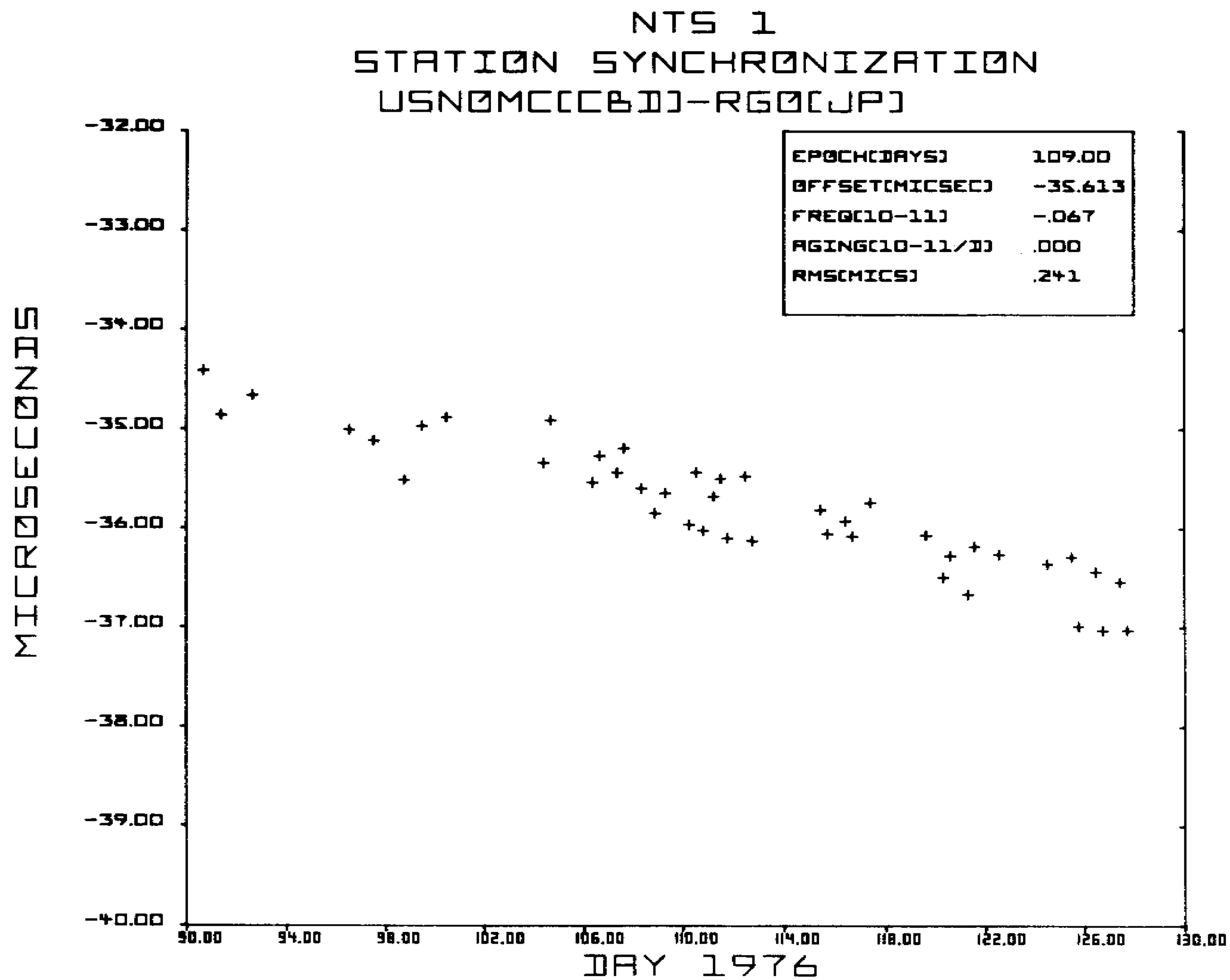

Figure 13. USNO-RGO (JP) Day 90-130, 1976

