GLOBAL POSITIONING SYSTEM TIME TRANSFER RECEIVER (GPS/TTR) PROTOTYPE DESIGN AND INITIAL TEST EVALUATION

J. Oaks, A. Frank, S. Falvey, M. Lister, and J. Buisson
Naval Research Laboratory
Washington, D. C.

C. Wardrip
NASA Goddard Spaceflight Center
Greenbelt, Maryland

H. Warren
Bendix Field Engineering Corporation
Columbia, Maryland

ABSTRACT

Time transfer equipment and techniques used with the NRL Navigation Technology Satellites have been modified and extended for use with the GPS satellites. A prototype receiver was built and field tested at NASA's Kennedy Spaceflight Center.

The receiver uses the GPS L1 link at 1575 MHz with C/A code only to resolve a measured range to the satellite. A theoretical range is computed from the satellite ephemeris transmitted in the data message and the user's coordinates. Results of user offset from GPS time are obtained by differencing the measured and theoretical ranges and applying calibration corrections. These results may be referenced to Naval Obsrvatory Time through published values of offsets of GPS Time from USNO Master Clock 1.

Results of the first field test evaluation of the receiver are presented. Measurements were made at NASA Goddard's MILA facility located in the Kennedy Spaceflight Center, Fla. Portable clock measurements were made for comparison, and all measurements were referenced to the Naval Observatory.

INTRODUCTION

Present time synchronization techniques with the NASA laser network rely on LORAN-C and portable clocks to provide very accurate time tagging of laser ranging data. In applications where the data from two or more stations will be merged to determine baselines for geodetic work and polar motion determinations, it is necessary that the clocks at the several stations be synchronized to within ± 1 microsecond with respect to a master clock, such as that of the U.S. Naval Observatory (USNO). Best synchronization results using the LORAN-C system have been obtained from the West Coast chain at the Goldstone, California laser tracking station (MOBLAS 3). Figure 1 shows the MOBLAS 3 clock relative to the USNO Master Clock for the period of July 1980 through June of 1981. The x's are phase difference measurements made through LORAN-C referenced to USNO, and the O's are the phase measurements corrected for known offsets such that a linear least squares fit may be performed on the data. The standard deviation of the fit to this data shows a time synchronization of about a half a microsecond.

MOBLAS 5 located in Yarragadee, Australia has obtained a synchronization of only four microseconds using the LORAN-C Northwest Pacific chain as evidenced by the data in figure 2. Direct reception of LORAN-C signals is not possible at this location, and uncertainties in the path length of bounced signals cause large errors. In this instance MOBLAS 5 required frequent portable clock measurements (also shown in figure 2) to maintain microsecond synchronization.

Time transfers by satellite have been performed by NASA Goddard Spaceflight Center (GSFC) and the Naval Research Laboratory (NRL) initially using the NRL Navigation Technology Satellites (NTS).(1,2) Accuracies of several hundred nanoseconds were obtained.(3) As an outgrowth of the NTS effort, a Time Transfer Receiver (TTR) which operates with the NAVSTAR Global Positioning System (GPS) satellites is presently being developed jointly by GSFC and NRL. GSFC will use the GPS TTR in the Laser Ranging Network. The network consists of eight mobile vans, a permanent installation at GSFC, and eventually four highly transportable laser systems. The laser systems will be deployed to various locations around the world (figures 3 and 4) and will be used in support of the NASA GSFC Crustal Dynamics Program.

NAVSTAR GPS is a tri-service Department of Defense (DOD) program.(4) The first GPS satellite flown was NTS-II(5,6) which was designed and built by NRL personnel. GPS will provide the capability of very precise instantaneous navigation and transfer of time from any point on-or-around the earth. At present six NAVSTAR satellites are on-orbit, providing instantaneous navigation over selected areas for limited parts of each day. This constellation is part of the GPS Phase I configuration. Additional space vehicles (SV) are to be launched during the next year.

The major objective of a satellite time transfer receiver is to determine precise time differences between a given satellite and a local ground clock referenced to the TTR (figure 5). Precise time can then be obtained between the SV and a single remote ground station clock or between the SV and any number of remote stations. The remote sites can then be synchronized among themselves.

THE NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)

GPS is comprised of three segments. The space segment consists of a constellation of satellites for global coverage.(7) Phase III GPS will have a total of 24 satellites, eight in each of three orbital planes. The GPS orbits are near-circular at an altitude of approximately 10,000 nautical miles, inclined at 55 degrees to the equator. The period is adjusted such that a repeating ground trace is obtained for a given ground tracking station. Each satellite transmits its own identification and orbital information continuously. The GPS signal is spread spectrum in nature, formed by adding the data to a direct sequence code which is then biphase modulated onto a carrier.

The control segment consists of a master control station (MCS) and monitor stations (MS) placed at various locations around the world.(8) The current Phase I MCS is located at Vandenberg Air Force Base with the supporting monitor tracking stations at Alaska, Guam, Hawaii, and Vandenberg. The monitor stations collect data from each satellite and transmit to the MCS. The data is processed to determine the orbital characteristics of each satellite and the trajectory information is then uploaded to each satellite, once every 24 hours as the spacecraft passes over the MCS.

The user segment consists of a variety of platforms containing GPS receivers which track the satellite signals and process the data to determine position.(9,10) Coverage of the Phase III constellation is such that at least four satellites will always be in view from any point on the earth's surface.

TIME TRANSFER METHOD

To perform a satellite time transfer with GPS, pseudo-range measurements are made that consist of the propagation delay in the signal plus the difference between the satellite clock and the ground station receiver reference clock. Data from the satellite is processed to obtain satellite position and satellite clock information (offset from GPS time). The propagation delay is subtracted from the pseudo-range by knowing the exact locations of the satellite and the station. This difference is then corrected by the GPS time offset to determine the final result of ground station time relative to GPS time. The Phase I GPS time is normally maintained at the Vandenberg MCS using a cesium oscillator. The Phase III GPS time is planned to be referenced from the MCS to the U.S. Naval Observatory (USNO) Master Clock. The final results obtained from a single-frequency receiver, such as the one described in this paper, will contain a small error due to the ionospheric delay which may be modeled and corrected.

GPS TIME TRANSFER RECEIVER (TTR)

The GPS TTR is a microcomputer based system which was designed to replace existing receivers that formerly used the NTS satellites for time transfer. The design uses hardware and software from these receivers whenever possible. The following is a summary of the design requirements:

A. GPS Signal Detection Characteristics

1) Operates at the single L1 frequency of 1575 MHz.
2) Has sufficient bandwidth to track satellites throughout their doppler range from horizon to horizon.
3) Uses only the course/acquisiton (C/A) code of 1.023 MHz.
4) Tracks the C/A code to within 3% of a chip (30 nanoseconds).
5) Tracks any GPS satellite by changing to the appropriate code.
6) Detects and decodes the navigation data as required to determine a time transfer.

B. Operational Characteristics

1) Requires a stationary platform during operation.
2) Determines the time difference between the 1 pps input station reference and GPS system time.

3) Measures the time difference once every six seconds.
4) Has an RMS of less than 50 nanoseconds on the time difference measurements.
5) Controls the operation of the receiver by inputs from a keyboard.
6) Outputs data to the CRT display and records on a flexible disc.

C. Input Requirements

1) Antenna position in WGS-72 coordinates.
2) 1 pps from the station time standard.
3) 5 MHz from the station time standard.

With these design requirements, the receiver block diagram in figure 6 was implemented. The following is a description of the major components shown in the diagram.

RF Subsystem

The RF subsystem provides carrier and code tracking capabilities for the GPS signal. It demodulates the data message into the non-return to zero (NRZ) format and provides the voltage controlled crystal oscillator (VCXO) frequency for coherent code generation. An external control voltage input to the VCXO is used for acquisition tuning.

C/A Code Generator

The C/A code generator accepts the code sequence of any GPS satellite from the microprocessor. It then derives the 1.023 MHz C/A code from the VCXO frequency and outputs it to the RF subsystem for code tracking. A satellite time epoch is derived from the C/A code period and output for the time interval pseudo-range measurement.

Time Interval Measurement

A time interval counter is controlled by the microprocessor to measure the time difference between the satellite epoch and the station reference. This measurement occurs once every six seconds as commanded by the microprocessor. The time difference, which is pseudo-range, is output to the microprocessor for determining the time transfer. The time interval counter is also used to determine the VCXO frequency for tuning control.

I/O Terminal

The receiver contains a CRT display with a keyboard and a dual flexible disc drive recorder. The keyboard provides an operator interface for inputs and control of the receiver. The time transfer results are displayed on the CRT and recorded on the flexible disc.

Microprocessor

The microprocessor controls hardware functions in the receiver, decodes the navigation message, and calculates the time transfer. Receiver tuning is provided during acquisition by taking frequency measurements of the VCXO, comparing these measurements to predicted values and outputting corrections to the control voltage through a digital-to-analog converter.

The appropriate satellite C/A code is loaded into the code generator after being calculated using a linear feedback shift register algorithm implemented in the microprocessor. The code phase is also controlled by the microprocessor until a correlation or "code lock" is established in the RF subsystem. After signal acquisition, the microprocessor decodes the navigation data and commands pseudo-range measurements to be performed using the time interval counter to calculate the final time transfer result. This result is output to the CRT display and recorded on a flexible disc once every six seconds.

TIME TRANSFER FIELD TEST

The prototype GPS TTR was installed and tested at NASA's Merrit Island tracking site (MILA) at Kennedy Spaceflight Center, Fla. Figure 7 shows the horizon of the MILA facility and the portion of the orbit of NAVSTAR 5 in view at the MILA site. Figure 8 shows the orbits of all five NAVSTAR satellites along with approximate rise and set times for the period during which the tests were performed. Most of the data was taken during a segment of time when all the satellites passed through a high elevation angle (60° to 90°) with approximately the same azimuth. Figure 9 shows the segments of each orbit where the data collection was concentrated.

Figures 10 through 14 present data collected from individual satellite passes which gives the difference between the MILA station ground clock and the GPS spacecraft clocks. On each graph a calculated time transfer is presented for an epoch close to the mid-time of the observed period. The RMS of a least squared data fit is also given. The RMS of any one pass varies from 11 to 13 nanoseconds for a given satellite. Figure 15 is an extended track (two hour) of a NAVSTAR 6 pass and also shows an RMS of 13 nanoseconds. NAVSTAR 1 has a quartz crystal oscillator, NAVSTAR 3 and 4 have rubidium oscillators, while NAVSTAR 5 and 6 have cesium oscillators.

Figure 16 summarizes the results relating the MILA clock to the USNO clock as determined through GPS, LORAN-C and portable clock measurements performed during the test. The GPS results are presented as single points which are the average of the five satellite values. The bar over each point represents the range of the five values. The GPS results show peak-to-peak agreement of 200 ns or less with the portable clock measurements which are considered to be truth. During Phase I of the NAVSTAR GPS program, no attempt is being made to precisely synchronize the satellites. In Phase III of the program, it is planned to maintain satellite synchronization to within 100 nsec.

Figures 17 through 20 present results using only the data taken from NAVSTAR 1, which uses a crystal oscillator, and NAVSTAR 5, which uses a cesium oscillator. Figures 17 and 19 show the MILA station clock relative to GPS time as determined by the data from each satellite. Each point is the result of a linear least squares fit to approximately 20 minutes of data from an individual satellite pass. When another linear fit is performed on this day-to-day data, the results show that the time transfers have an RMS of 25 nsec and 24 nsec for NAVSTAR 1 and NAVSTAR 5 respectively. Figures 18 and 20 show the same satellite data referenced to USNO through published differences of GPS time and USNO time as determined by a GPS receiver at the Naval Observatory. The time transfer results again show an RMS of 25 nsec and 24 nsec. This result is within the expected noise of a single cesium to which all the data is referenced at the MILA ground station.

CONCLUSIONS

Figure 21 presents a comparison of the resulting time transfer RMS of all the GPS satellites during the test. When data is considered on a single satellite basis, the results always yield a time transfer with better than a 100 nsec accuracy. No ionospheric corrections have been made to obtain these results, and tests are planned in the future to determine how much error this contributes. Also, it was determined that the receiver has small biases that are frequency dependent. Improvements are being made in the receiver to account for these biases, and it is expected that follow-on tests will demonstrate even better accuracies.

FUTURE PLANS

Increased receiver performance and capabilities development is continuing based on results and operational feedback from field tests and on-going experiments. Extensive evaluation of the receiver is planned through several additional field tests. A joint experiment is scheduled with the Jet Propulsion Laboratory (JPL) to evaluate ionospheric delay error. Co-location tests are planned to compare nanosecond accuracy VLBI data with GPS TTR data. The co-location tests will involve VLBI stations at NRL Maryland Point, Haystack/Westford Observatory, NASA Deep Space Network (DSN), Goldstone, CA., and NASA DSN, Madrid, Spain. Future activities also include joint participation by GSFC, USNO, NBS, and NRL in the European Space Agency (ESA) SIRIO/LASSO time transfer experiment during 1982. This experiment will use a global baseline and will provide nanosecond accurate laser time transfers for comparison with the GPS time transfers.

