GPS NAVIGATION EXPERIMENT USING HIGH PRECISION GPS TIMING RECEIVERS

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ABSTRACT

Global Positioning System (GPS) Time Transfer receivers were developed by the Naval Research Laboratory (NRL) to provide synchronization for the NASA Global Laser Tracking Network (GLTN).

The capabilities of the receiver are being expanded mainly through software modification to:

* Demonstrate the position location capabilities of a single channel receiver using the GPS C/A code.

* Demonstrate the time/navigation capability of the receiver onboard a moving platform, by sequential tracking of GPS satellites.

Several advanced navigation algorithms were tested, tracking either a full or reduced constellation of the current Phase I GPS satellites.

The experiment was conducted during October 1983 onboard the Italian Navy hydrographic ship "MAGNAGHI". The ship provided a stable platform, able to move with constant speed, while keeping track of its own position with high accuracy. The ship was equipped with a wide range of radionavigation equipment, including Raydist, Motorola Mini-Ranger, Toran, Loran-C, Omega and Transit receivers. There were also onboard atomic clocks with submicrosecond accuracy. To keep an accurate track of the ship's position at sea during the experiment, the

Mini-Ranger system was used with transponders located on the seashore. The Mini-Ranger system provided position to an accuracy of 5 to 10 meters.

This experiment was a joint effort between the following U.S. and Italian agencies and organizations: The U.S. Naval Research Laboratory, the NASA/Goddard Space Flight Center, with the support of the Bendix Field Engineering Corporation, the Italian Navy, the Istituto Elettrotecnico "G. Ferraris" and the Politecnic of Torino (Italy).

INTRODUCTION

The Naval Research Laboratory developed a GPS time transfer receiver for the NASA Goddard Spaceflight Center which was first deployed and tested in June 1981[1]. Since then, six receivers have been completed and delivered to NASA for deployment in the NASA Global Laser Tracking Network (GLTN). The receiver was designed to provide precise time measurements between the time standard of the U.S. Naval Observatory and clocks at remote locations.[2] The primary application is synchronization of remote clocks and clock evaluation. NASA is using the receivers to synchronize remote mobile laser stations to the U.S. Naval Observatory time standard. Precise time is required at each station in order to time tag the data and to acquire satellites with the laser ranging systems.

Before time measurements can be made with the receiver, the position of the antenna must be input in WGS-72 coordinates. Currently, this position is determined by an independent survey before deployment of the receiver. This experiment tests the capability of the GPS time transfer receiver to perform a navigation both on a fixed point and on a slow moving platform. An accurate fixed point navigation capability would allow the GPS receiver to perform cold start synchronizations of field deployed clocks in a stand alone capacity. The moving navigation was performed in order to evaluate the feasibility of providing accurate time synchronization on a slow moving platform.

This navigation experiment uses the existing Phase I NAVSTAR GPS satellites which are a partial set of the final constellation of satellites to be deployed in the 1980s. The results presented here are an evaluation of a time transfer receiver operating in a navigation mode. They are not intended to be used as an evaluation of NAVSTAR GPS accuracy or capability.

Moving Navigation Solution

To perform a navigation, the GPS receiver makes independent range measurements to a number of NAVSTAR satellites. The position of each satellite at the time of measurement is computed from ephemeris data transmitted by each satellite. A ground antenna position is assumed, and the distance to each satellite is calculated. The calculated ranges are subtracted from the measured ranges giving residuals which are used to correct the assumed position. The corrected position is then used to calculate a new residual, and the iterative process continues until the position converges to within some delta value of error. The basic equation in matrix form is

$$P = (A^TWA)^{-1}A^TW(O-C) \qquad (1)$$

where P is the improvement in position

A is the measurement matrix

W is a weighting matrix

and (O-C) is the matrix of differences between measured and computed ranges.

The sequential range navigation is explained in detail in reference 3 and reference 4 and therefore, is presented here as the method used without derivation.

In the moving navigation solution, a five dimensional navigation is performed to determine latitude, longitude, clock offset, course direction, and velocity. A minimum of five satellite measurements are made for each position determination. The solution assumes a constant velocity and course for each fix and a constant height on the surface of the earth at all times. These assumptions are reasonable for the case of a slow moving ship in open seas.

In order to determine the goodness of each solution fit to the data, the geometric dilution of precision (GDOP) was calcualted. The GDOP is defined here as:

$$GDOP = \sqrt{\sigma^2_{LAT} + \sigma^2_{LONG} + \sigma^2_{CLOCK}} \qquad (2)$$

where σ^2_{LAT}, σ^2_{LONG}, and σ^2_{CLOCK} are diagonal terms of the covariance matrix $(A^TWA)^{-1}$ in the navigation solution. GDOP in the classical sense may include all five diagonal terms of the covariance matrix, however, the intention is only to provide a relative measure of goodness of solution for the data presented.

Navigation Exercise

The moving navigation was performed onboard the Italian Navy research vessel "Ammiraglio Magnaghi". The ship's home port is in LaSpezia, Italy, and the experiment was performed off the coast of LaSpezia as shown in figure 1. The ship had a Motorola Mini-Ranger system of navigation which was used as a comparison for the GPS receiver results. The Mini-Ranger system consisted of a two channel transceiver onboard the ship and two transponders located at known positions on the shore. One transponder was located at P^{ta} del Mesco and the other at $I.^{a}$ Palmaria. The navigation was performed while the ship was steering courses of approximately 090° and 270° with a velocity of 8-9 knots. The Mini-Ranger system provided continuous positions of the ship to an accuracy of 5-10 meters. The data was recorded at the epochs of GPS measurements for later comparison at the conclusion of the experiment.

GPS Measurements

A minimum of five satellite tracks were made for each navigation solution. Each satellite track requires approximately five minutes as shown in figure 2(a). Two minutes are required for signal search and acquisition, and then one minute for locking and synchronizing to the satellite data. Once locked and synchronized, satellite ephemeris and clock information is read from the data. Last, satellite range measurements are made, one measurement every six seconds for a period of a minute. A minimum of five of these such tracks are used in each navigation solution. Ideally five different satellites would be tracked as illustrated in figure 2(b). However, because of the limited satellite visibility using the Phase I satellites in Italy, most of the time less than five satellites were tracked, but they were repeated as shown in the example of figure 2(c).

GPS NAVSTAR Visibility

Figures 3 and 4 are two different ways of describing the satellite visibility for the time and place where the experiment was performed. Figure 3 shows the elevation versus time for each satellite. The navigations were performed during the time period from 6 to 9 hours. The plot shows the maximum of five satellites visible above 10° from 0630 to 0730. During the remainder of the time between 0600 and 0900, only three or four satellites were visible.

Figure 4 shows the satellite azimuth and elevation relative to the ship between 0600 and 0900 hours. The best satellite geometry occurs at approximately 0630 when all five satellites are in view above 10° elevation and separated the greatest distance in azimuth. As time approaches 0900 the satellites move closer together, and NAVSTAR 4 goes out of view giving poor geometry for navigation. The accuracy of the results can be correlated to the goodness of satellite geometry and is apparent in the data presented.

Navigation Data

Figures 5 - 14 are plots of the computed navigation solutions. The position of the ship is plotted in latitude and longitude for different sets of navigation data. Each set represents a run by the ship from one end of the area shown in figure 1 to the other. GPS determined positions are represented by O's and Mini-Ranger positions are X's. A value for accuracy is given as a range from the minimum to the maximum deviation of the GPS position from the Mini-Ranger position. The GDOP value as defined in equation (2), is also given. A NAVSTAR visibility plot shows the positions of the satellites used during each navigation solution. The X's on the satellite position arrows represent the times data were taken by the GPS receiver.

For example, figure 5 is run number 1 on October 5 and shows agreement between GPS and Mini-Ranger solutions of from 4 to 52 meters. The NAVSTAR visibility diagram shows that the solution was obtained from eight satellite tracks, three on NAVSTAR 5, one on NAVSTAR 4, and two each on NAVSTAR 3 and NAVSTAR 6. The GDOP of 1.1 is a factor of the number of total measurements used and satellite geometry. GDOP's of lower values indicate better fits of the data to the navigation solution. GDOP is reduced as the number of measurements increase and as the satellites are separated in position. The plot of Mini-Ranger data shows the deviation of the ship from a straight course. Some of the error is attributed to the assumption in the GPS solution that the course is a straight line and constant speed. The straight line fit is apparent in the GPS data.

The other figures (6 - 14) show absolute accuracy results in the range of 50 meters or better for various geometrys and number of tracks. Figures 15 - 17 summarize the results of the GPS navigation accuracy for this experiment using a time transfer receiver. Figure 15 is a plot of the differences in the latitude solutions of GPS from Mini-Ranger for all solutions obtained. The average difference in latitude was 10.8 meters. Figure 16 is the same type of plot showing an average difference in longitude of 23.6 meters. Figure 17 is a plot of ΔTNAV, which is the RSS position difference between the two systems, for all the solutions obtained. The average difference of 45.1 meters is an indication of how good the GPS time transfer receiver can navigate using a partial GPS constellation and, at times, poor geometry.

Stationary Position Determination

The solution of the stationary postion determination is the same as the moving navigation with the velocity constrained to zero. Equation (1) becomes three dimensional solving only for latitude, longitude, and clock offset. A position determination was made using GPS measurements obtained over a period of six days at the Istituto Elettrotecnico Nazionale in Turin, Italy. The results are presented in figure 18. A known position was given in WGS-72 coordinates and the GPS solutions for each day are tabulated. The data used to obtain the solutions were taken over a period of hours from all NAVSTAR satellites whenever the satellites were in view and at positions which provided good geometry. Since the receiver was not moving there was no time constraint to take data from all satellites simultaneously. The results show the differences in latitude and longitude to be less than 10 meters.

Conclusions

The results of the moving navigation experiment demonstrate accuracy of 10 to 50 meters. This shows promise of the possibility of an accurate time transfer on a slow moving platform using existing GPS time transfer receivers.

The 10 meter accuracy in determining the position of a stationary platform demonstrates the ability of the GPS time transfer receiver to become a stand alone system for setting field deployed clocks. NASA has plans to implement this capability on existing receivers in the future and make it operational in the mobile laser systems.

References

1. J. Oaks, A. Frank, et. al., "Global Positioning System Time Transfer Receiver (GPS/TTR) Prototype Design and Initial Test Evaluation," proceedings 13th Annual PTTI Applications and Planning Meeting, December 1 - 3, 1981.