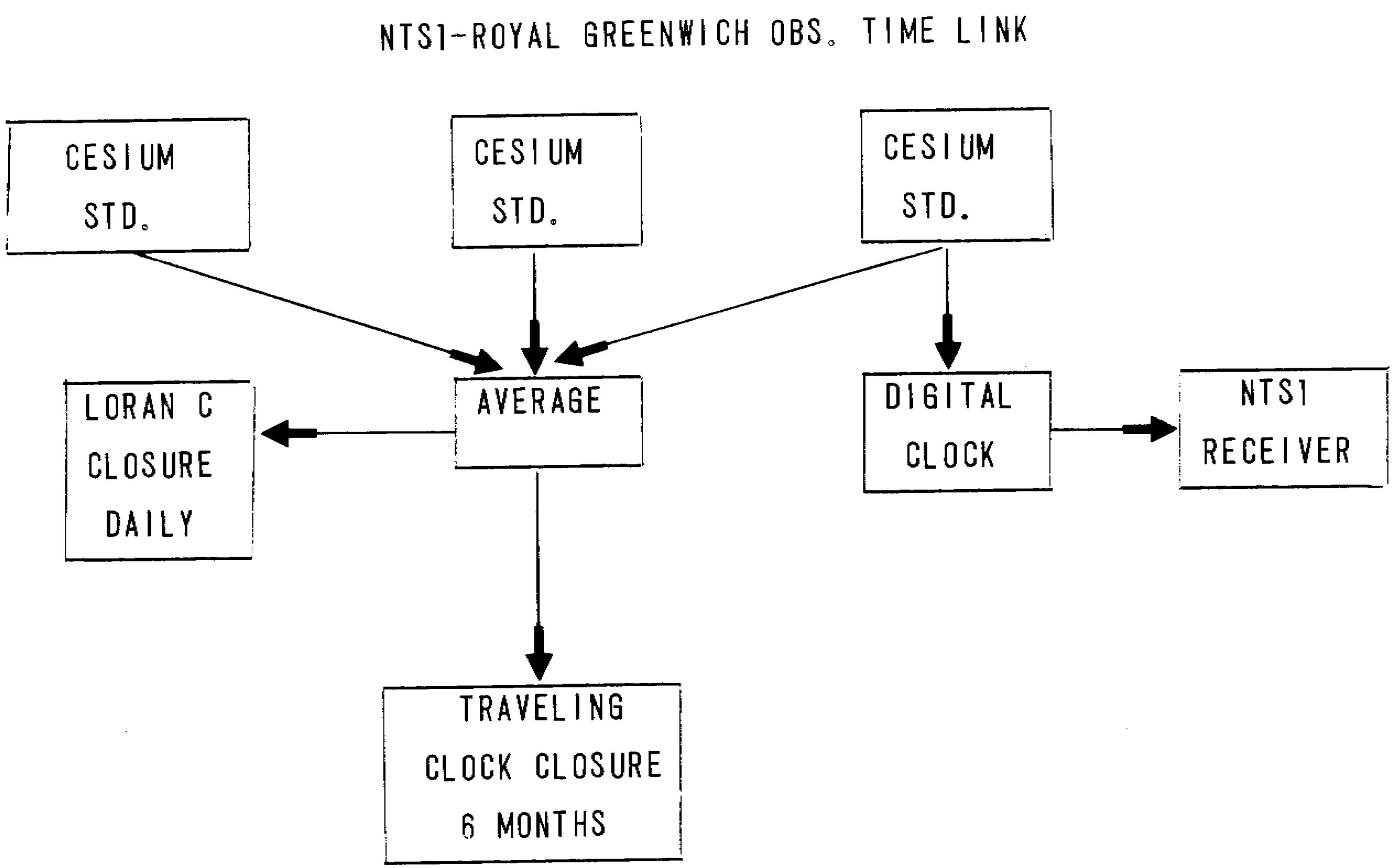

Figure 14. GRO-NTS Time Link