The first operational field test of the GPS TTR is scheduled in the second quarter of fiscal year (FY) 1982 with the deployment of the NASA GSFC Transportable Laser Ranging System (TLRS) prototype to Easter Island. Four additional receivers are scheduled to be deployed with mobile laser systems later in FY 1982.

REFERENCES

1. L. Raymond, O. J. Oaks, J. Osbone, G. Whitworth, J. Buisson, P. Landis, C. Wardrip, and J. Perry, "Navigation Technology Satellite (NTS) Low Cost Timing Receiver," Goddard Space Flight Center Report X-814-77-205, Aug. 1977.

2. J. A. Buisson, T. B. McCaskill and O. J. Oaks, "Initial Design for Navigation Technology Satellite Time Transfer Receiver (NTS/TTR)," NRL Report 8312, 16 May 1979.

3. J. Buisson, T. McCaskill, J. Oaks, D. Lynch, C. Wardrip, and G. Whitworth, "Submicrosecond Comparisons of Time Standards via the Navigation Technology Satellites (NTS)," Proc. PTTI, Nov. 1978, pp 601-627.

4. B. W. Parkinson, "NAVSTAR Global Positioning System (GPS)," National Telecommunications Conference, Conference Record, Vol. iii, 1976, pp 41.1-1 to 41.1-5.

5. J. A. Buisson, R. L. Easton, and T. B. McCaskill, "Initial Results of the NAVSTAR GPS NTS-2 Satellite," NRL Report 8232,

May 25, 1978.

6. R. L. Easton, J. A. Buisson, T. B. McCaskill, O. J. Oaks, S. Stebbins, and M. Jeffries, "The Contribution of Navigation Technology Satellites to the Global Positioning System," NRL Report 8360, Dec. 28, 1979.

7. J. A. Buisson and T. B. McCaskill, "TIMATION Navigation Satellite System Constellation Study," NRL Report 7389, June 27, 1972.

8. S. S. Russell and J. H. Schaibly, "Control Segment and User Performance," J. Inst. Navigation 25(2), Summer 1978, pp. 166-172.

9. J. J. Spilker, "GPS Signal Structure and Performance Characteristics," J. Inst. Navigation, 25(2), Summer 1978, pp. 121-146.

10. A. Dierendock, S. Russell, E. Kipitzke, and M. Birnbaum, "The GPS Navigation Message." J. Inst. Navigation, 25(2), Summer 1978, pp. 147-165.

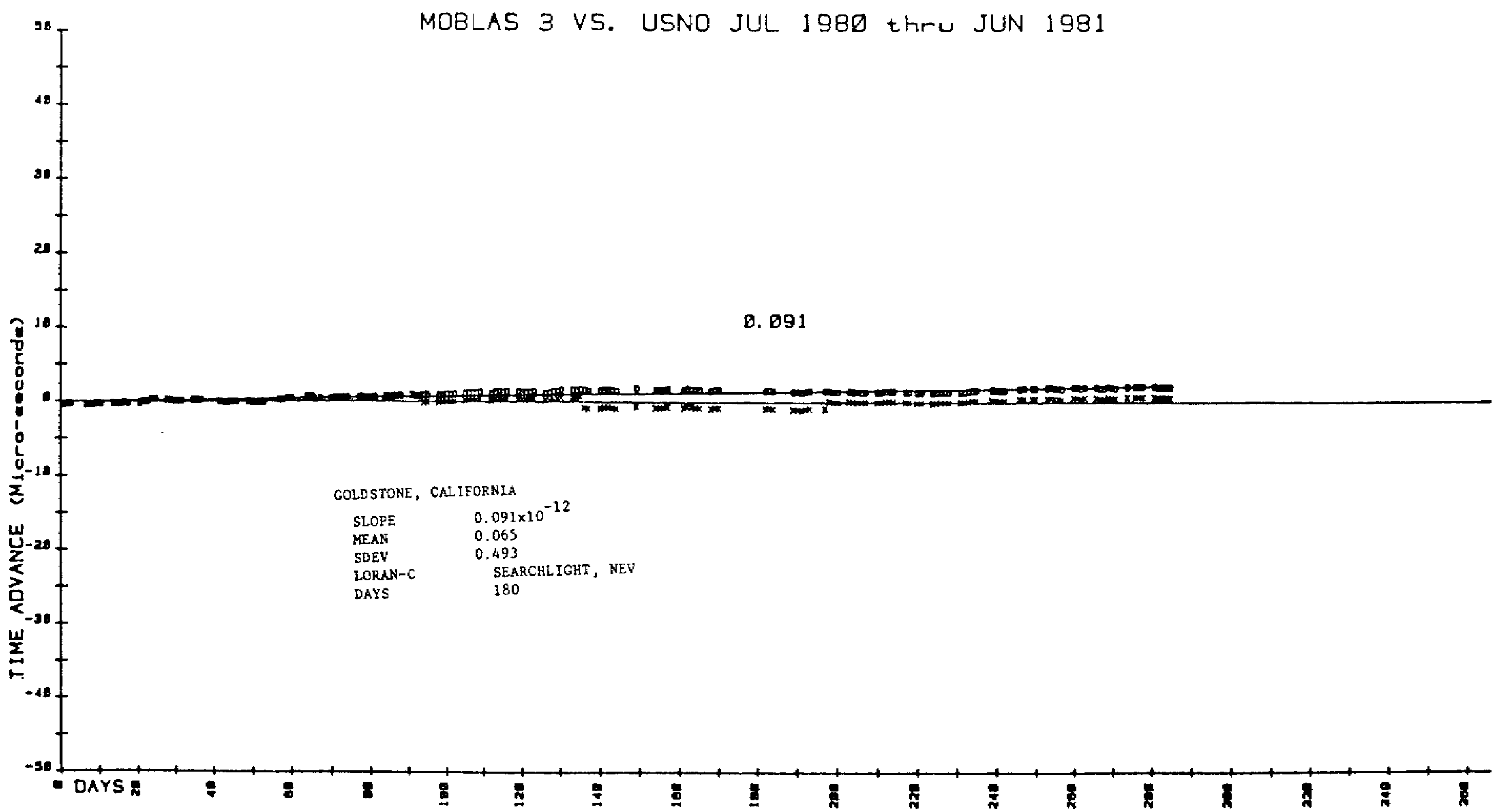

MOBLAS 3 VS. USNO JUL 1980 thru JUN 1981
TIME ADVANCE (Micro-seconds)
DAYS
Ø.091
GOLDSTONE, CALIFORNIA
SLOPE 0.091x10^-12
MEAN 0.065
SDEV 0.493
LORAN-C SEARCHLIGHT, NEV
DAYS 180

Figure 1

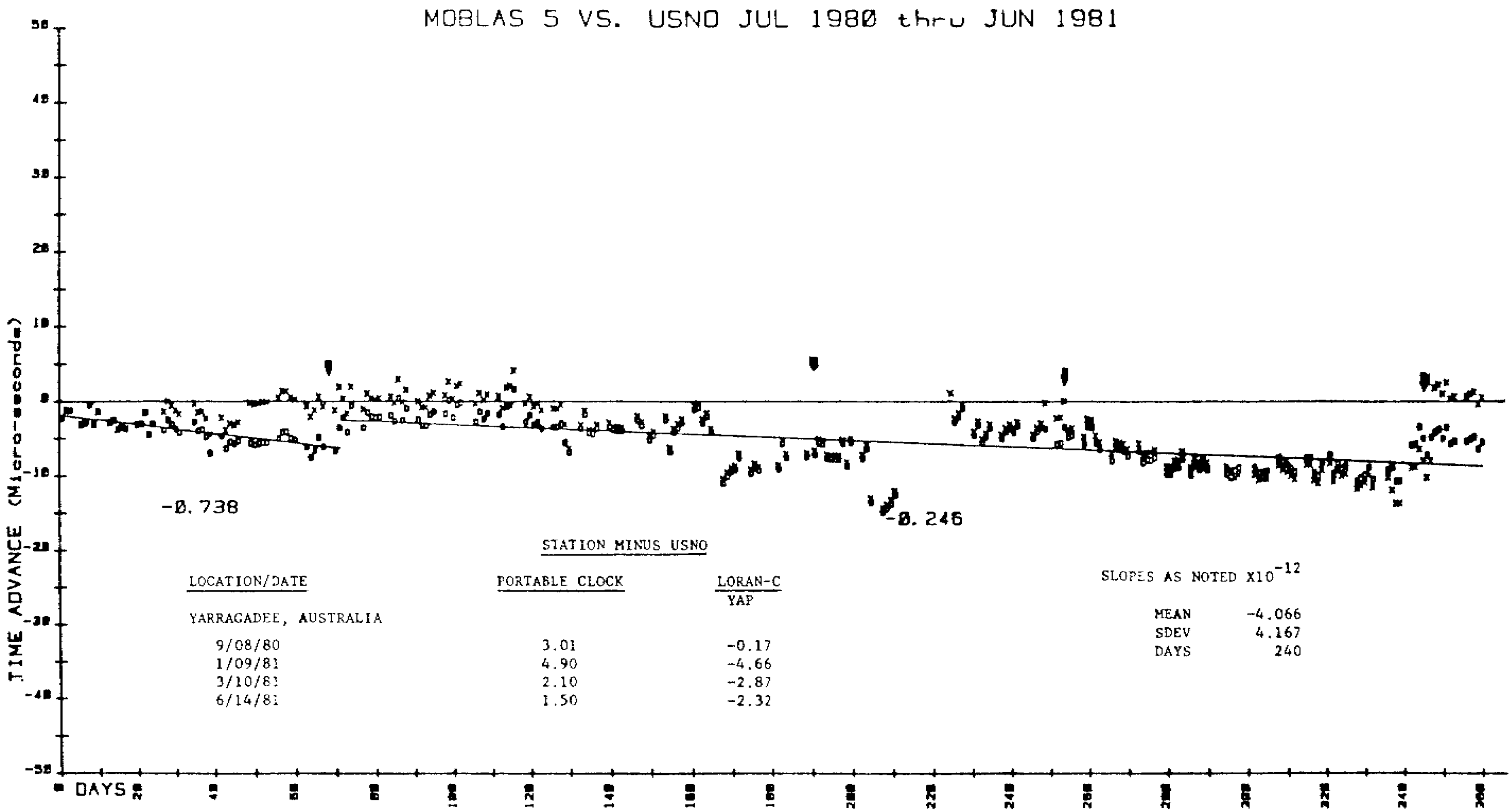

MOBLAS 5 VS. USNO JUL 1980 thru JUN 1981
TIME ADVANCE (Micro-seconds)
DAYS
-0.738
-0.246
STATION MINUS USNO
LOCATION/DATE
PORTABLE CLOCK
LORAN-C YAP
YARRAGADEE, AUSTRALIA
9/08/80 3.01 -0.17
1/09/81 4.90 -4.66
3/10/81 2.10 -2.87
6/14/81 1.50 -2.32
SLOPES AS NOTED X10^-12
MEAN -4.066
SDEV 4.167
DAYS 240