2. C. Wardrip, J. Buisson, et. al., "An International Time Transfer Experiment," Proceedings 37th Annual Symposium on Frequency Control, 1983.

3. T. B. McCaskill, J. A. Buisson, and D. W. Lynch, "Principles and Techniques of Satellite Navigation Using the TIMATION II Satellite," NRL Report 7252, June 17, 1971.

4. A. Bunaguro, T. B. McCaskill, and J. A. Buisson, "Sequential Range Navigation for the NAVSTAR Global Positioning System," NRL Report 7880, July 11, 1975.

5. S. C. Wardrip, et. al., "International Time Transfer and Portable Clock Evaluation Using GPS Timing Receivers," Proceedings 15th Annual PTTI Applications and Planning Meeting, December 6 - 8, 1983.

GPS NAVIGATION EXPERIMENT IN LA SPEZIA, ITALY

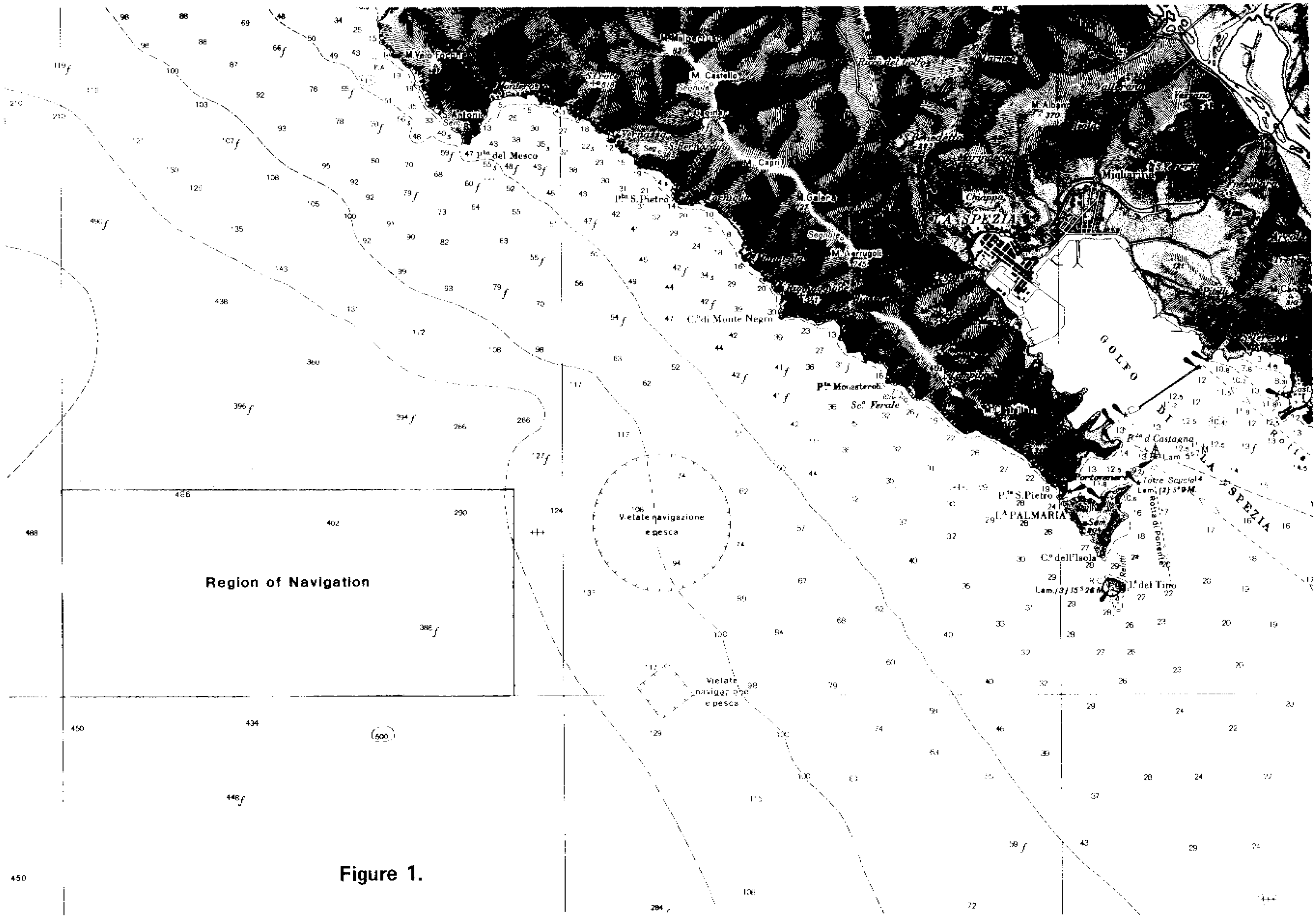
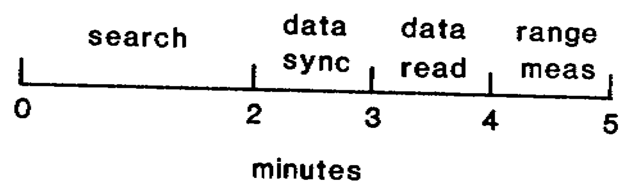


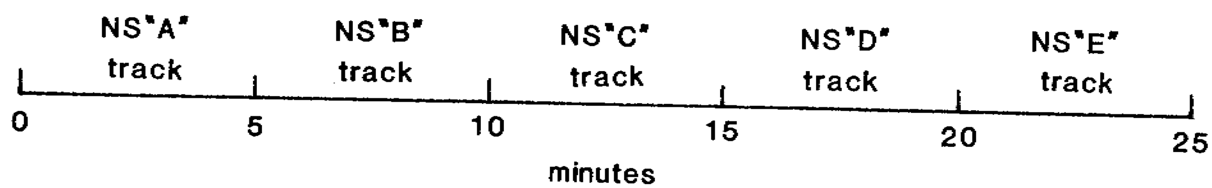
Figure 1.

NAVIGATION MEASUREMENTS

a) Satellite track



b) Navigation fix (2 to 5 satellites, 5 tracks minimum)



c) Example: navigation fix (3 satellites, 5 tracks)

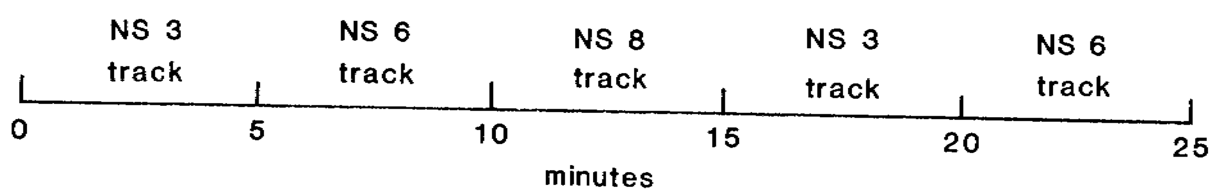


Figure 2

NAVSTAR GPS TIME & ELEVATION VISIBILITIES ON OCT 5, 1983 FOR 44° 6′ N LATITUDE 9° 19′ E LONGITUDE

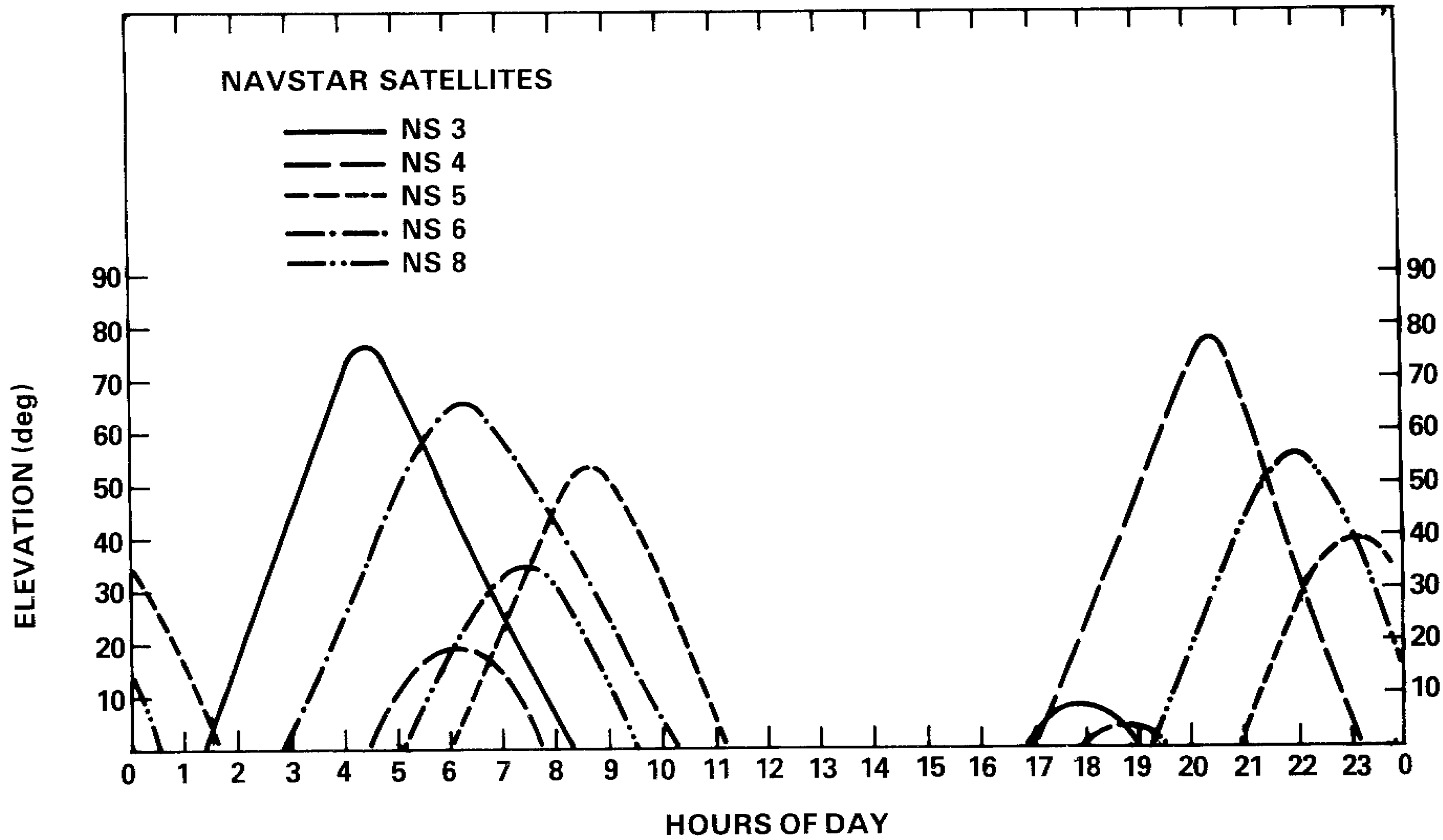


Figure 3.