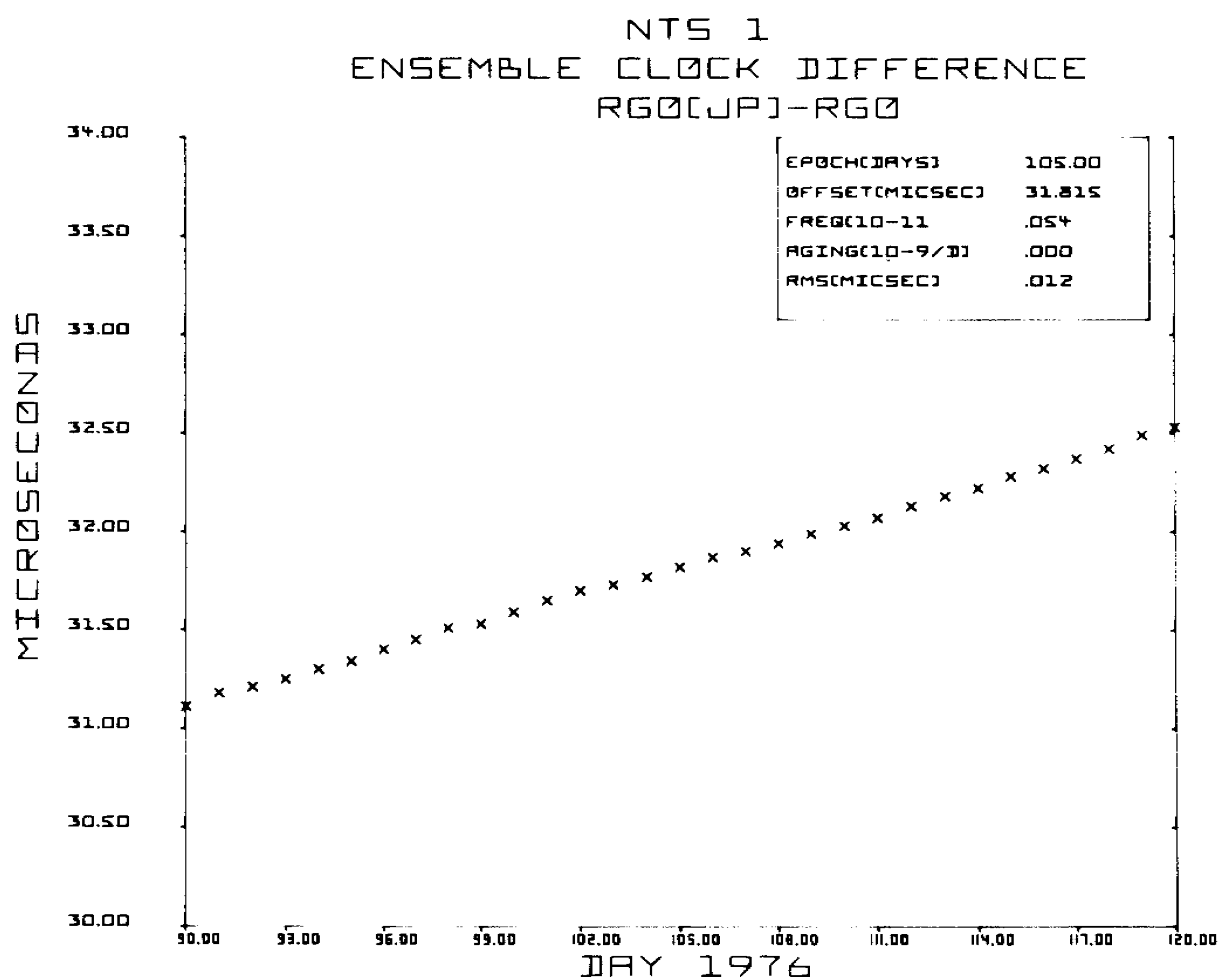

Figure 15. RGO Clock Ensemble

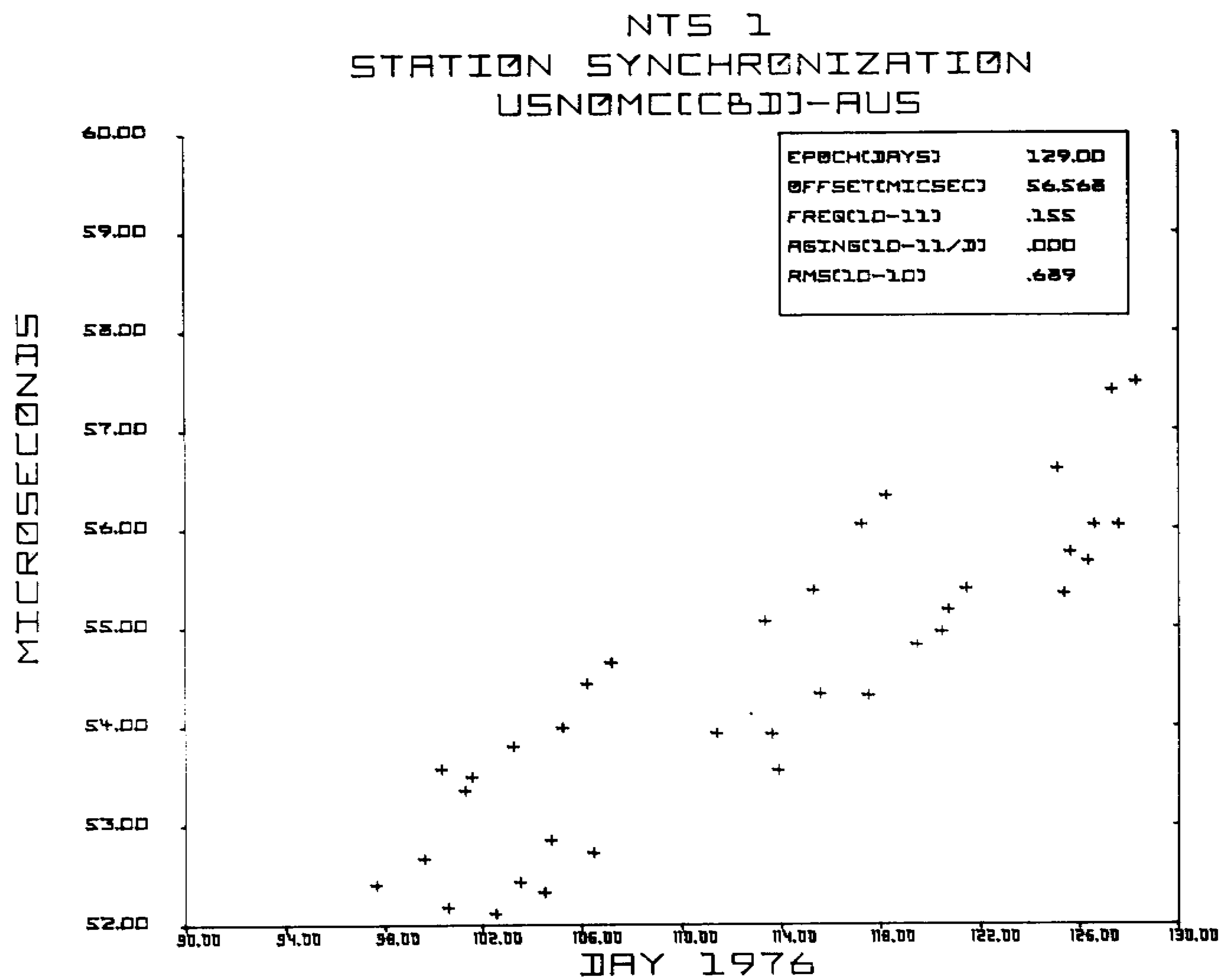