Figure 2

NASA-GSFC LASER TRACKING SITES 1980 - 1986

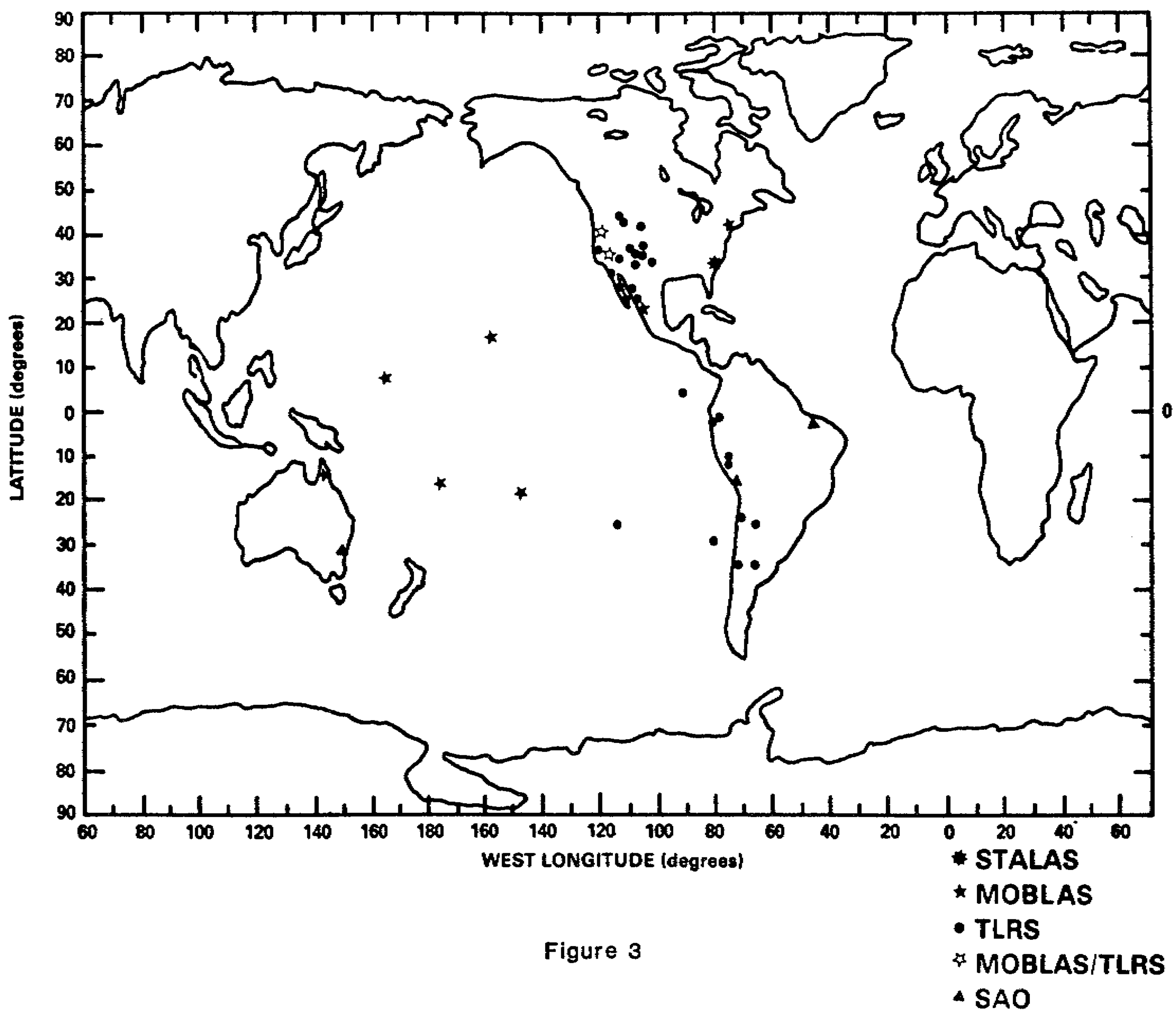
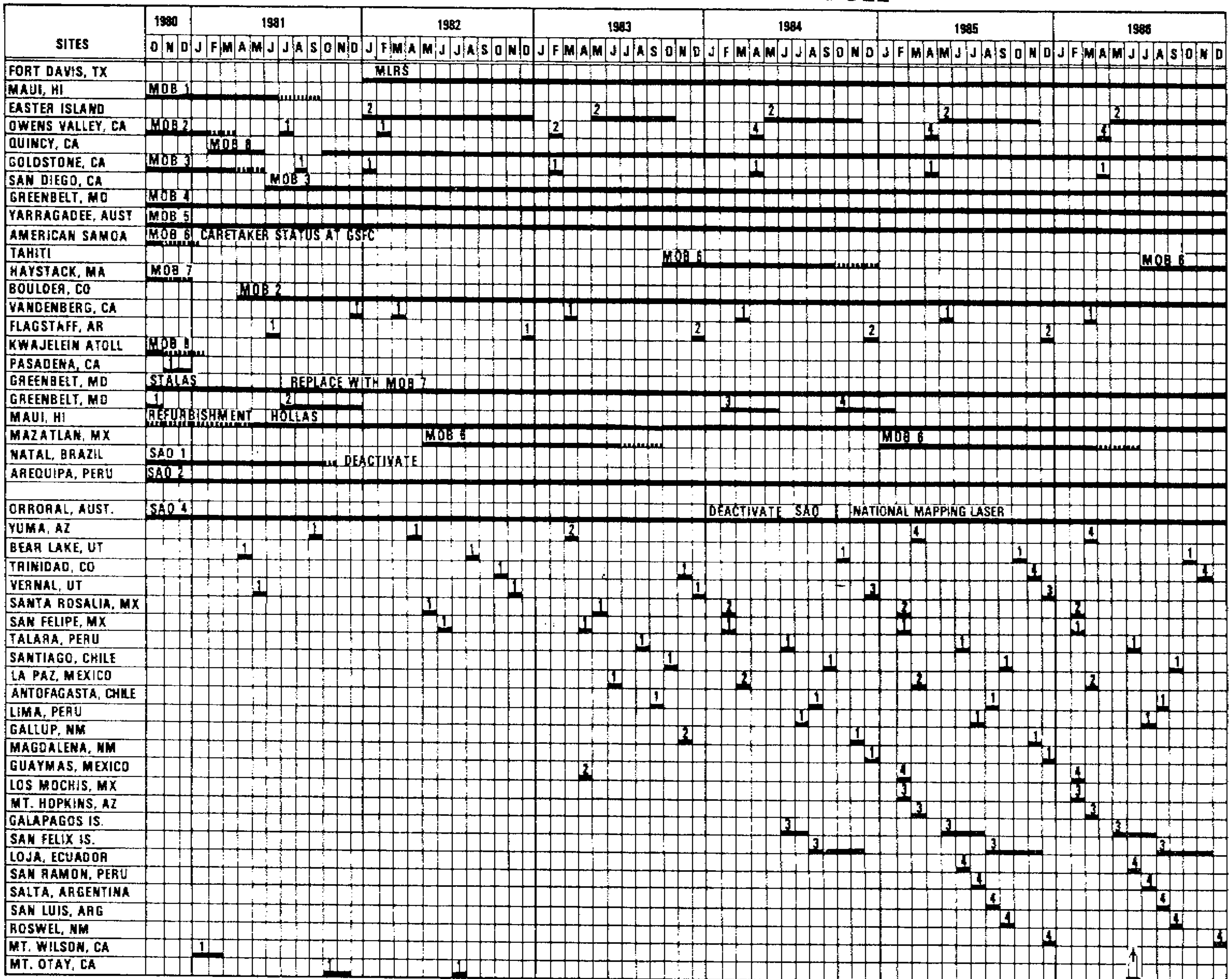


Figure 3

TENTATIVE LASER DEPLOYMENT SCHEDULE



NOTES: ——— OPERATIONAL ········· PACKING, SHIPPING, SET-UP, CHECKOUT   1 TLRS-1 2 TLRS-2 3 TLRS-3 4 TLRS-4

TLRS-TRANSPORTABLE LASER RANGING SYSTEM

GSFC   6/1/81

LASER NETWORK MANAGER   LASER PROJECT MANAGER   CRUSTAL DYNAMICS PROJECT MANAGER

Figure 4

NAVSTAR GPS STATION SYNCHRONIZATION BY TIME TRANSFER

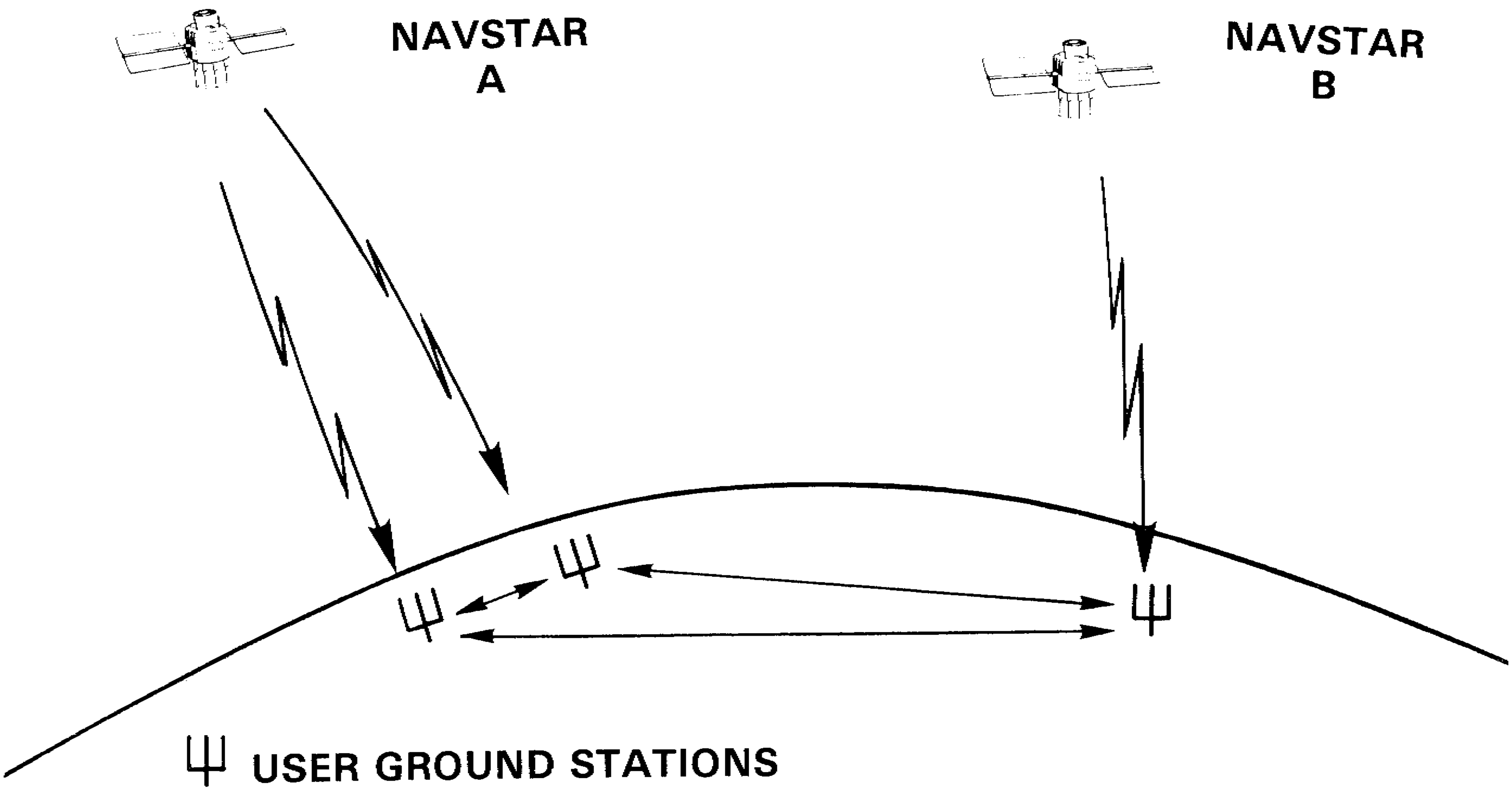
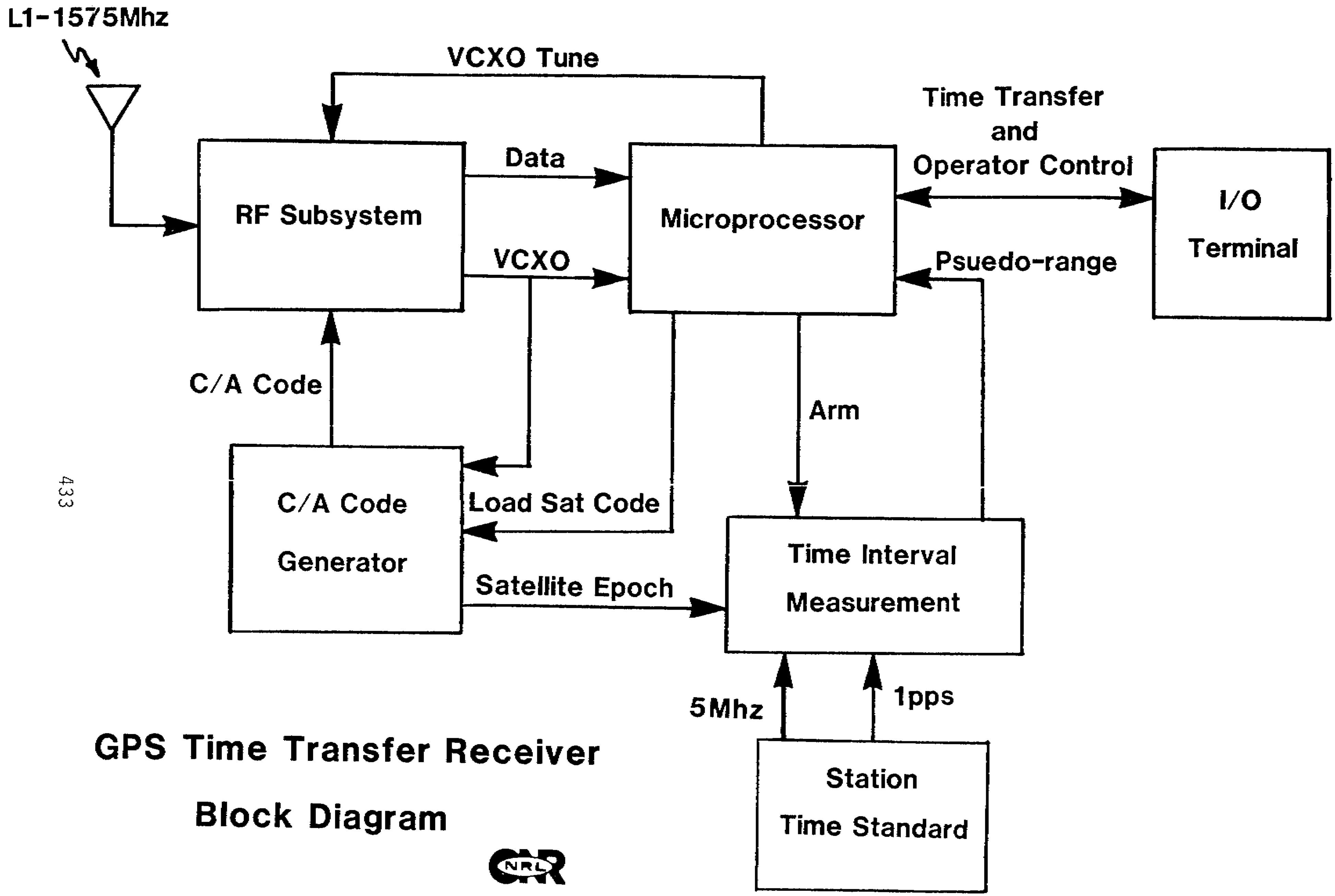