GPS NAVSTAR AZIMUTH & ELEVATION VISIBILITIES ON OCT 5, 1983 FOR 44°6′ N LATITUDE 9°49′ E LONGITUDE

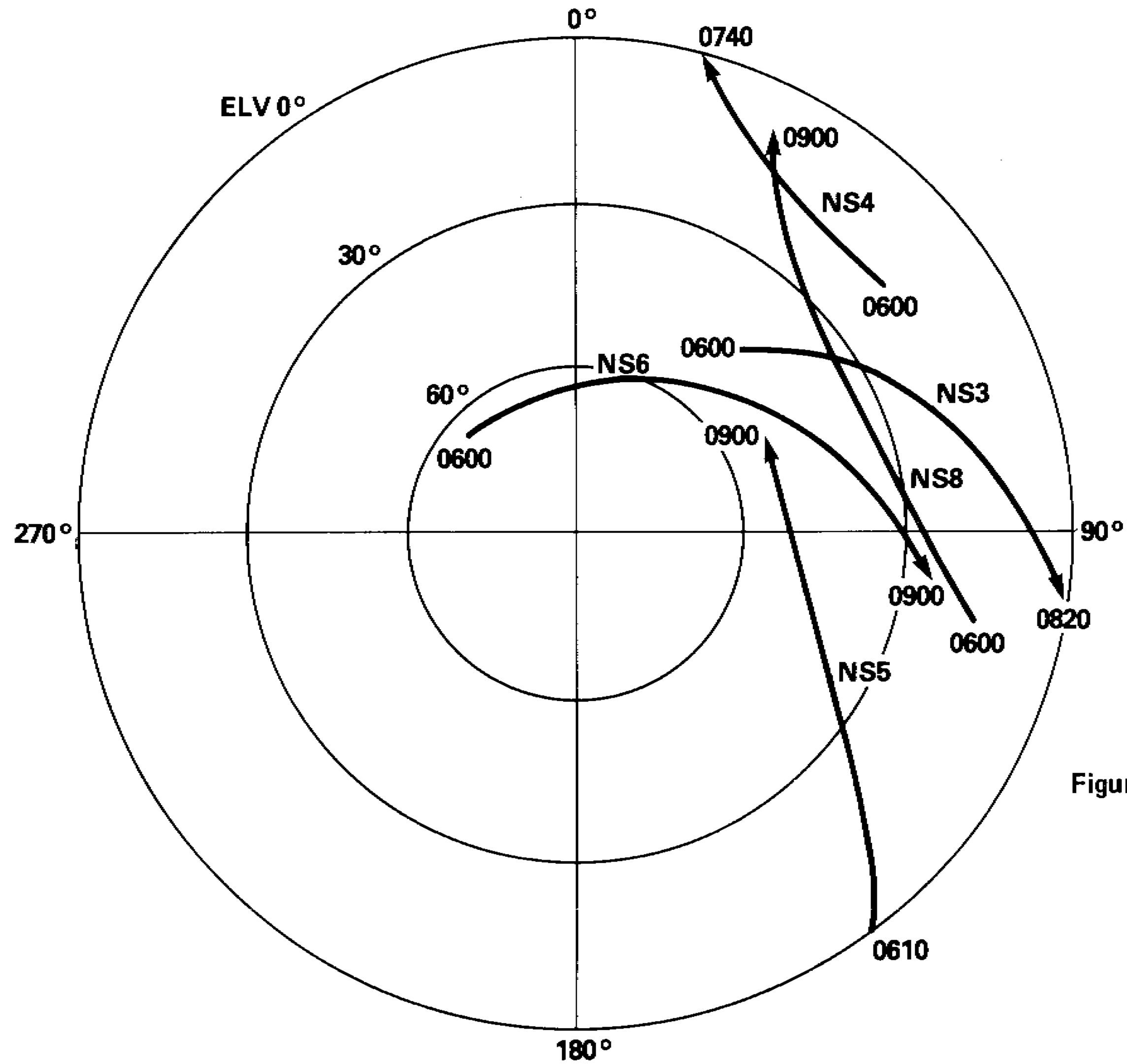


Figure 4.

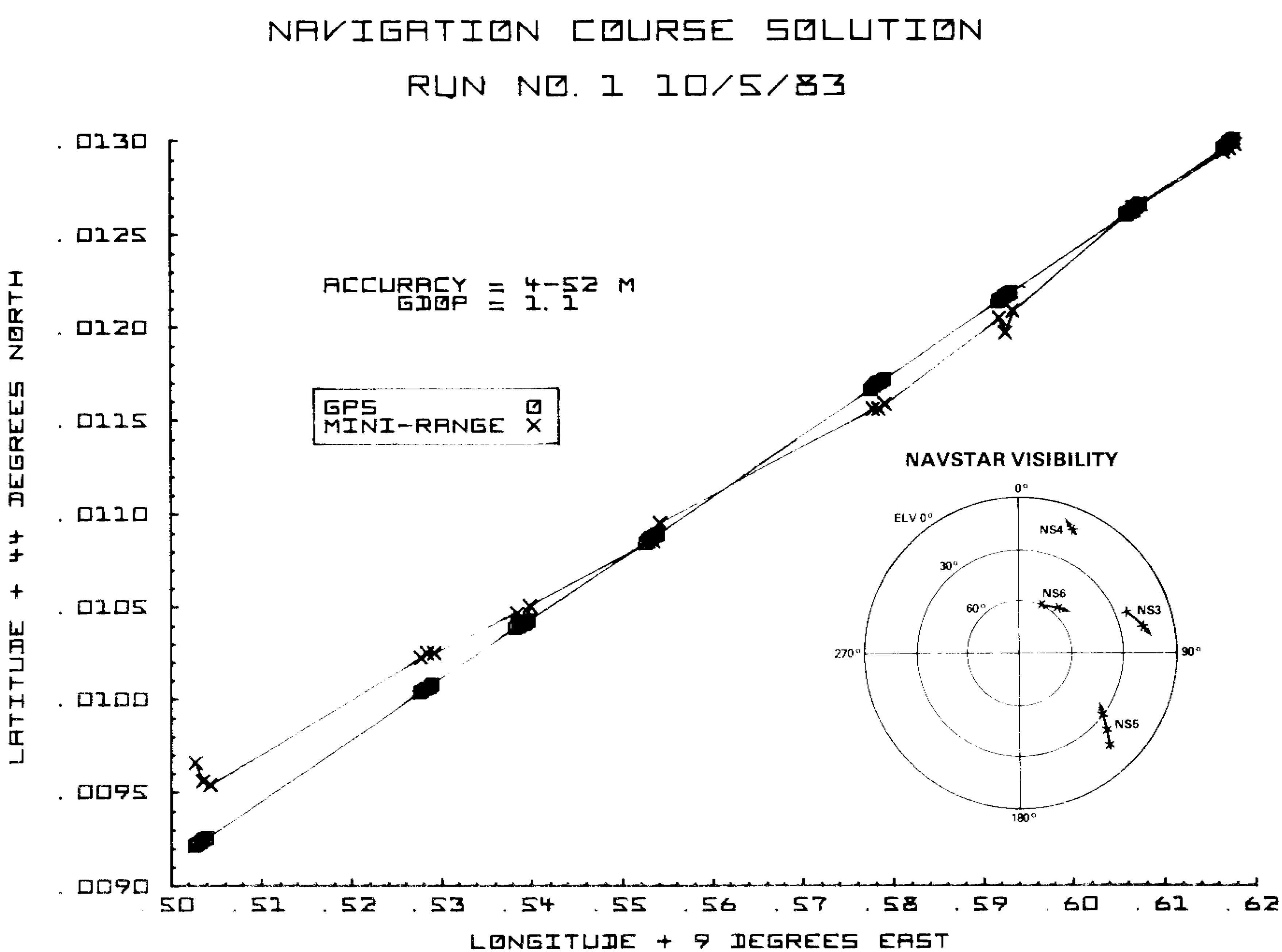

NAVIGATION COURSE SOLUTION
RUN NO. 1 10/5/83
ACCURACY = 4-52 M
GDOP = 1.1
GPS
MINI-RANGE
LATITUDE + 44 DEGREES NORTH
.0130
.0125
.0120
.0115
.0110
.0105
.0100
.0095
.0090
50
.51
.52
.53
.54
.55
.56
.57
.58
.59
.60
.61
.62
LONGITUDE + 9 DEGREES EAST
NAVSTAR VISIBILITY
0°
ELV 0°
30°
60°
270°
90°
180°
NS4
NS6
NS3
NS5

Figure 5.