Figure 16. USNO-AUS (205) Day 98-129, 1976

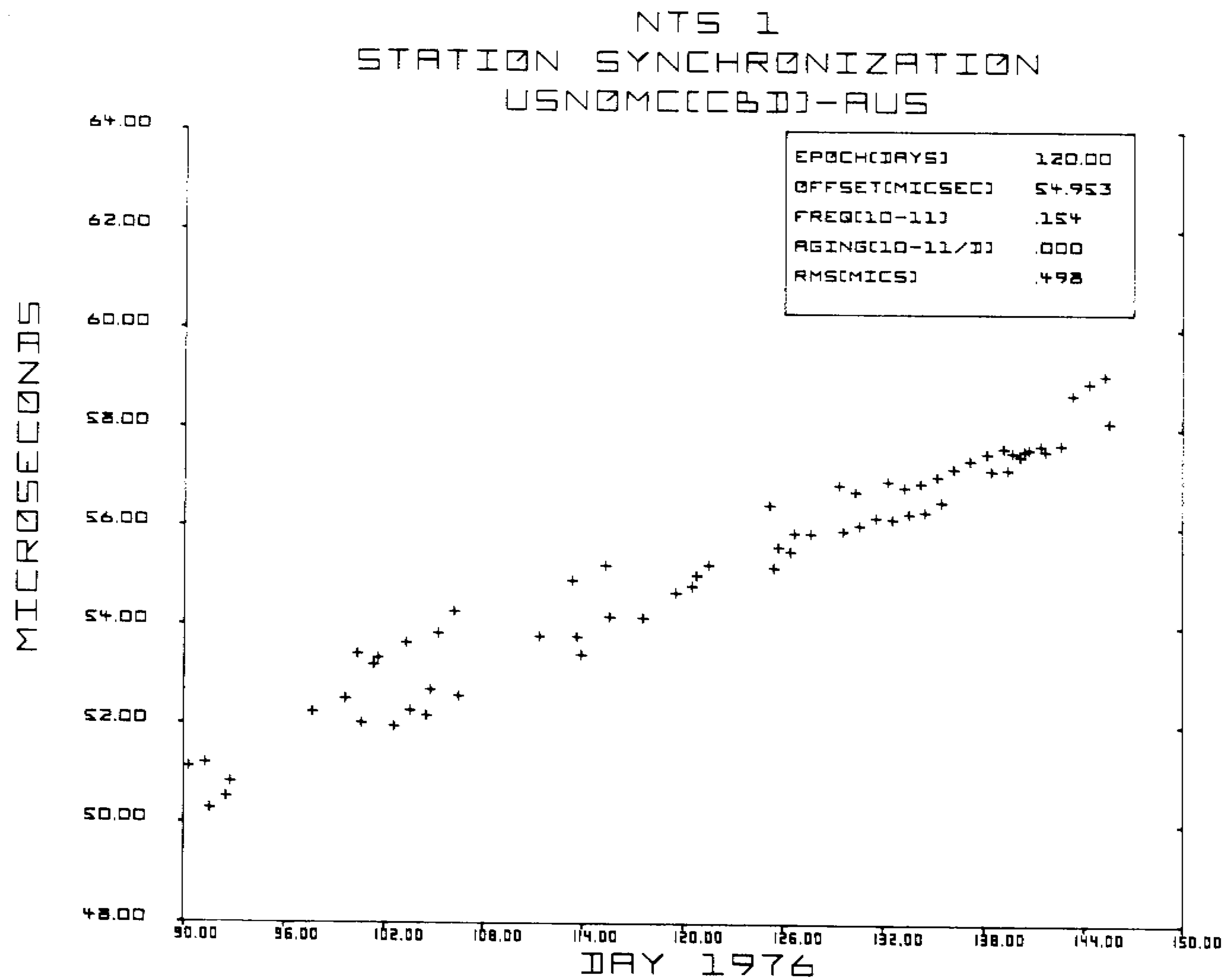

Figure 17. USNO-AUS (205) Day 90-150, 1976