Figure 5



GPS Time Transfer Receiver

Block Diagram

Figure 6

GPS NAVSTAR
MILA
GROUND TRACK
(6/15/81)

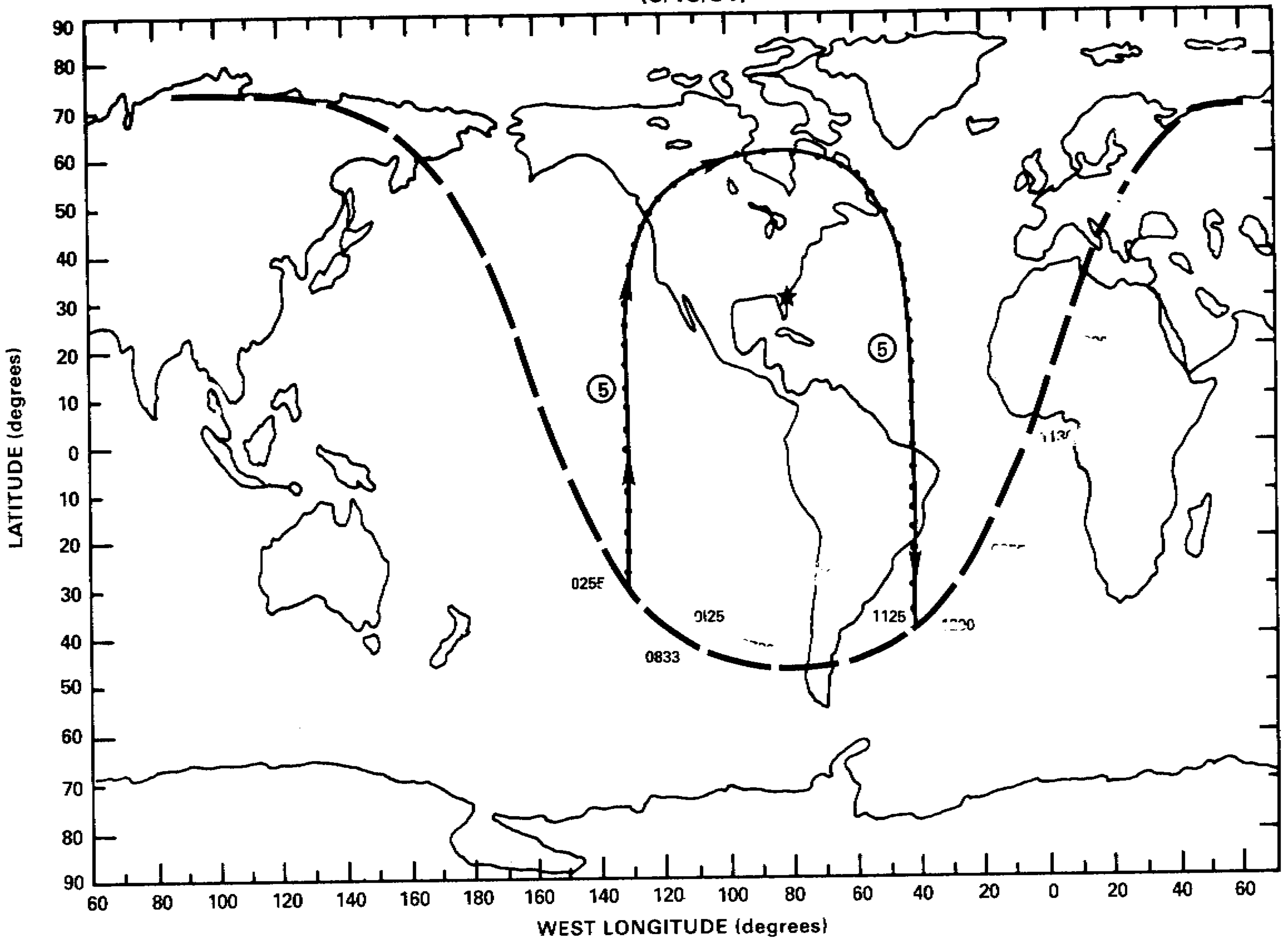


Figure 7

GPS NAVSTAR
MILA
GROUND TRACK

(6/15/81)

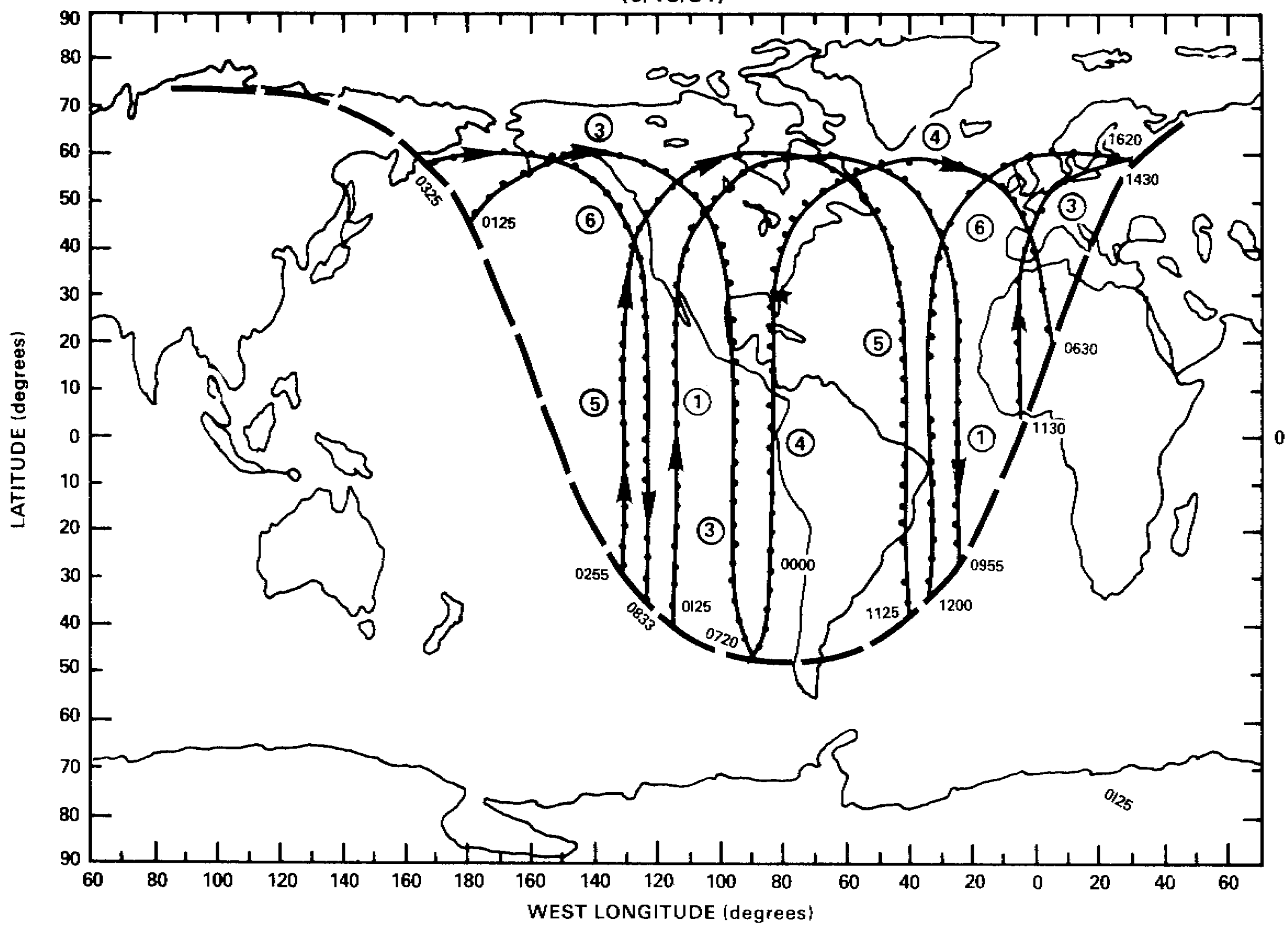


Figure 8

GPS NAVSTAR
MILA
GROUND TRACK

(6/15/81)