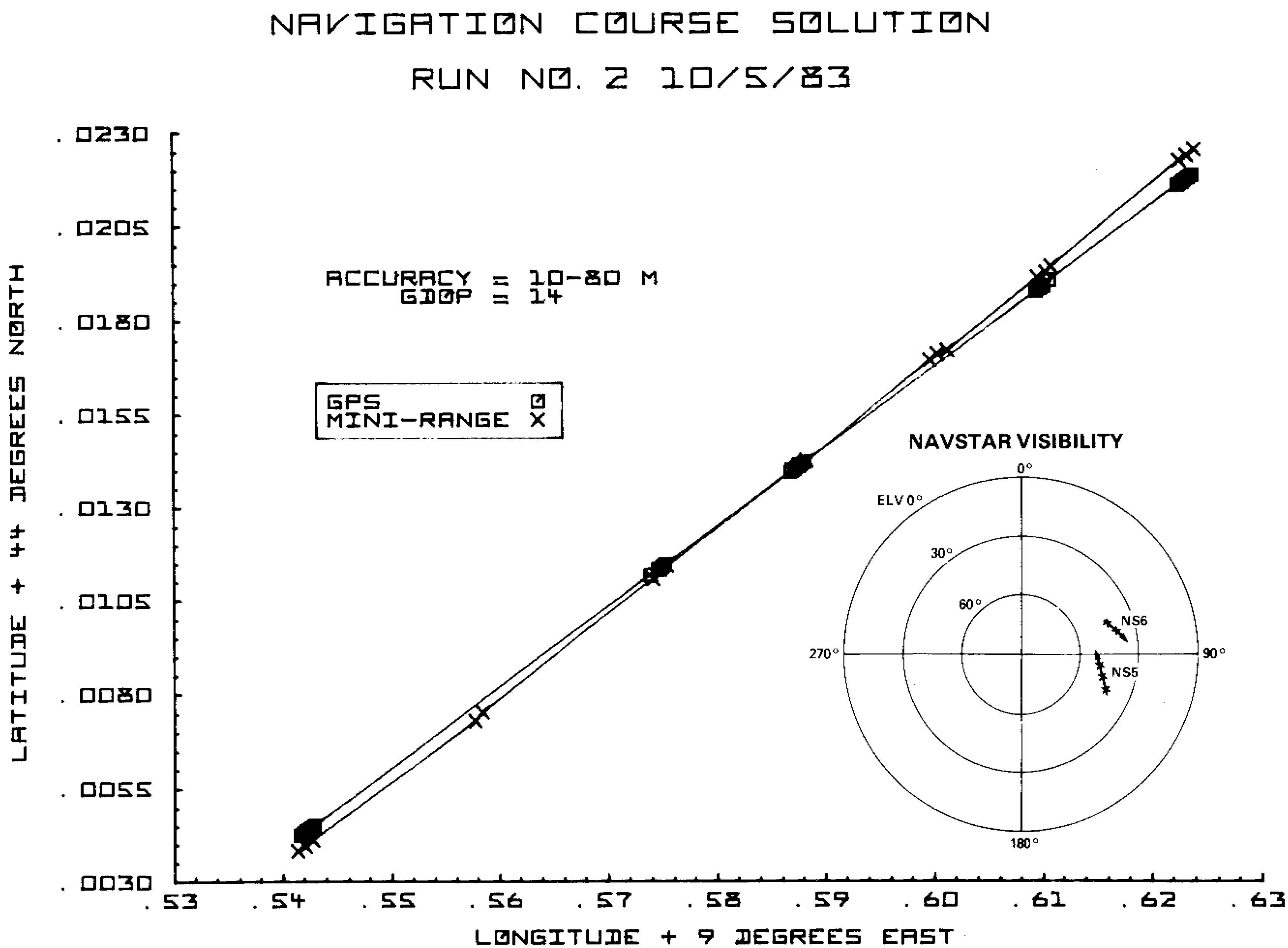

NAVIGATION COURSE SOLUTION
RUN NO. 2 10/5/83
ACCURACY = 10-80 M
GDOP = 14
GPS
MINI-RANGE X
NAVSTAR VISIBILITY
0°
ELV 0°
30°
60°
270°
90°
180°
NS6
NS5
.0230
.0205
.0180
.0155
.0130
.0105
.0080
.0055
.0030
.53
.54
.55
.56
.57
.58
.59
.60
.61
.62
.63
LATITUDE + 44 DEGREES NORTH
LONGITUDE + 9 DEGREES EAST

Figure 6.

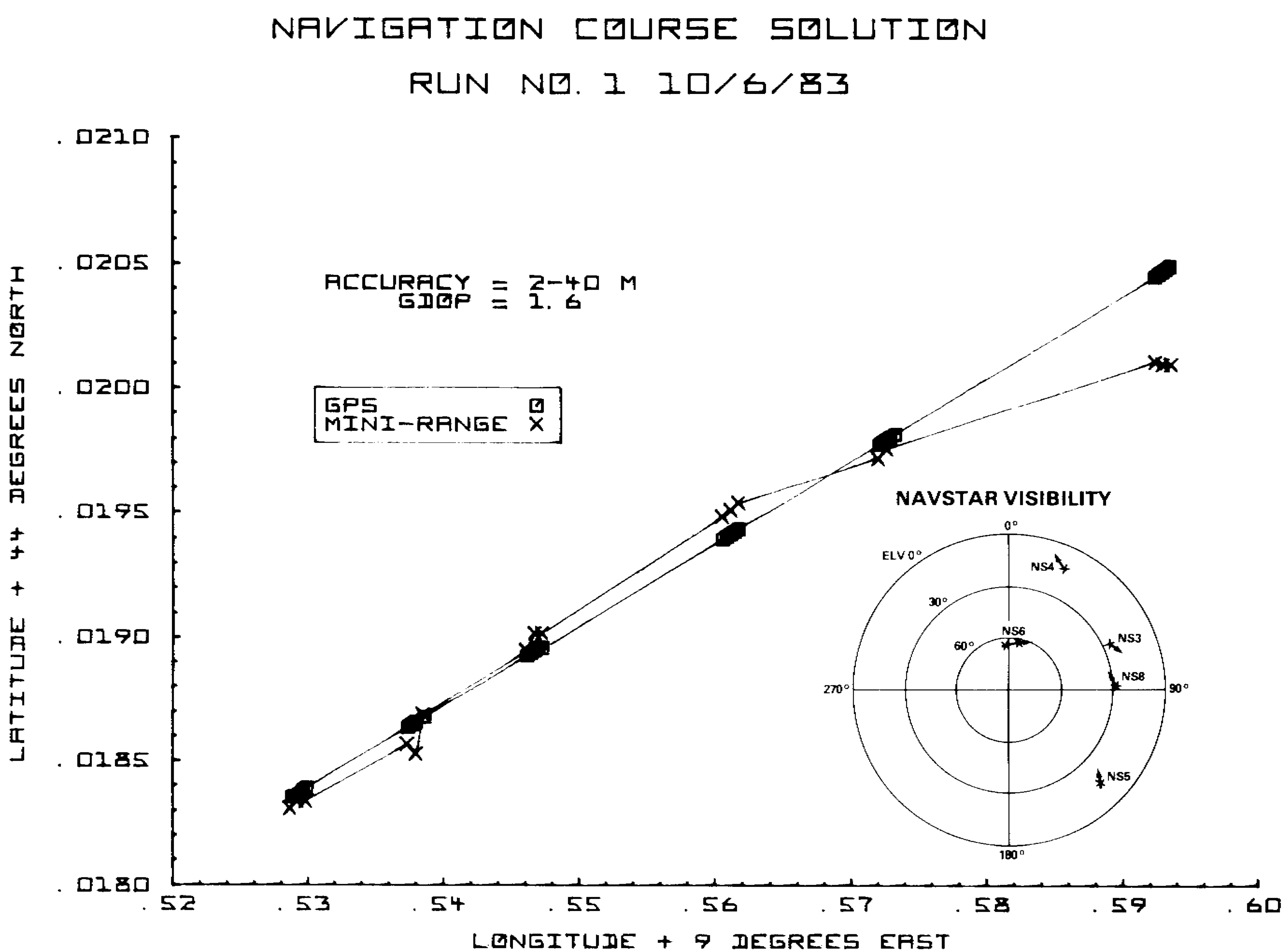

NAVIGATION COURSE SOLUTION
RUN NO. 1 10/6/83
ACCURACY = 2-40 M
GDOP = 1.6
GPS
MINI-RANGE X
LATITUDE + 44 DEGREES NORTH
.0210
.0205
.0200
.0195
.0190
.0185
.0180
.52
.53
.54
.55
.56
.57
.58
.59
.60
LONGITUDE + 9 DEGREES EAST
NAVSTAR VISIBILITY
0°
ELV 0°
30°
60°
90°
180°
270°
NS3
NS4
NS5
NS6
NS8

Figure 7.

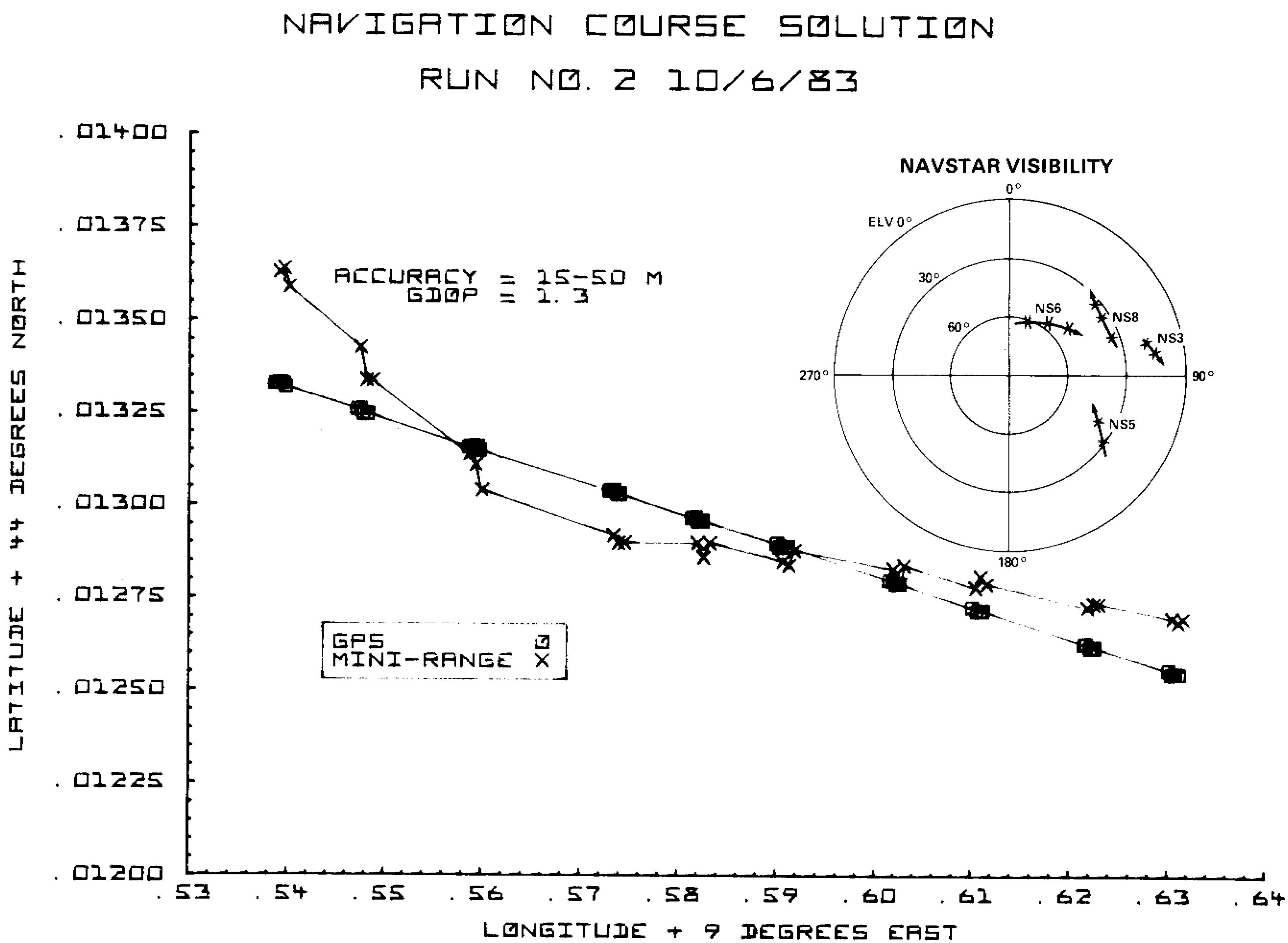

NAVIGATION COURSE SOLUTION
RUN NO. 2 10/6/83
ACCURACY = 15-50 M
GDOP = 1.3
GPS
MINI-RANGE X
NAVSTAR VISIBILITY
0°
90°
180°
270°
ELV 0°
30°
60°
NS6
NS8
NS3
NS5
.01400
.01375
.01350
.01325
.01300
.01275
.01250
.01225
.01200
LATITUDE + 44 DEGREES NORTH
.53
.54
.55
.56
.57
.58
.59
.60
.61
.62
.63
.64
LONGITUDE + 9 DEGREES EAST

Figure 8.