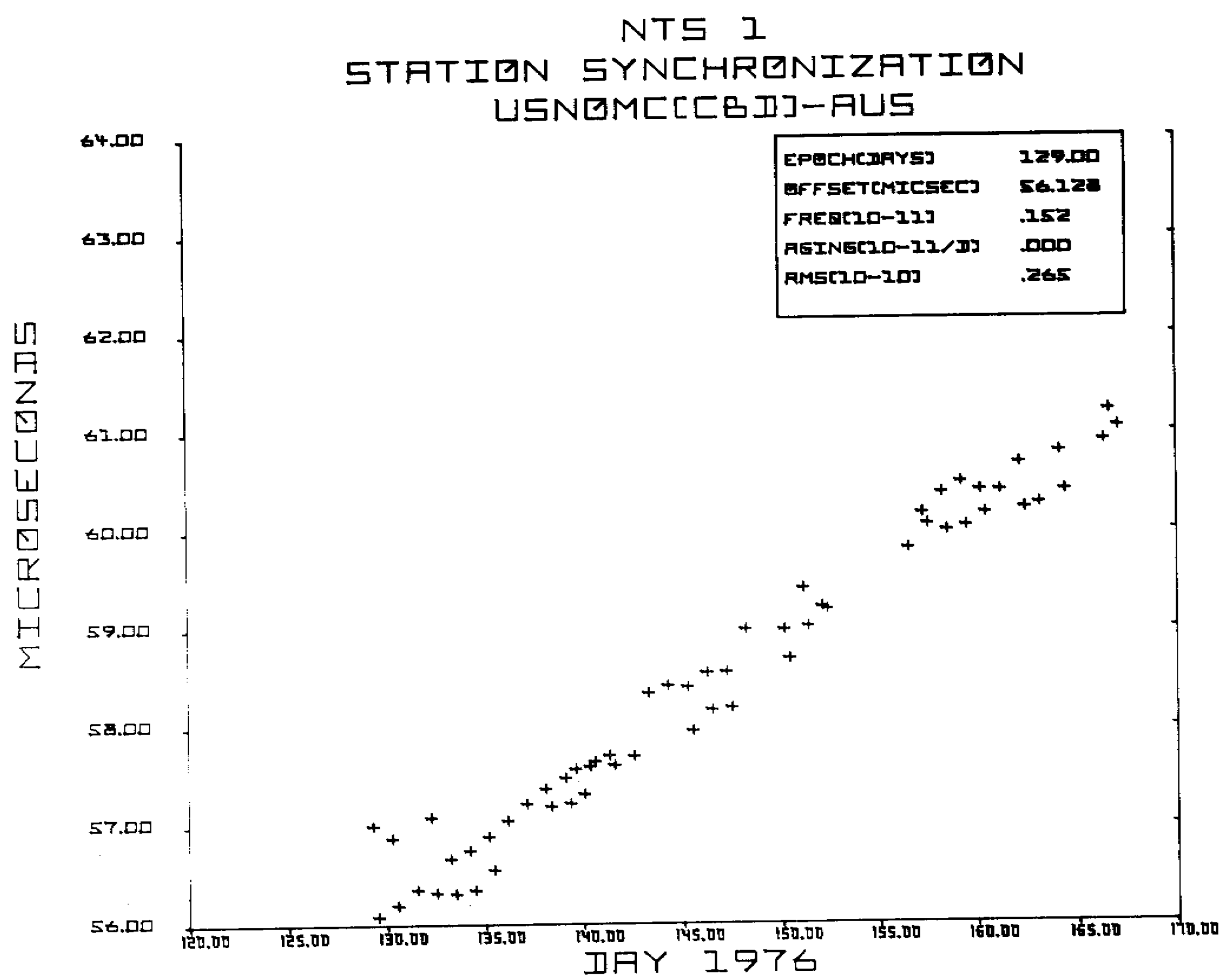

Figure 18. USNO-AUS (205) Day 130-170, 1976