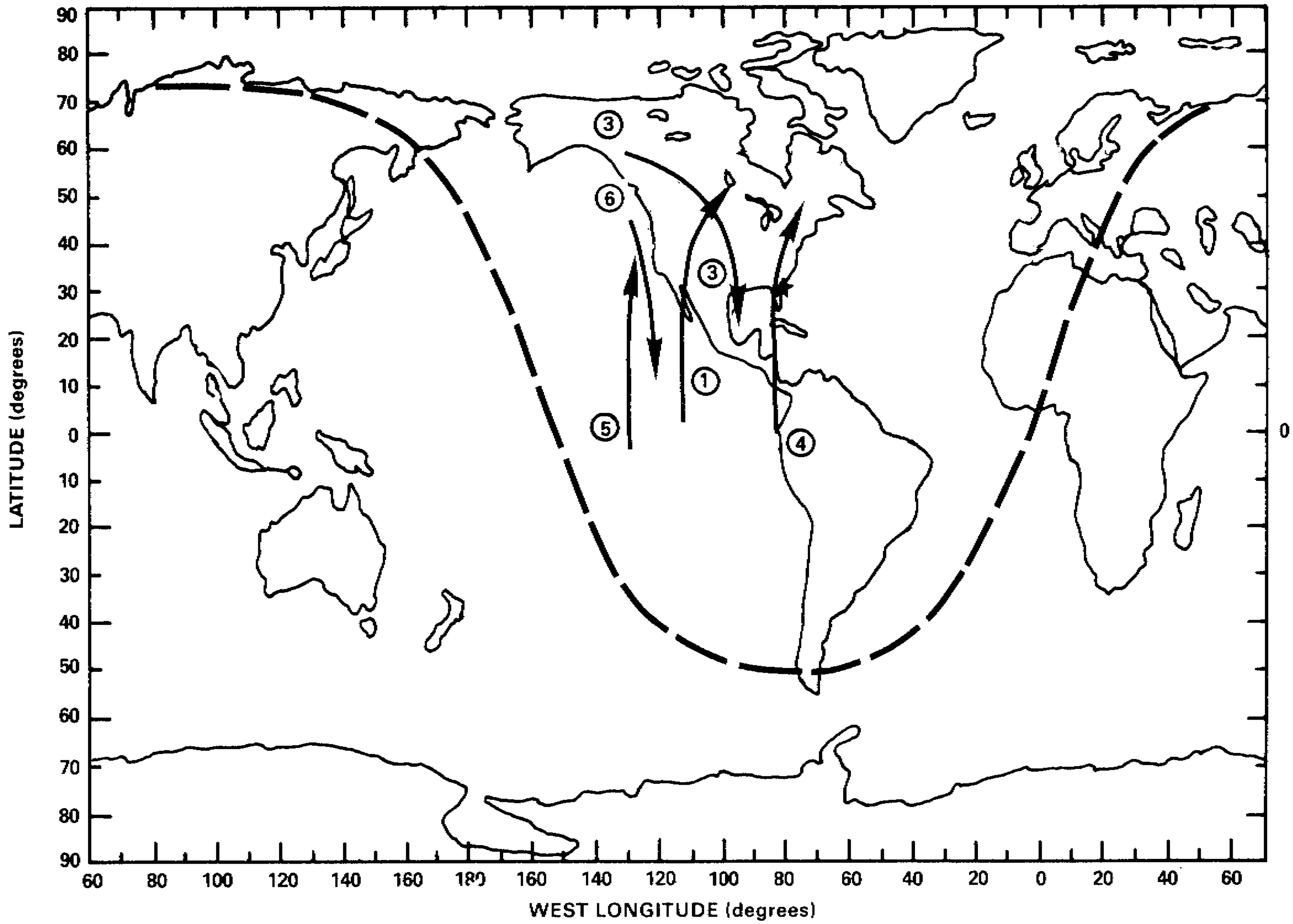


Figure 9

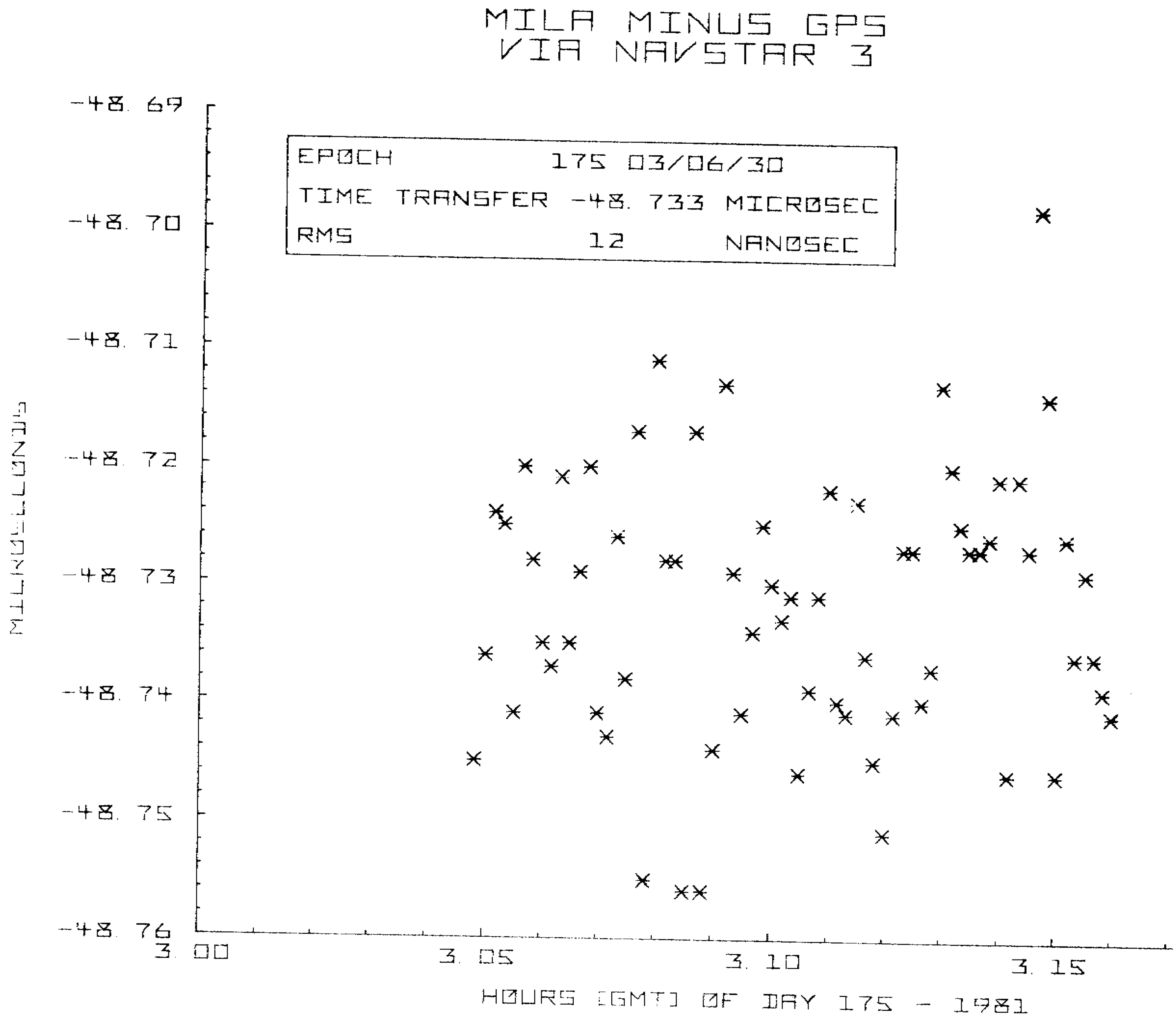

MILA MINUS GPS
VIA NAVSTAR 3
EPØCH 175 03/06/30
TIME TRANSFER -48.733 MICRØSEC
RMS 12 NANØSEC
-48.69
-48.70
-48.71
-48.72
-48.73
-48.74
-48.75
-48.76
3.00
3.05
3.10
3.15
HØURS [GMT] ØF DAY 175 - 1981

Figure 11

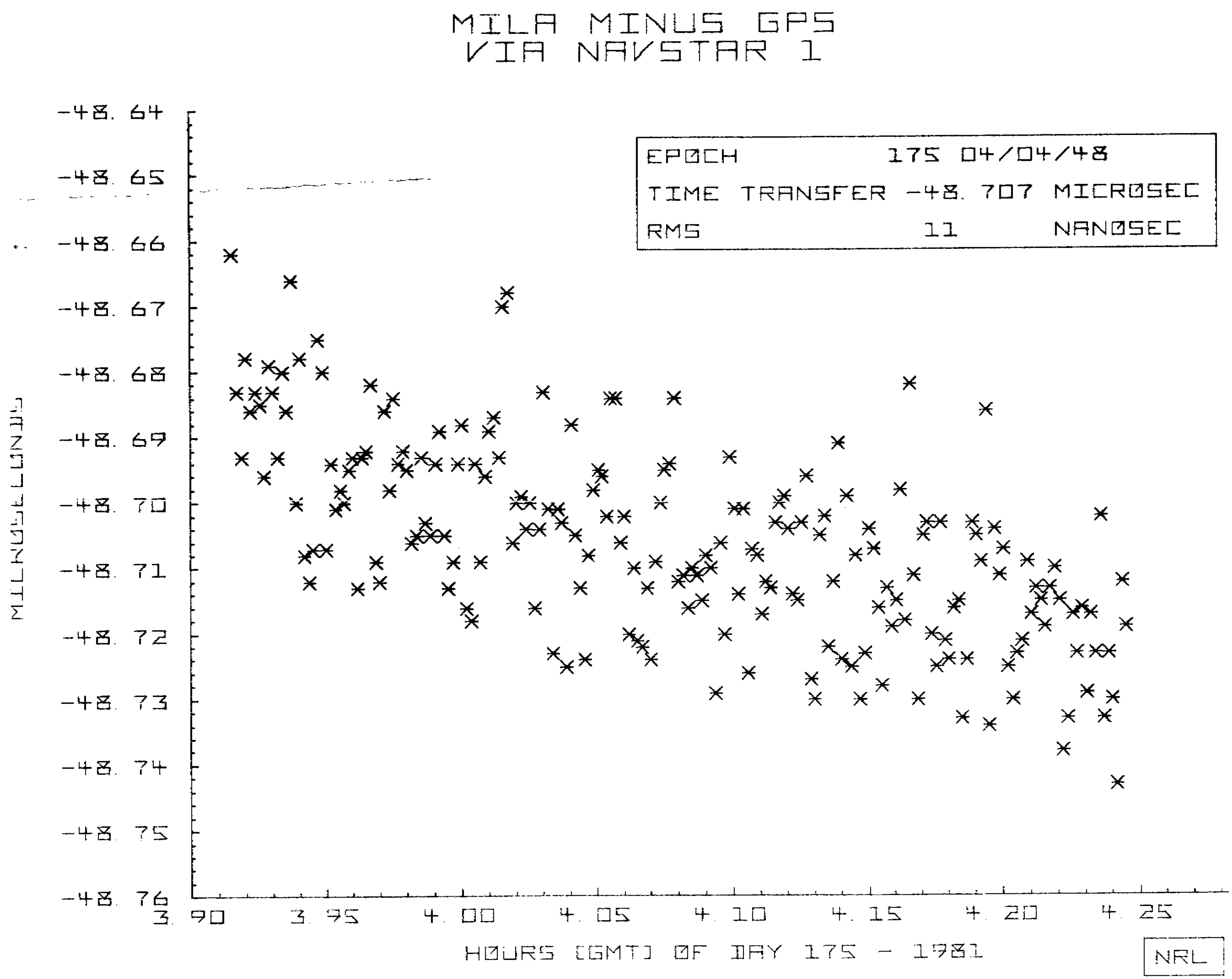

MILA MINUS GPS
VIA NAVSTAR 1
EPØCH 175 04/04/48
TIME TRANSFER -48.707 MICRØSEC
RMS 11 NANØSEC
MICRØSECØNDS
-48.64
-48.65
-48.66
-48.67
-48.68
-48.69
-48.70
-48.71
-48.72
-48.73
-48.74
-48.75
-48.76
3.90
3.95
4.00
4.05
4.10
4.15
4.20
4.25
HØURS [GMT] ØF DAY 175 - 1981
NRL

Figure 10

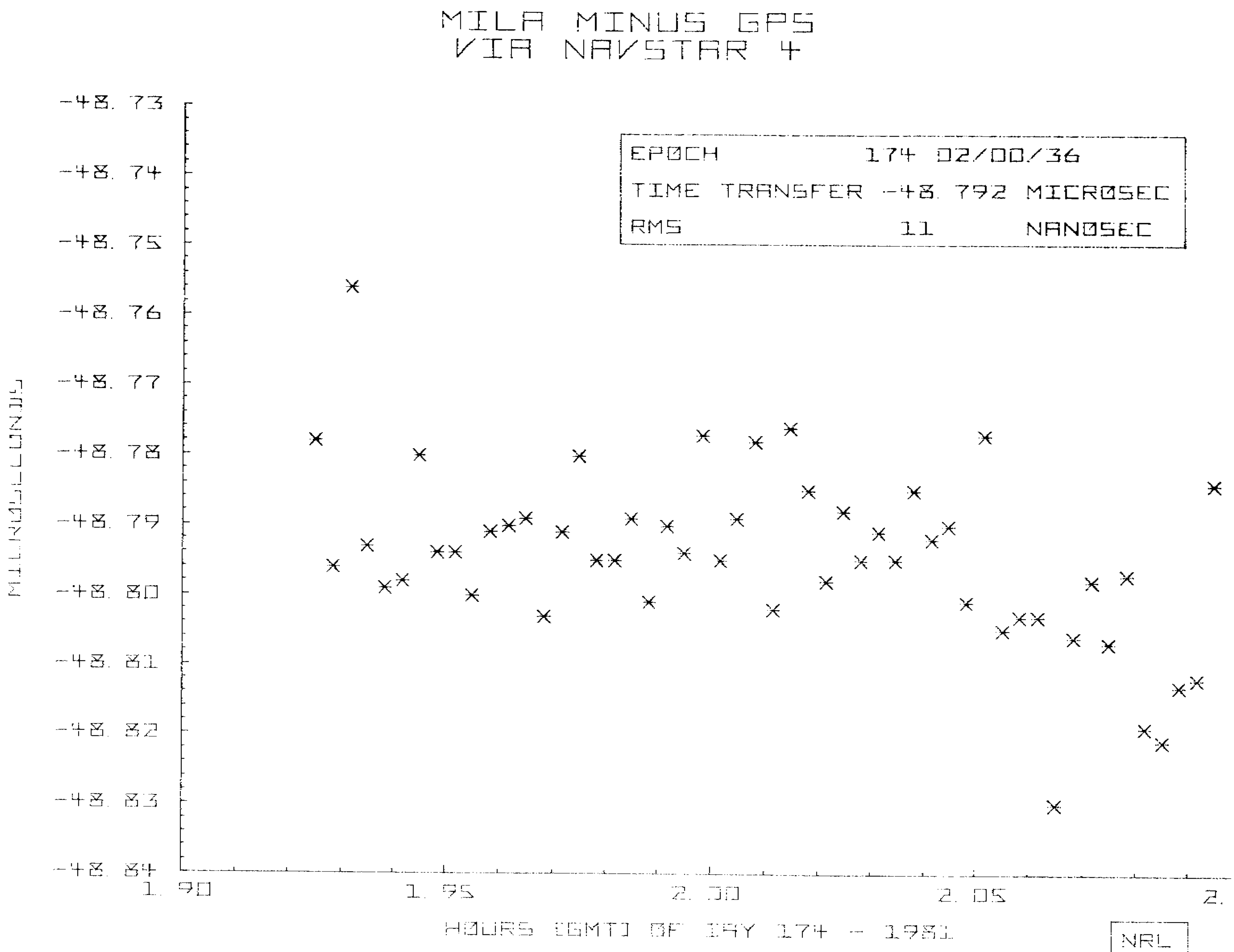

MILA MINUS GPS
VIA NAVSTAR 4
EPØCH 174 02/00/36
TIME TRANSFER -48.792 MICRØSEC
RMS 11 NANØSEC
-48.73
-48.74
-48.75
-48.76
-48.77
-48.78
-48.79
-48.80
-48.81
-48.82
-48.83
-48.84
1.90
1.95
2.00
2.05
2.
NRL