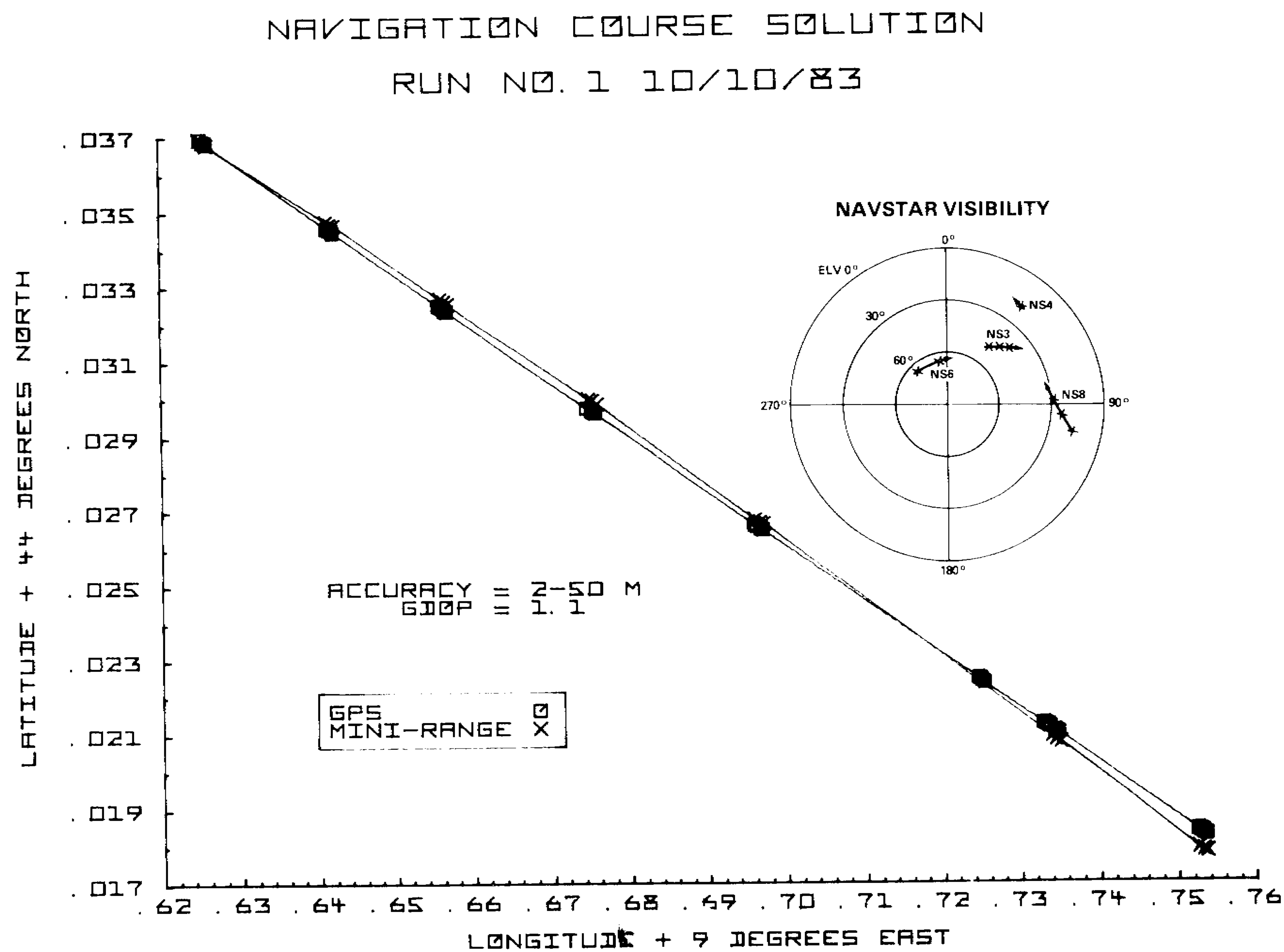

NAVIGATION COURSE SOLUTION
RUN NO. 1 10/10/83
LATITUDE + 44 DEGREES NORTH
.037
.035
.033
.031
.029
.027
.025
.023
.021
.019
.017
.62 .63 .64 .65 .66 .67 .68 .69 .70 .71 .72 .73 .74 .75 .76
LONGITUDE + 9 DEGREES EAST
ACCURACY = 2-50 M
GDOP = 1.1
GPS O
MINI-RANGE X
NAVSTAR VISIBILITY
0°
ELV 0°
30°
60°
270°
90°
180°
NS3
NS4
NS6
NS8

Figure 9.