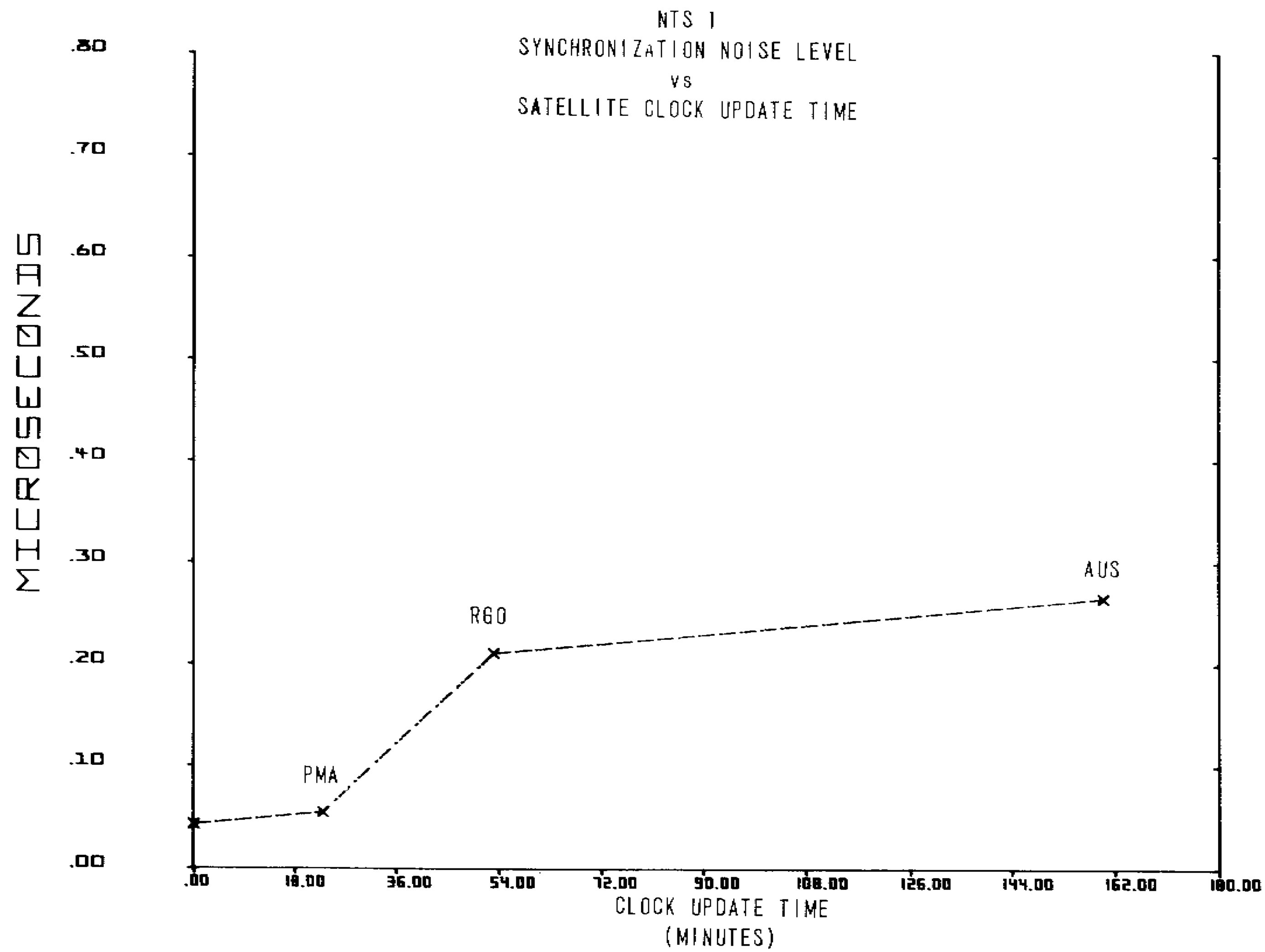

Figure 19. NTS-1 Synchronization Noise Level versus