Figure 12

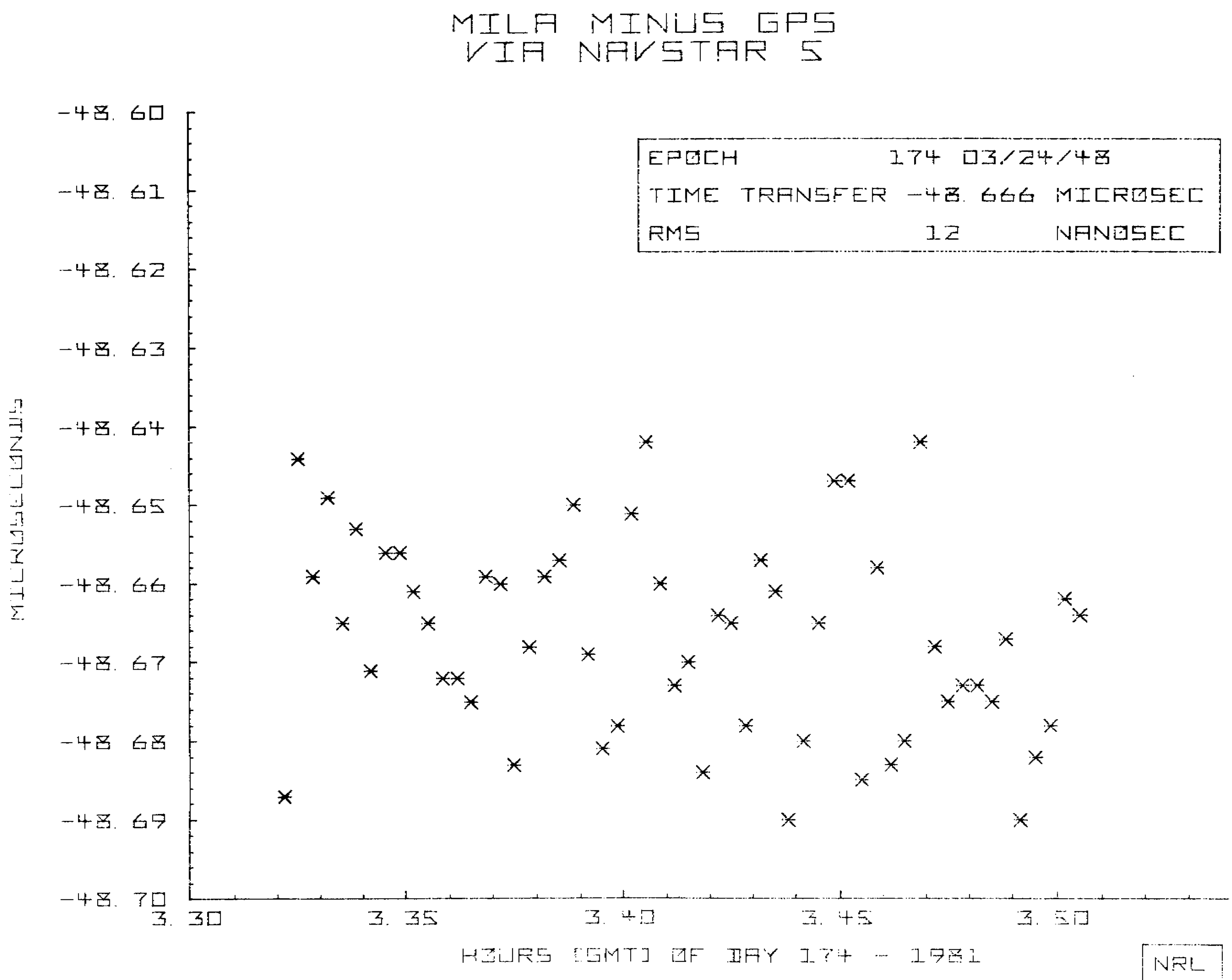

MILA MINUS GPS
VIA NAVSTAR 5
EPØCH 174 03/24/48
TIME TRANSFER -48.666 MICRØSEC
RMS 12 NANØSEC
-48.60
-48.61
-48.62
-48.63
-48.64
-48.65
-48.66
-48.67
-48.68
-48.69
-48.70
3.30
3.35
3.40
3.45
3.50
HØURS (GMT) ØF DAY 174 - 1981
NRL

Figure 13

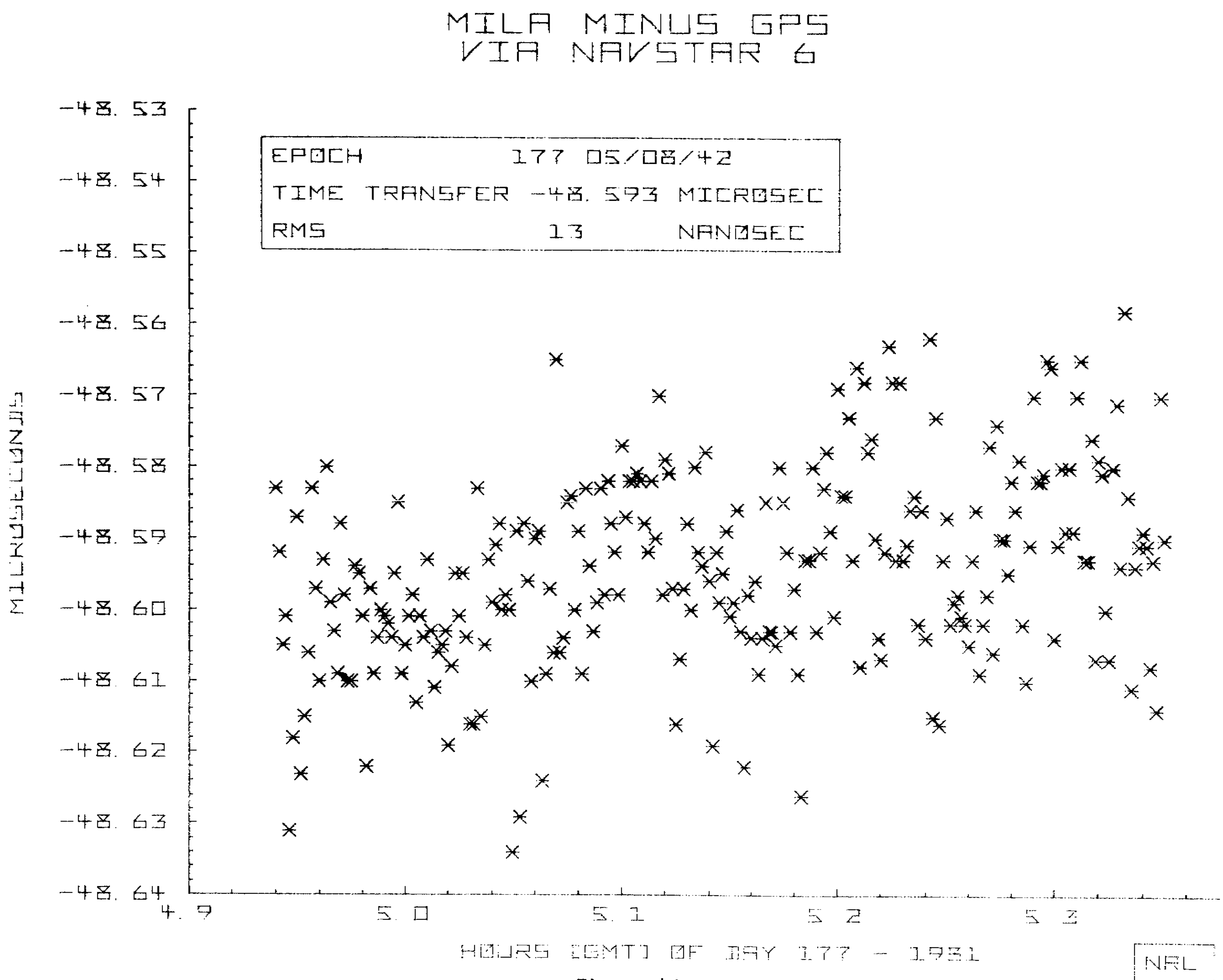

MILA MINUS GPS
VIA NAVSTAR 6
EPOCH 177 05/08/42
TIME TRANSFER -48.593 MICROSEC
RMS 13 NANOSEC
-48.53
-48.54
-48.55
-48.56
-48.57
-48.58
-48.59
-48.60
-48.61
-48.62
-48.63
-48.64
MICROSECONDS
4.9
5.0
5.1
5.2
5.3
HOURS [GMT] OF DAY 177 - 1981
NRL

Figure 14

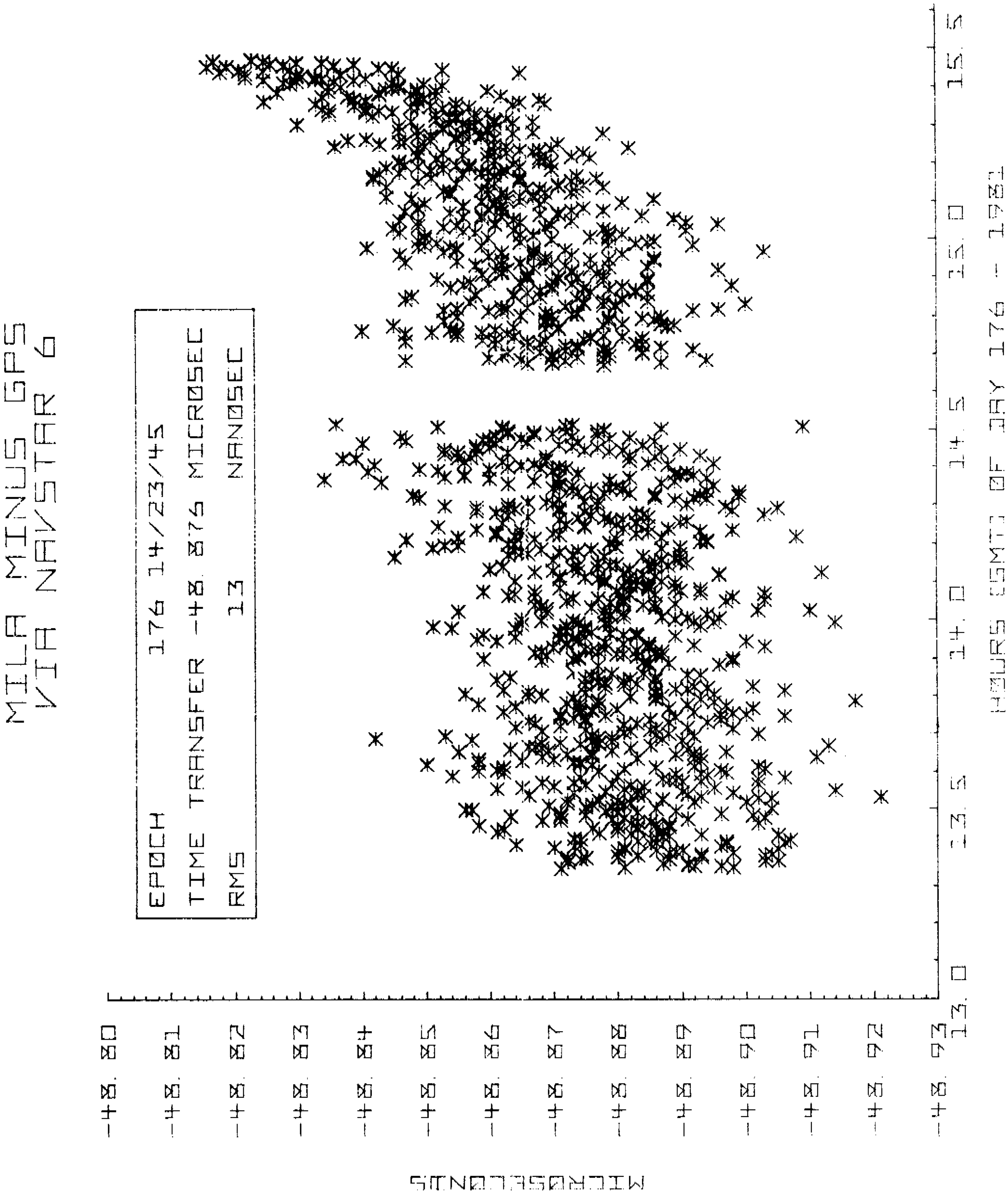

MILA MINUS GPS
VIA NAVSTAR 6
EPOCH 176 14/23/45
TIME TRANSFER -48.875 MICROSEC
RMS 13 NANOSEC
-48.80
-48.81
-48.82
-48.83
-48.84
-48.85
-48.86
-48.87
-48.88
-48.89
-48.90
-48.91
-48.92
-48.93
MICROSECONDS
13.0
13.5
14.0
14.5
15.0
15.5
HOURS (GMT) OF DAY 176 - 1981