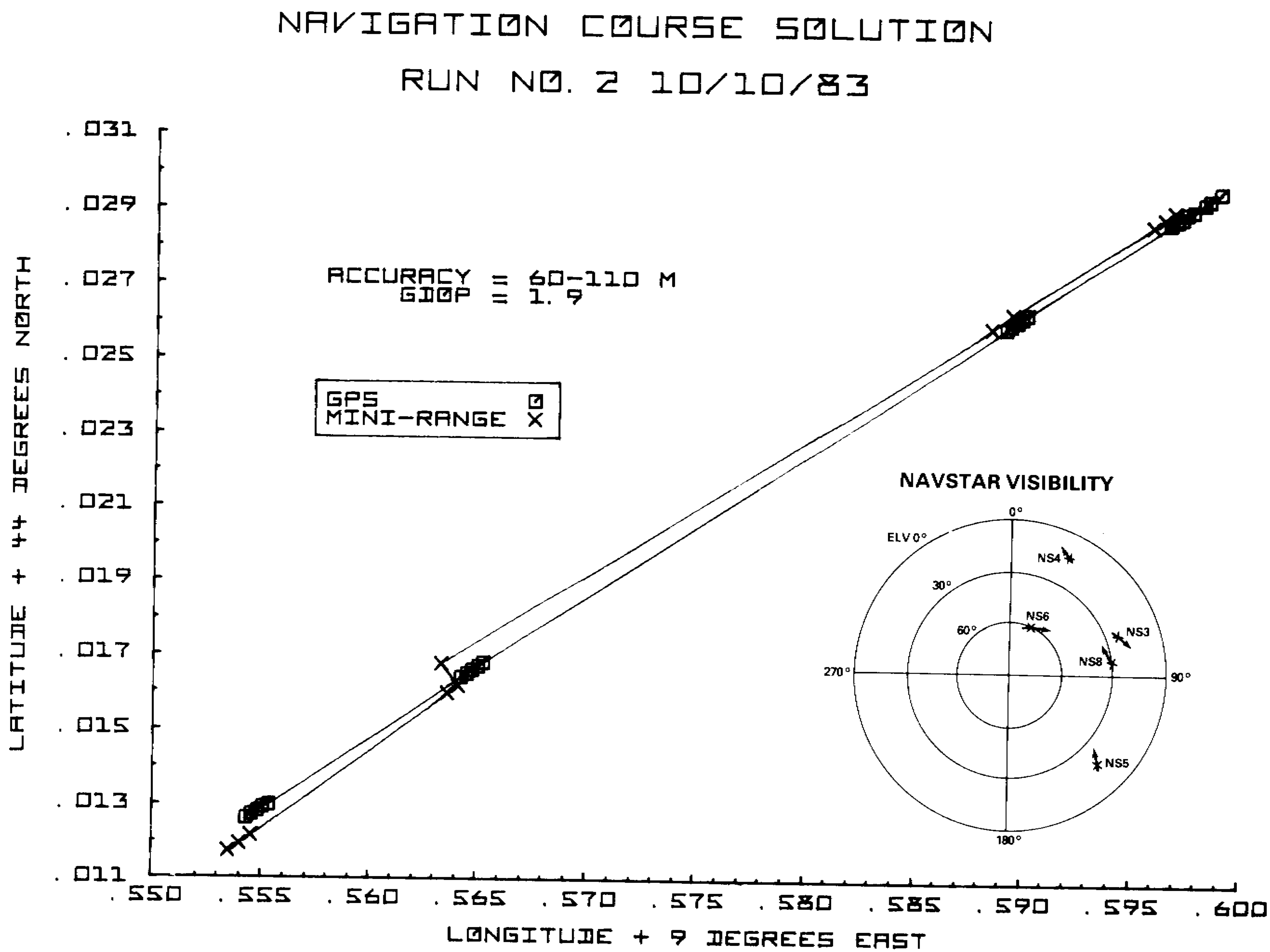
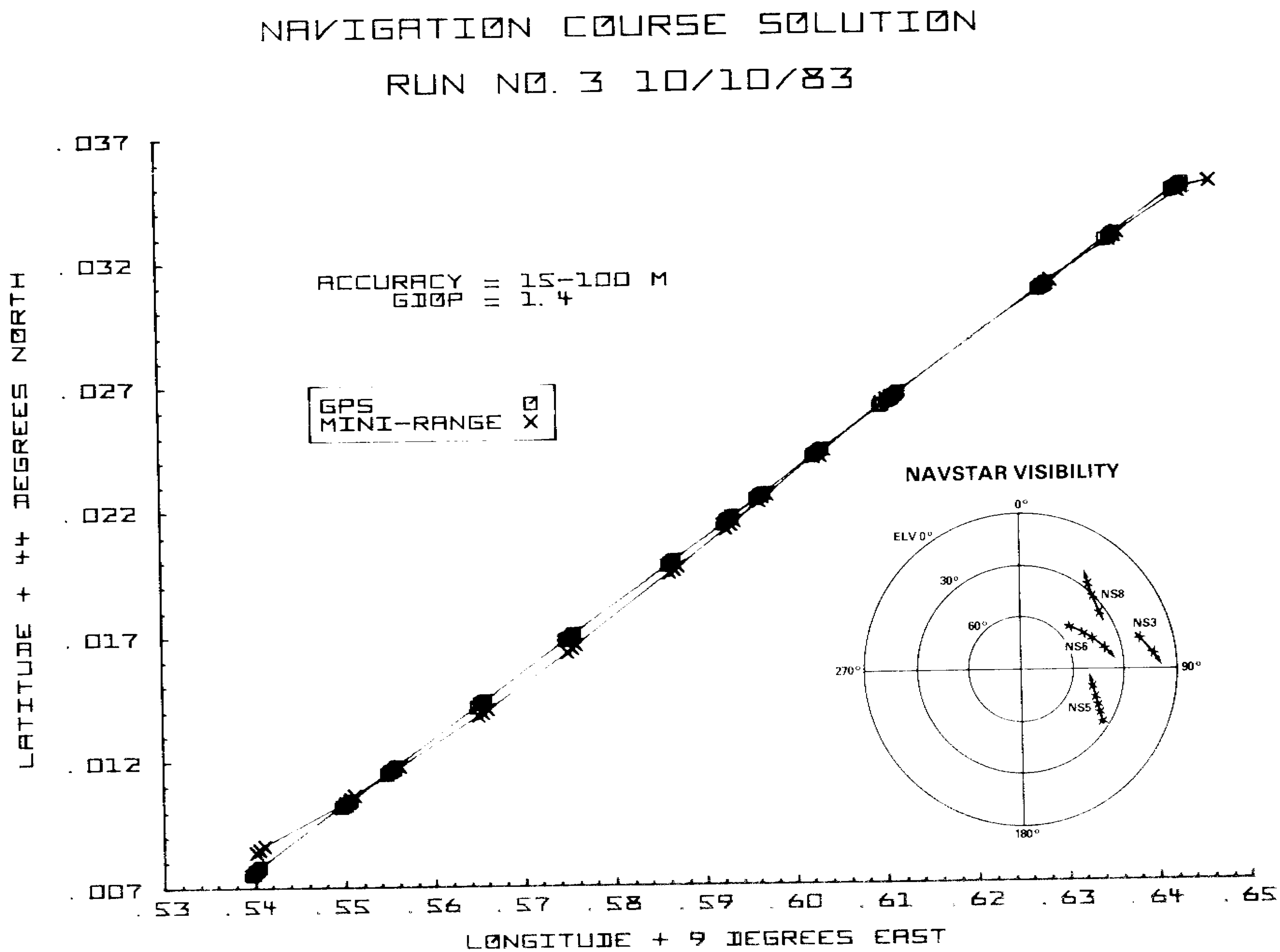
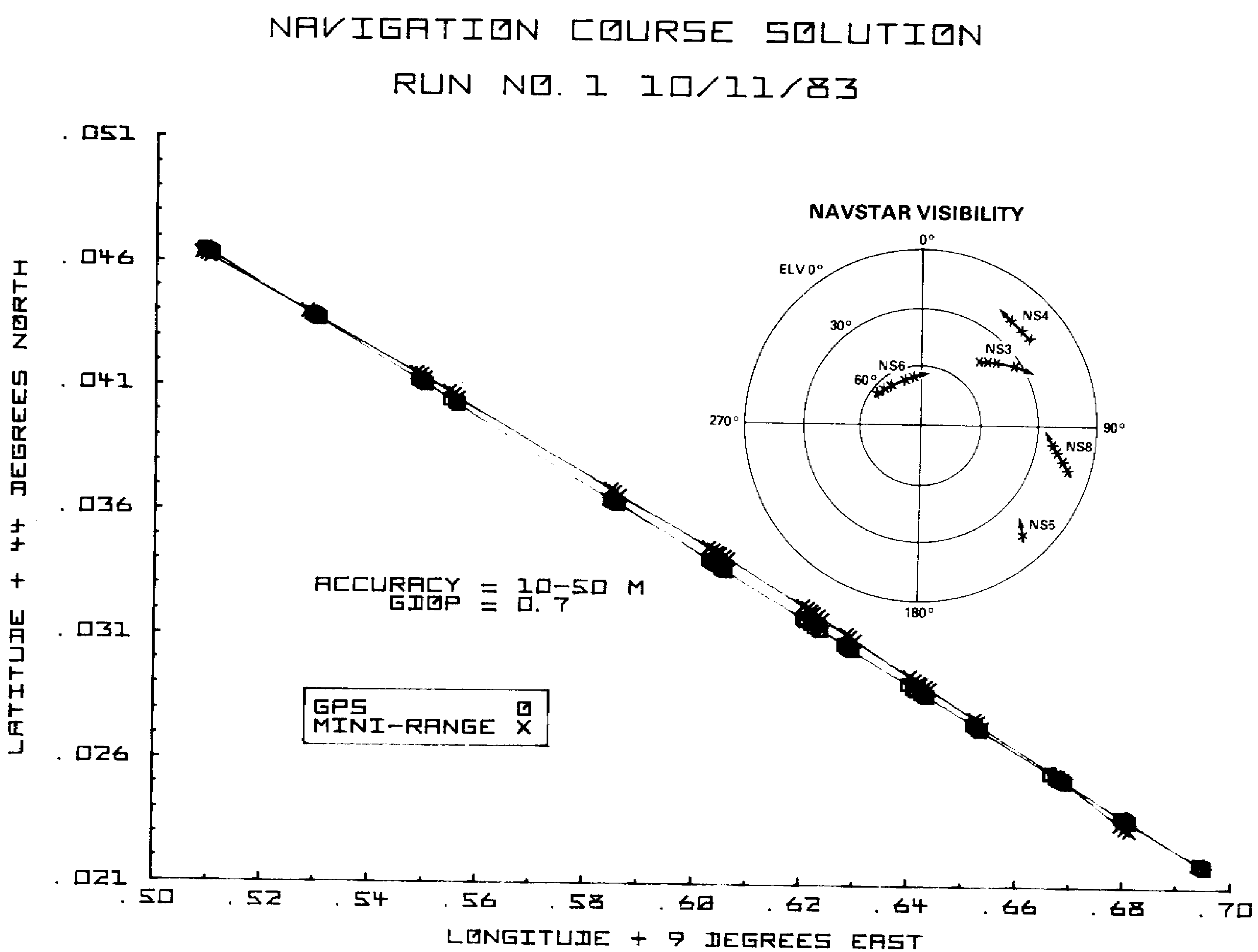

NAVIGATION COURSE SOLUTION
RUN NO. 2 10/10/83
ACCURACY = 60-110 M
GDOP = 1.9
GPS
MINI-RANGE
NAVSTAR VISIBILITY
0°
ELV 0°
30°
60°
270°
90°
180°
NS4
NS6
NS3
NS8
NS5
.031
.029
.027
.025
.023
.021
.019
.017
.015
.013
.011
.550
.555
.560
.565
.570
.575
.580
.585
.590
.595
.600
LATITUDE + 44 DEGREES NORTH
LONGITUDE + 9 DEGREES EAST

Figure 10.



NAVIGATION COURSE SOLUTION
RUN NO. 3 10/10/83
ACCURACY = 15-100 M
GDOP = 1.4
GPS
MINI-RANGE
NAVSTAR VISIBILITY
0°
ELV 0°
30°
60°
270°
90°
180°
NS8
NS3
NS6
NS5
.037
.032
.027
.022
.017
.012
.007
.53
.54
.55
.56
.57
.58
.59
.60
.61
.62
.63
.64
.65
LATITUDE + 44 DEGREES NORTH
LONGITUDE + 9 DEGREES EAST

Figure 11.



NAVIGATION COURSE SOLUTION
RUN NO. 1 10/11/83
.051
.046
.041
.036
.031
.026
.021
LATITUDE + 44 DEGREES NORTH
.50
.52
.54
.56
.58
.60
.62
.64
.66
.68
.70
LONGITUDE + 9 DEGREES EAST
ACCURACY = 10-50 M
GDOP = 0.7
GPS
MINI-RANGE X
NAVSTAR VISIBILITY
0°
ELV 0°
30°
60°
270°
90°
180°
NS3
NS4
NS5
NS6
NS8

Figure 12.