Satellite Clock Update Time

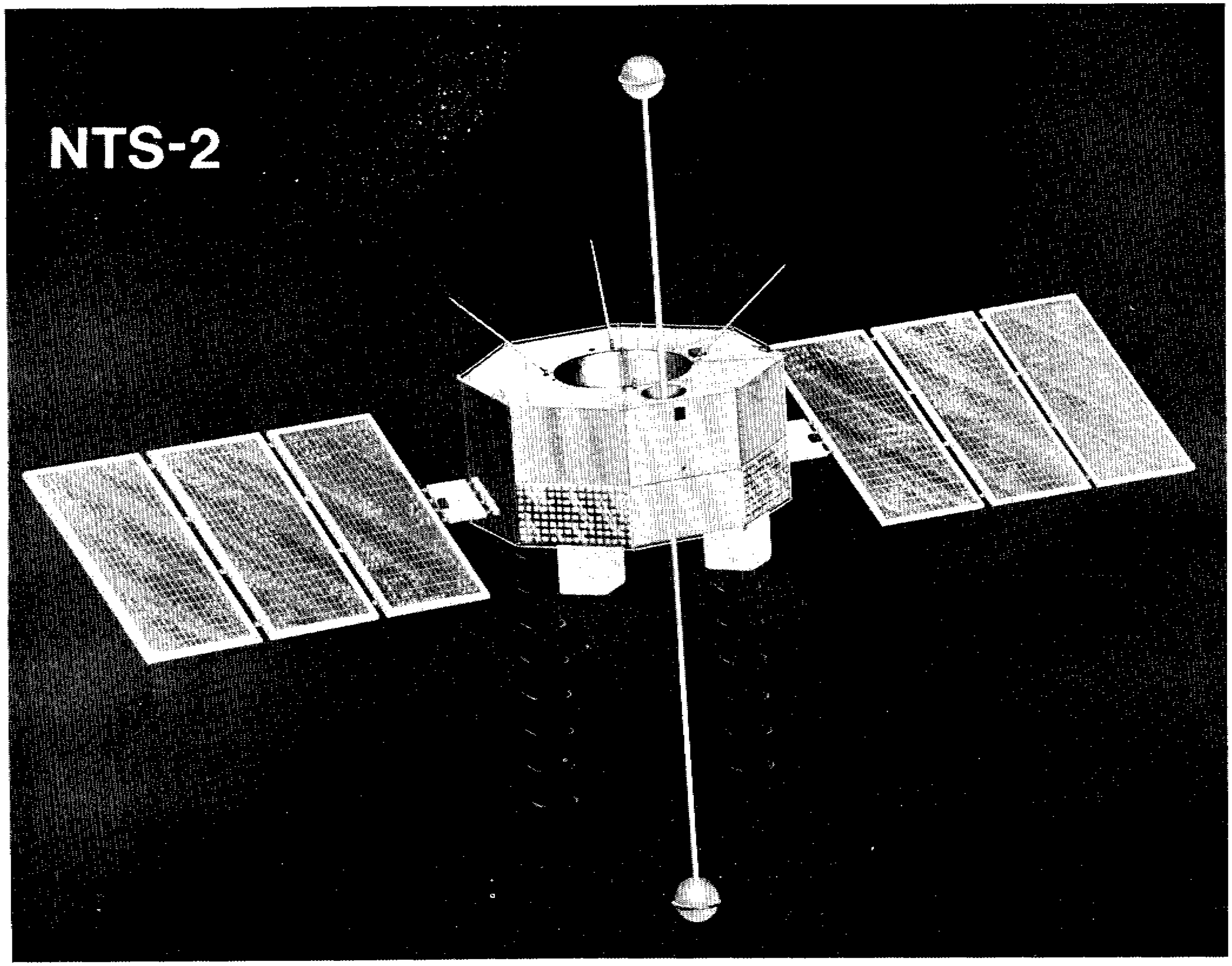

Figure 20. NTS-2