Figure 15

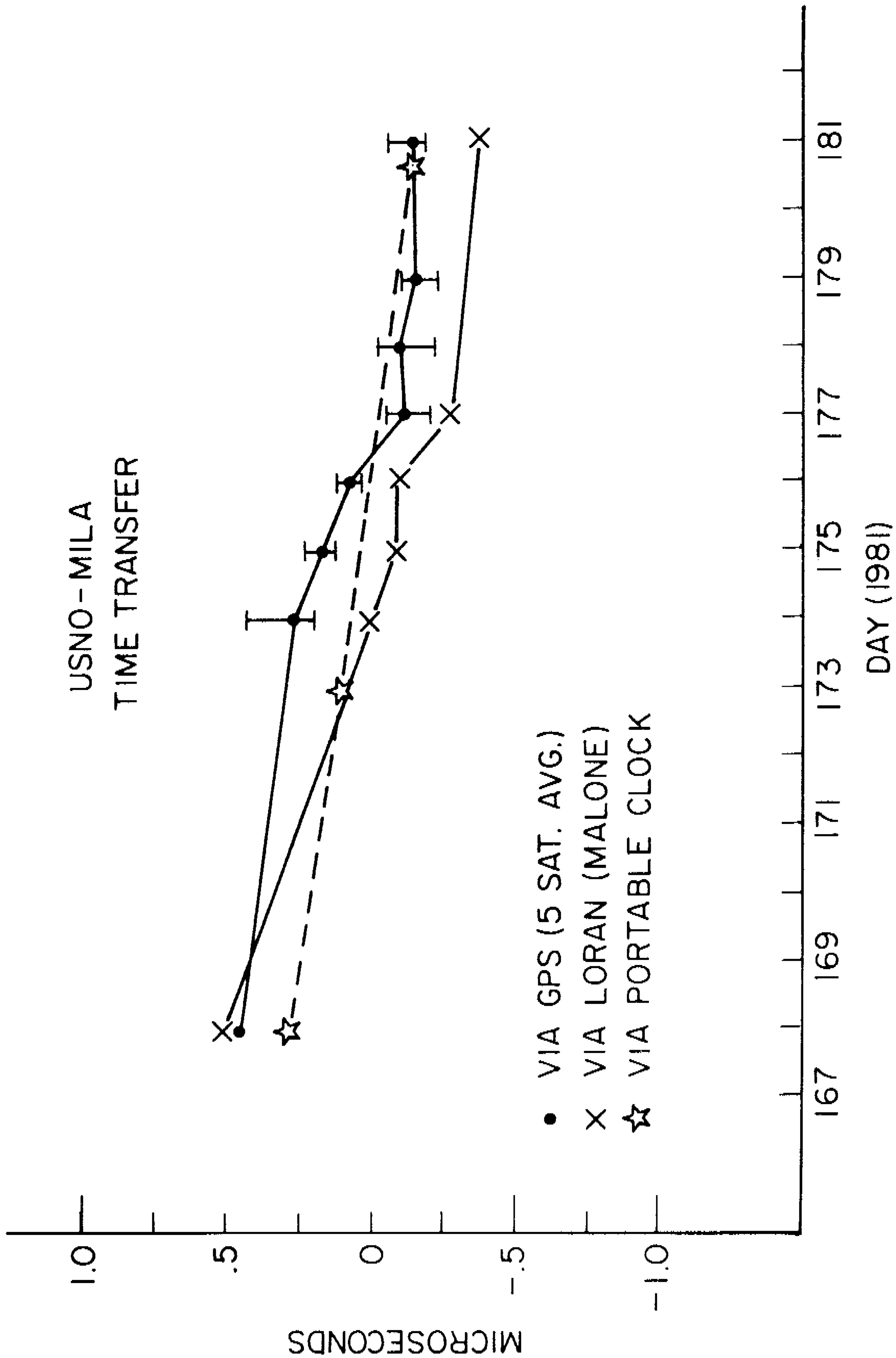

USNO-MILA
TIME TRANSFER
• VIA GPS (5 SAT. AVG.)
× VIA LORAN (MALONE)
☆ VIA PORTABLE CLOCK
1.0
.5
0
-.5
-1.0
MICROSECONDS
167
169
171
173
175
177
179
181
DAY (1981)

Figure 16

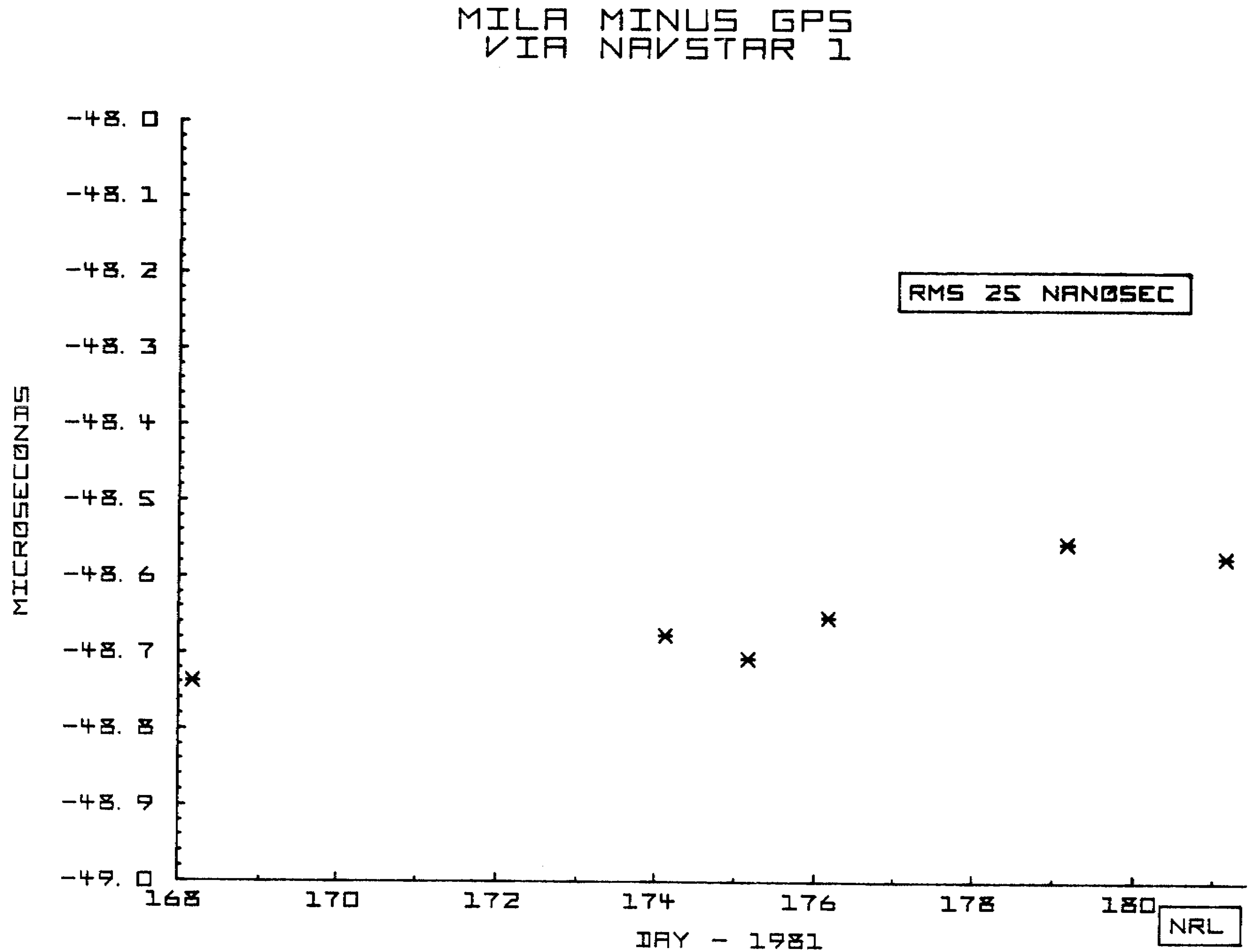

MILA MINUS GPS
VIA NAVSTAR 1
RMS 25 NANOSEC
MICROSECONDS
-48.0
-48.1
-48.2
-48.3
-48.4
-48.5
-48.6
-48.7
-48.8
-48.9
-49.0
168
170
172
174
176
178
180
NRL
DAY - 1981

Figure 17

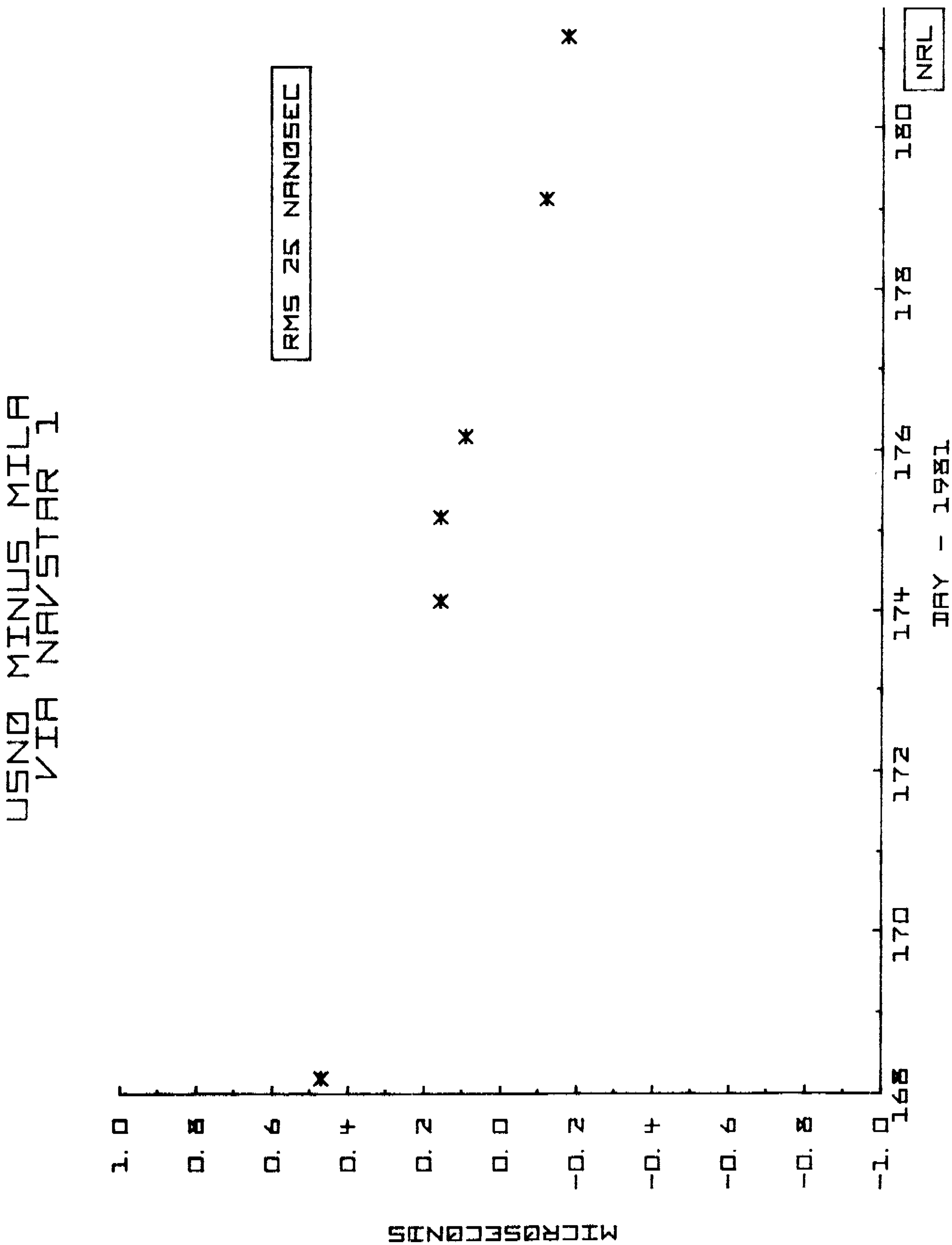

USNO MINUS MILA
VIA NAVSTAR 1
RMS 25 NANOSEC
NRL
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
MICROSECONDS
168
170
172
174
176
178
180
DAY - 1981