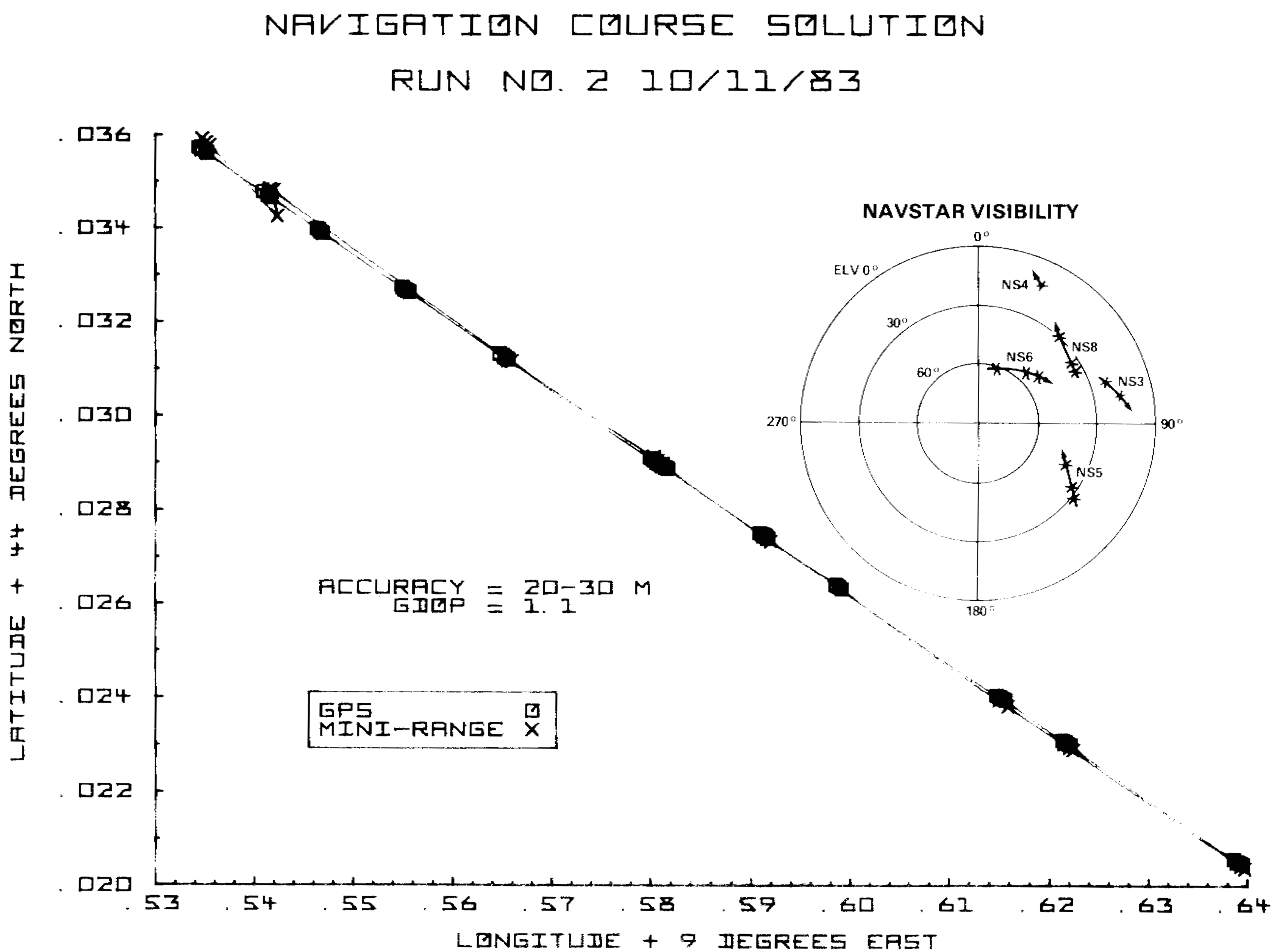

NAVIGATION COURSE SOLUTION
RUN NO. 2 10/11/83
NAVSTAR VISIBILITY
0°
ELV 0°
30°
60°
270°
90°
180°
NS4
NS8
NS6
NS3
NS5
ACCURACY = 20-30 M
GDOP = 1.1
GPS
MINI-RANGE X
.036
.034
.032
.030
.028
.026
.024
.022
.020
.53
.54
.55
.56
.57
.58
.59
.60
.61
.62
.63
.64
LATITUDE + 44 DEGREES NORTH
LONGITUDE + 9 DEGREES EAST

Figure 13.

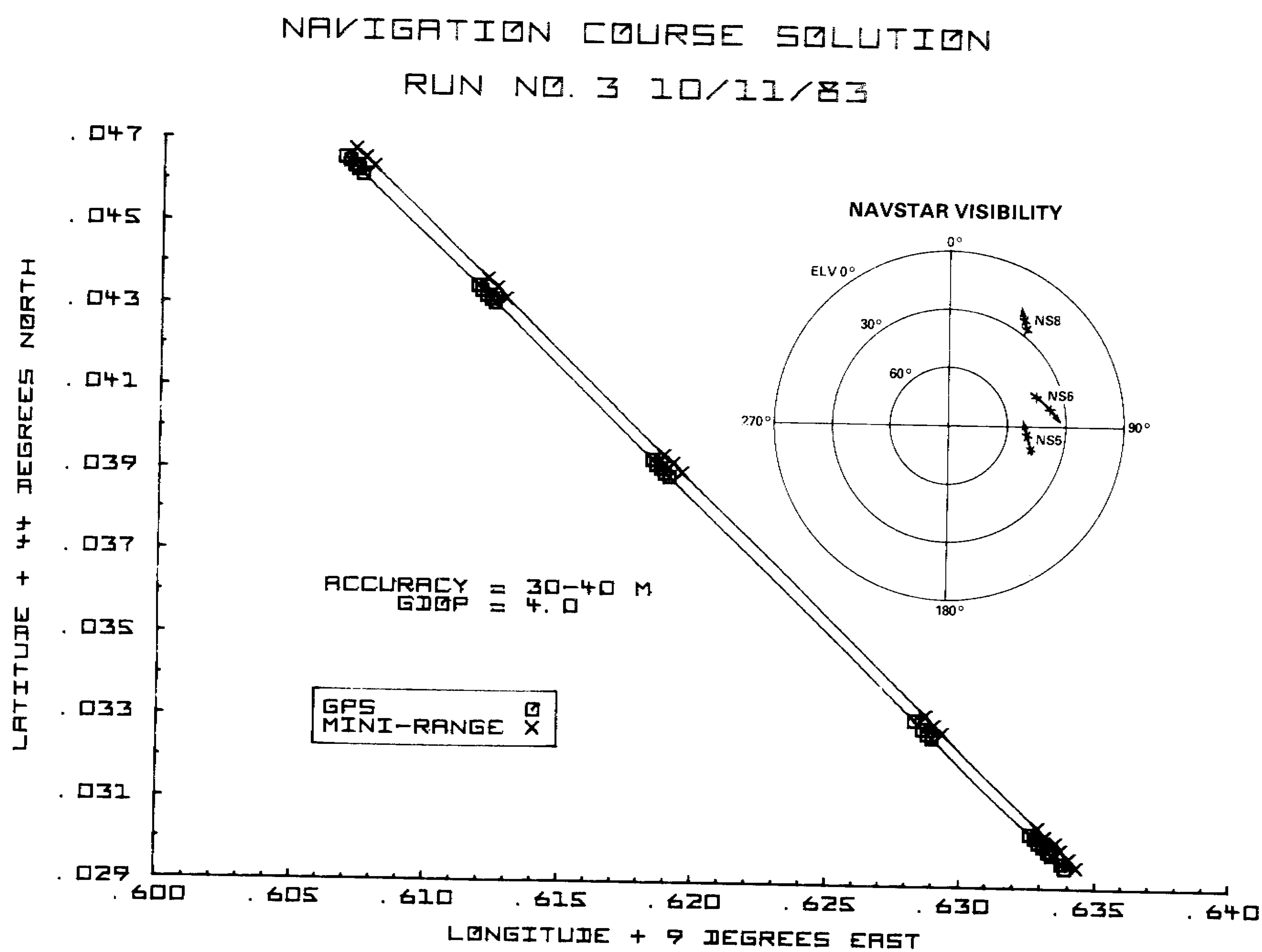

NAVIGATION COURSE SOLUTION
RUN NO. 3 10/11/83
.047
.045
.043
.041
.039
.037
.035
.033
.031
.029
.600
.605
.610
.615
.620
.625
.630
.635
.640
LATITUDE + 44 DEGREES NORTH
LONGITUDE + 9 DEGREES EAST
ACCURACY = 30-40 M
GDOP = 4.0
GPS ☐
MINI-RANGE X
NAVSTAR VISIBILITY
0°
ELV 0°
30°
60°
270°
90°
180°
NS8
NS6
NS5

Figure 14.

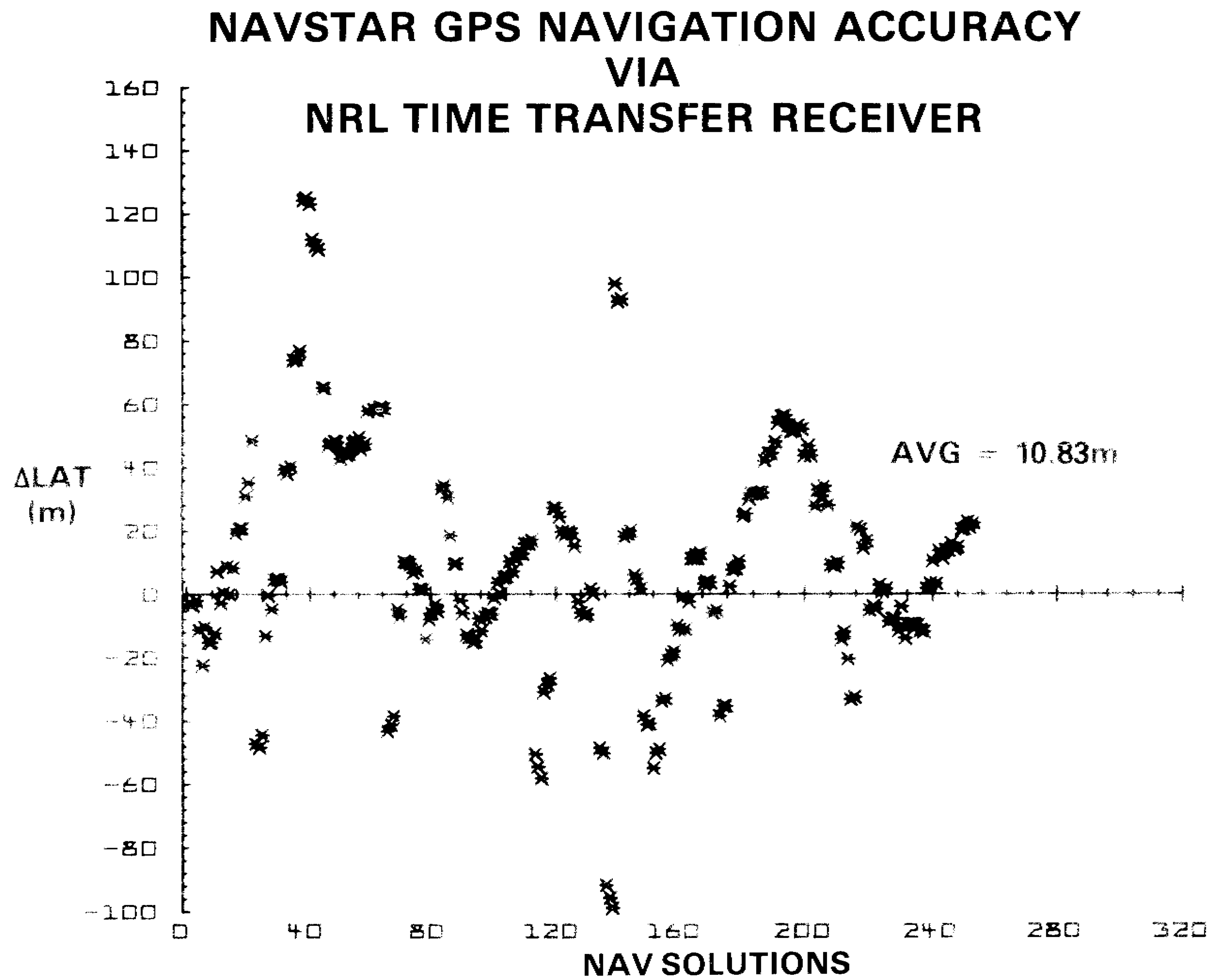

NAVSTAR GPS NAVIGATION ACCURACY
VIA
NRL TIME TRANSFER RECEIVER
ΔLAT
(m)
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
0
40
80
120
160
200
240
280
320
NAV SOLUTIONS
AVG = 10.83m

Figure 15.