Figure 18

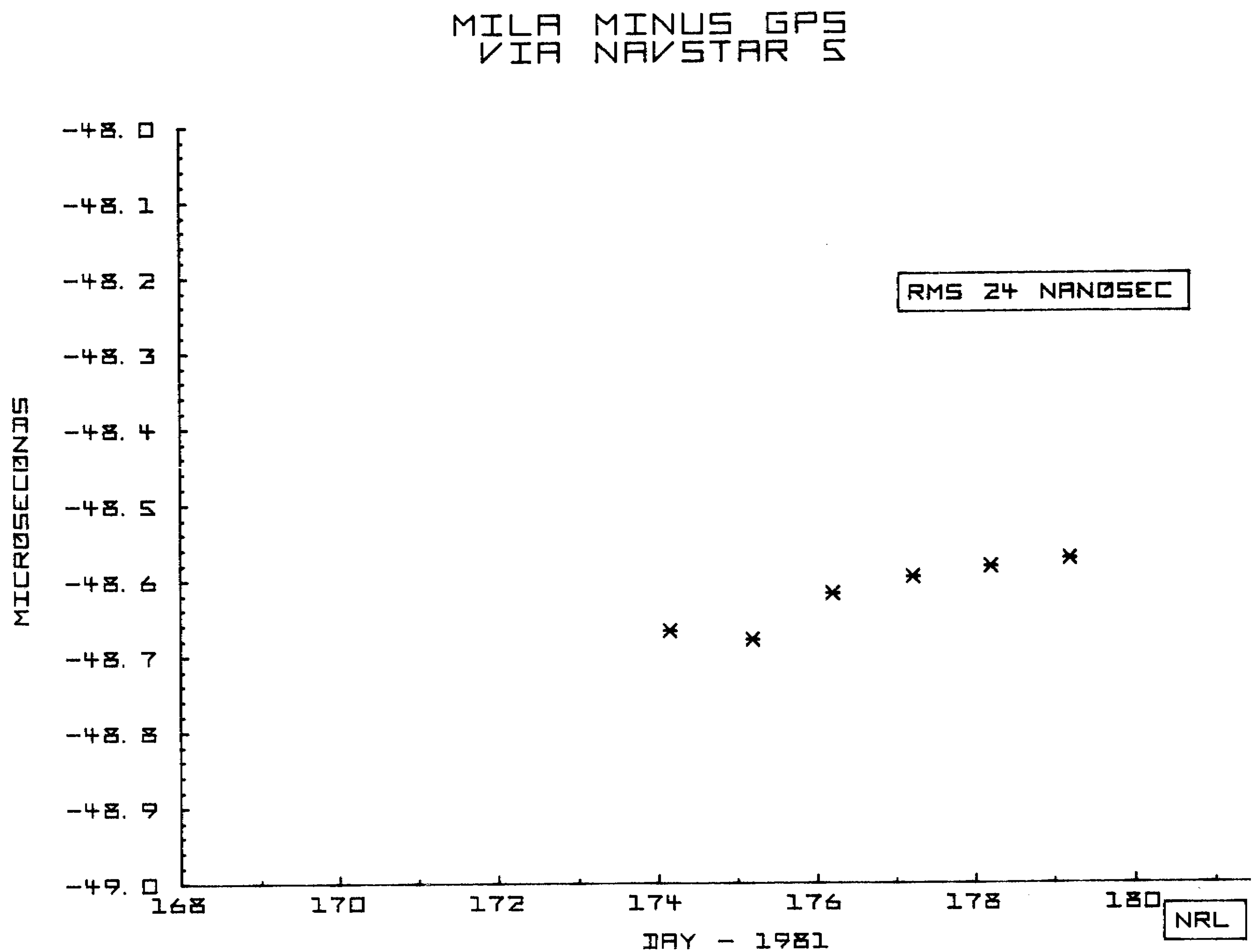
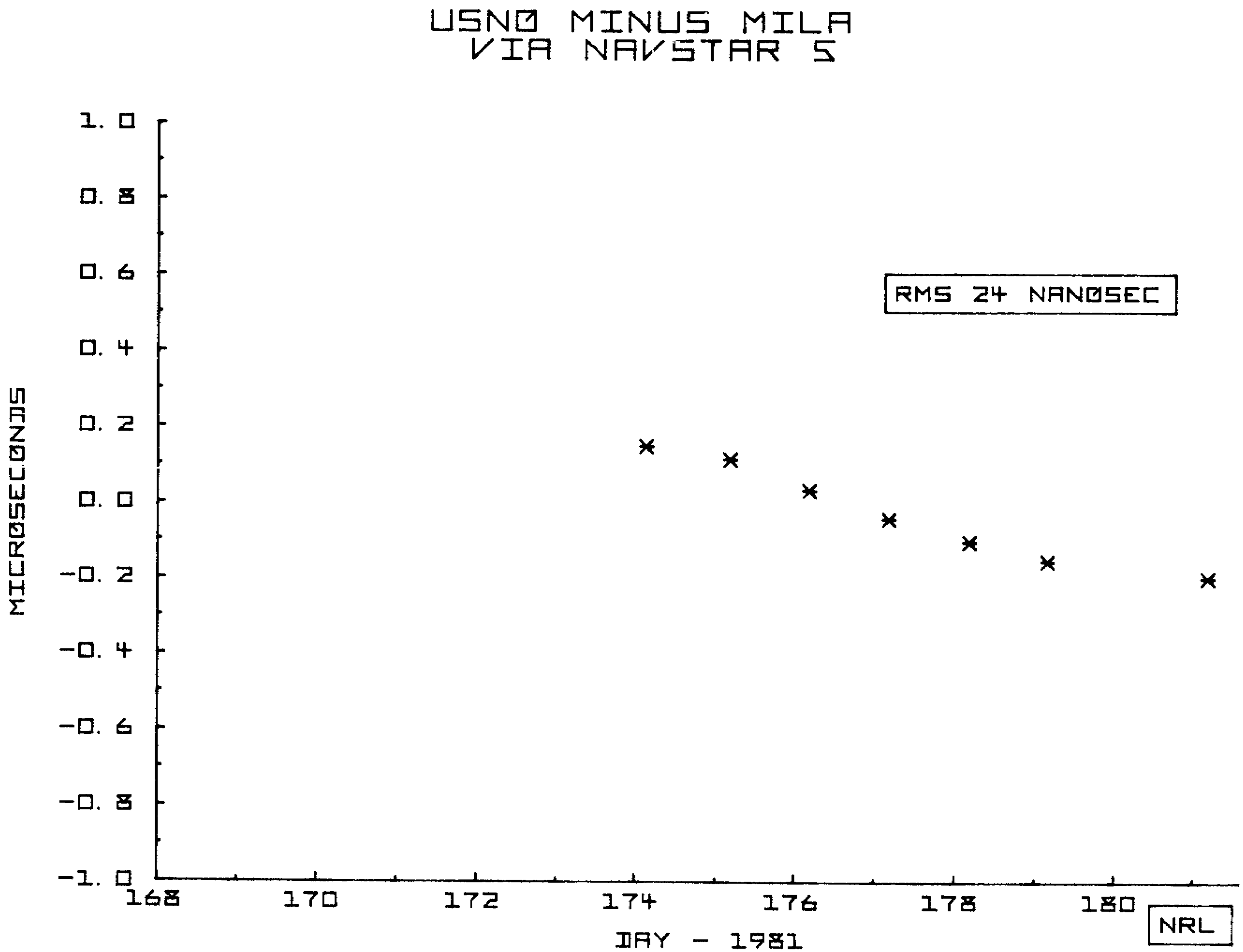

MILA MINUS GPS
VIA NAVSTAR 5
RMS 24 NANOSEC
MICROSECONDS
-48.0
-48.1
-48.2
-48.3
-48.4
-48.5
-48.6
-48.7
-48.8
-48.9
-49.0
168
170
172
174
176
178
180
NRL
DAY - 1981

Figure 19



USNO MINUS MILA
VIA NAVSTAR 5
RMS 24 NANOSEC
MICROSECONDS
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
168
170
172
174
176
178
180
DAY - 1981
NRL

Figure 20

TIME TRANSFER RMS OF USNO-MILA

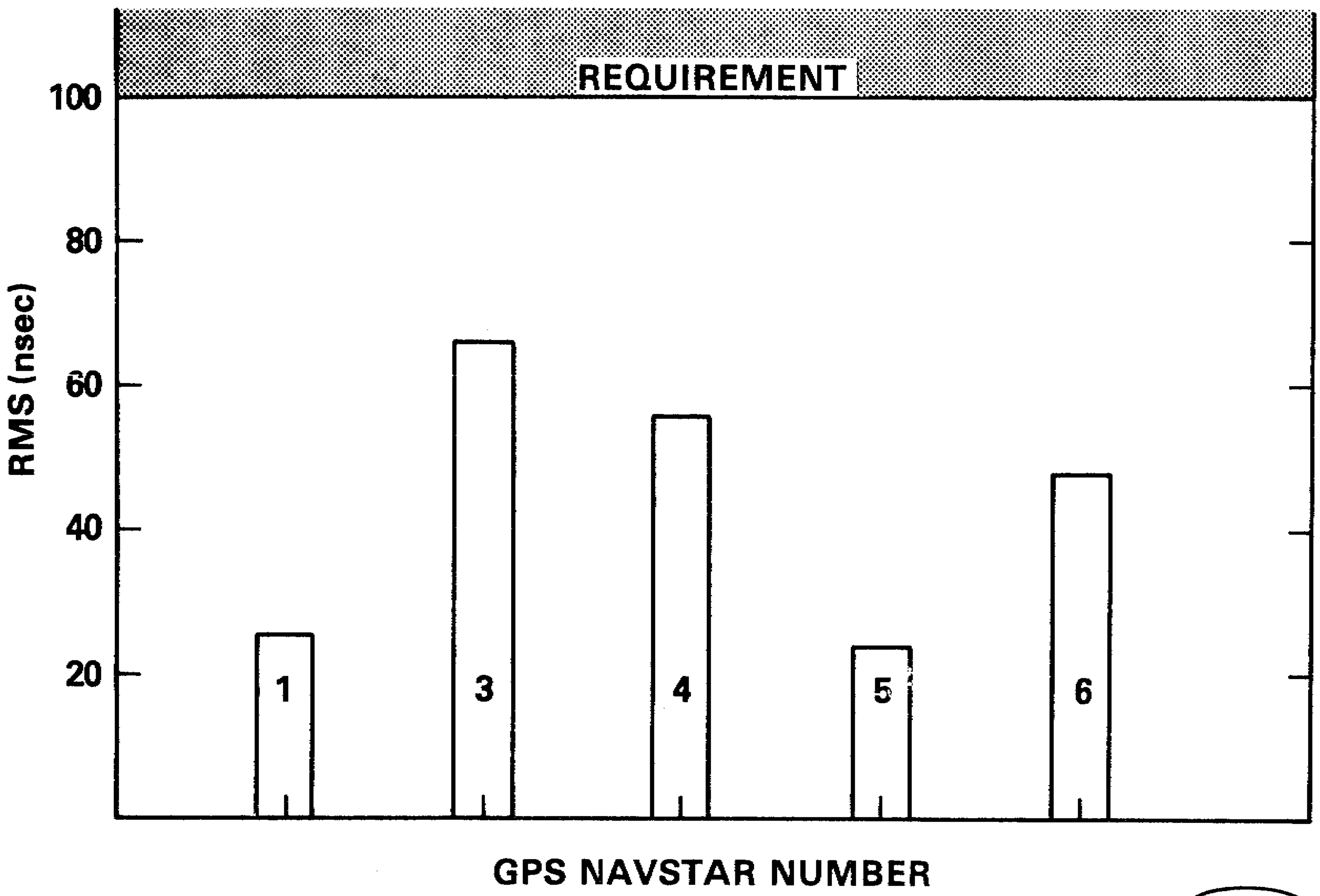


Figure 21

QUESTIONS AND ANSWERS

MR. ALLAN:

I might make one comment. In regard to the same noise from all the satellites, I think one can deduce from that that it is basically not anything in the satellite, but rather in the signal or in the receiver.

MR. OAKES:

Right.

MR. ALLAN:

And, secondly, I think you can also deduce from the long-term data, the 25 nanosecond RMS numbers. That says probably nothing about GPS, but only about the clocks.

MR. OAKES:

Yes. I didn't point that we were making a one clock comparison against the USNO ensemble.

MR. ALLAN:

Right.

In the long term, that is not bad performance for a clock, and that is what you are seeing. So, it really doesn't say anything about GPS per se.