NAVSTAR GPS NAVIGATION ACCURACY
VIA
NRL TIME TRANSFER RECEIVER

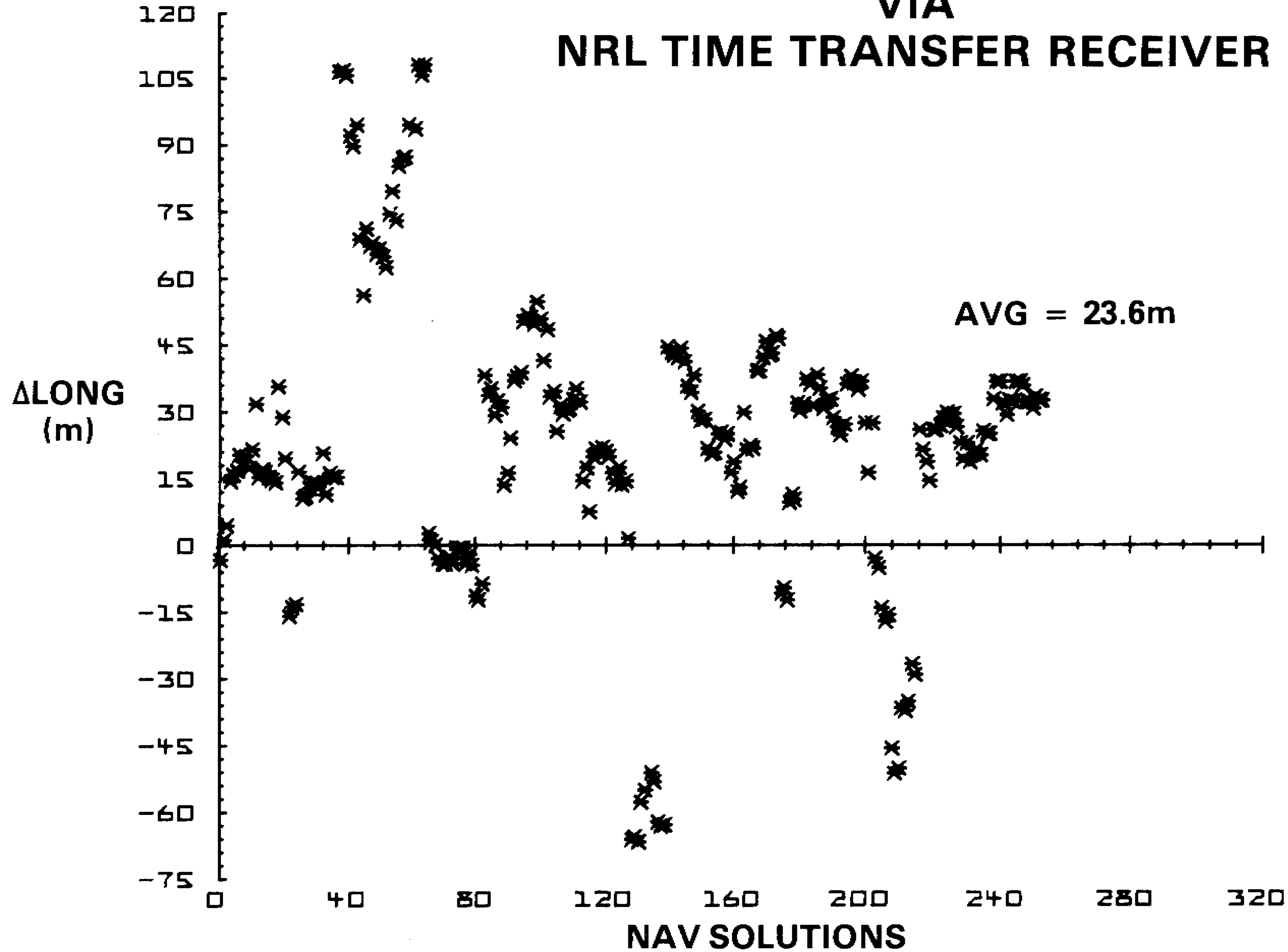


Figure 16.

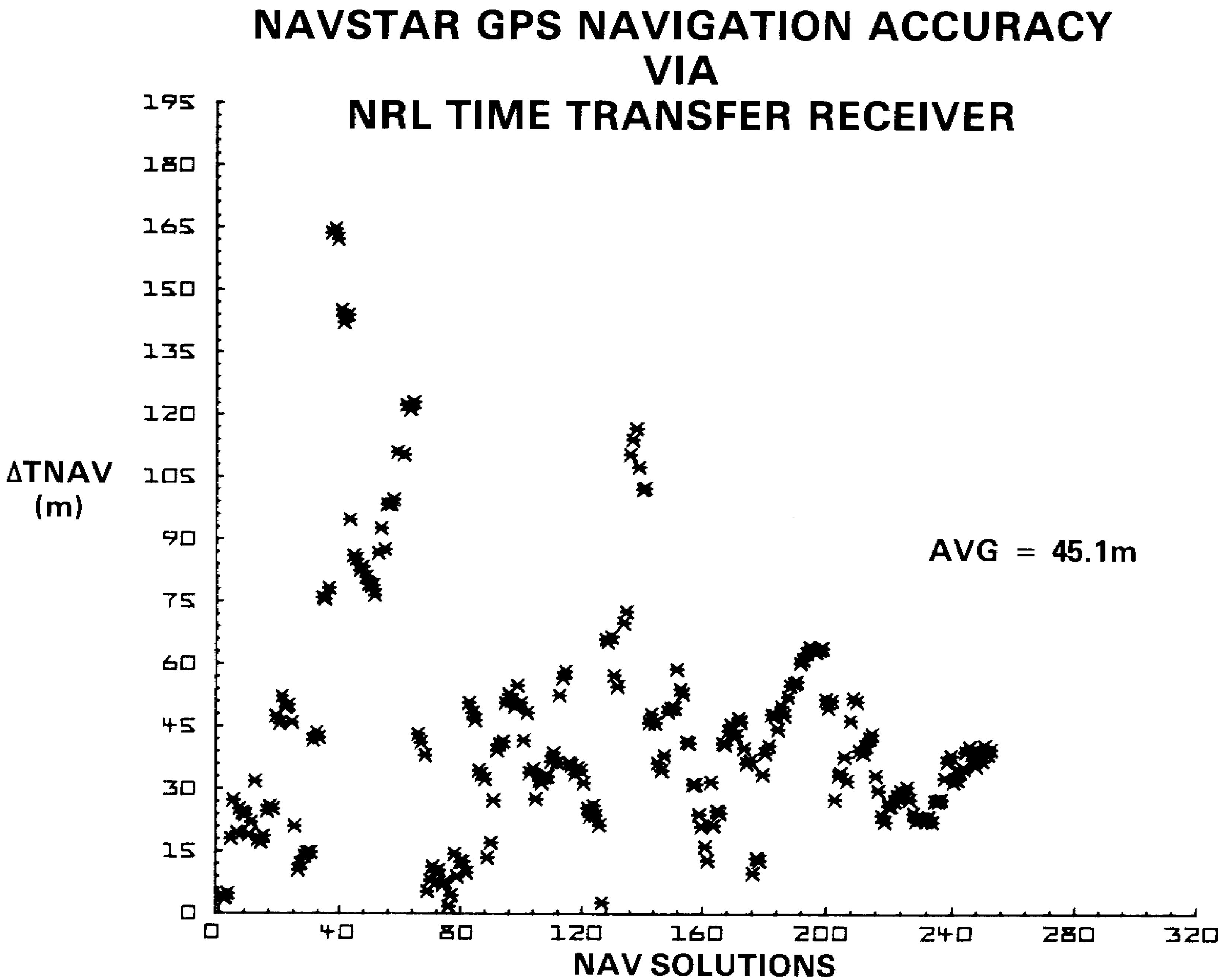

NAVSTAR GPS NAVIGATION ACCURACY
VIA
NRL TIME TRANSFER RECEIVER
ΔTNAV
(m)
195
180
165
150
135
120
105
90
75
60
45
30
15
0
40
80
120
160
200
240
280
320
NAV SOLUTIONS
AVG = 45.1m

Figure 17.

NAVSTAR GPS NAVIGATION POSITION RESULTS AT IEN VIA NRL TIME TRANSFER RECEIVER

KNOWN POSITION WGS-72	MEASURED POSITION					
	DAY 287	DAY 288	DAY 289	DAY 290	DAY 291	DAY 292
LAT 45° 0′ 53.78″	53.35″	53.68″	53.79″	54.11″	53.95″	53.78″
LNG 7° 38′ 20.05″	19.63″	19.98″	19.87″	19.57″	19.83″	19.86″
HGT 299.37m						
ΔLAT (ARCSEC)	0.43	0.10	−0.01	−0.33	−0.17	0.00
ΔLNG (ARCSEC)	0.42	0.07	0.18	0.48	0.22	0.19
≈ ΔLAT (m)	13	3	−.3	−10	−5	0
≈ ΔLNG (m)	13	2	5	15	6	6

Figure 18.

QUESTIONS AND ANSWERS

MR. WARD:

Errors caused by tidal bulge, I would expect, to be of that magnitude, when you compared it with the ranging system, the ranging system is not sensitive to that Z-axis.

MR. OAKS:

I'm sorry. Errors caused by what?

MR. WARD:

Tidal bulge. When you're at sea, the tidal bulges on land, but it's much larger on the sea; and the space craft ephemeris is referred to the geoid and the higher the elevation of the space craft, the larger that error becomes; and you could see that the periodic function in your data there is basically, I guess, tied to the solar-lunar tide period.

MR. OAKS:

As I said, we constrained the height to be a constant in the navigation solution, and we hadn't really looked at how--what you're saying is that what we want to do is look at the elevation of the satellites as compared to the periods when we had disagreements in the navigation solution.

MR. WARD:

That's correct.

DR. REINHARDT:

I have one comment. You should RMS errors, not average them. You should average the squares of the errors if you want to talk about the total error of the experiments.

MR. OAKS:

In which data?

DR. REINHARDT:

In the data where you showed the average error for all the individual runs. I'm saying errors add in the square. You should average the square to get a proper answer for the average error, and then take the square root of that, rather than to average the individual errors.