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Accuracy of the GPS System Using Low Elevation Angle Satellites

Frank L. Lorge

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February 1988

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16. Abstract

This interim report describes a flight test in which Global Positoning System (GPS) satellites at low elevation angles were used to determine aircraft position. Results showed that the elevation angle does not significantly affect the accuracy of the navigational solution.

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EXECUTIVE SUMMARY

This interim report describes a flight test conducted by the Federal Aviation Administration (FAA) Technical Center to investigate the accuracy of the Global Positioning System (GPS) while using satellites at low elevation angles. Flights were conducted in the vicinity of the Atlantic City International Airport using a modified navigational GPS receiver which can track satellites down to the horizon. Accuracy data were collected using satellites at various elevation angles.

Results showed that there was little or no effect on navigational accuracy when satellites low to the horizon were in use. The most important consideration in using satellites at low elevation angles is that their signals are more susceptible to blockage. However, based on the results of this test, the effects on accuracy are almost negligible. The data collected during this project will be further analyzed in later reports.

INTRODUCTION

This interim report describes flight tests conducted by the Federal Aviation Administration (FAA) Technical Center to investigate performance of the NAVSTAR Global Positioning System (GPS) using satellites at low elevation angles. The results of the tests will be used to support technical decisions relative to the certification of GPS receivers. This is one part of a larger effort by the FAA to resolve these and other issues relating to the integration of GPS into the National Airspace System (NAS).

The primary goal of the flight test was to measure accuracy performance of a commercially available GPS receiver as it tracked satellites at various elevation angles. FAA's current policy is to require satellites to be at an elevation angle of 10° or higher before they may be used for navigation. However, the military and commercial communities feel that this is a restrictive requirement and have expressed their desire to have the limit reduced. This project has been designed to provide the technical basis for either maintaining or reducing the satellite elevation requirement.

The data collected will also be used in future studies to examine GPS signal characteristics and receiver performance which will aid in decision-making relative to GPS integration into the NAS. These include determination of accuracies associated with various receiver design implementations, as well as effects of signal strength and signal shielding on receiver performance.

The specific objective addressed by this interim report is to measure the accuracy of a commercially available GPS receiver while it tracks satellites at various elevation angles.

BACKGROUND

The GPS is a satellite-based navigation and timing system developed for the United States (U.S.) Department of Defense (DoD) for use by the military. It provides users with highly accurate position, velocity, and time under most operational conditions. There is widespread interest on the part of the civil community to use the system for aircraft navigational guidance. The U.S. policy is to provide a certain level of service to civil users at no charge. However, because the system was designed for the military user, there are aspects which must be addressed by the FAA before GPS can be certified for use by civil aviation. These include signal availability and performance, integrity monitoring, and user equipment performance. The focus of this test has been in the area of signal performance: in particular, the effects of using satellites at low elevation angles.

The GPS system will consist of a minimum of 18 satellites with 3 on-orbit spares when it becomes fully operational in the early 1990's. The orbits have been designed such that most areas of the Earth have nearly continuous coverage with a minimum of four satellites in view. Performance may be improved by the addition of 3 operational satellites for a total of 24. The DoD has recently modified its policy to add these satellites to the planned constellation, subject to Congressional approval and funding.

A receiver generally requires measurements from four satellites to resolve the four unknowns: position in three spatial dimensions and time. The measurements made in the receiver estimate the distance to each satellite based upon propagation time of the transmitted signal. These measurements, called pseudoranges, are then input to a Kalman filter which provides outputs of position and time bias. The resultant accuracy depends to a great degree upon the geometry of the satellites with respect to the user. A figure of merit called geometric dilution of precision (GDOP) provides an estimate of the effect of geometry on the position solution. Random errors which occur in measuring ranges are multiplied by GDOP to determine their effect on system accuracy. It follows that lower values of GDOP indicate more favorable geometry and result in higher system accuracy.

GPS provides two levels of service. Military users will have access to the precise positioning service (PPS) using the precision (p) code. This is a secure code and access to it is strictly controlled. Civil users will be permitted to use the standard positioning service (SPS) which utilizes the coarse/acquisition (C/A) code. The PPS uses two frequencies and is able to measure atmospheric delays, while the SPS is a single frequency service. Atmospheric effects are modeled rather than measured for the SPS. This is one reason that the PPS has greater inherent accuracy, as errors due to atmospheric delay modeling are one of the largest components in the SPS error budget.

Effects of the troposphere and ionosphere are modeled in the receiver in order to minimize the effects of propagation delays caused by the signal passing through these layers of the atmosphere. Models of these effects are imprecise (particularly ionospheric models) and the effects of modeling errors are magnified as the path length through the atmosphere increases. Satellites which are low to the horizon from the user's view have longer proportional path length through the ionosphere and, therefore, exhibit the greatest uncertainty in determining atmospheric effects. Another consequence of the use of low elevation satellites is attenuation of the signal as it passes through the atmosphere. The transmission pattern of the satellite's antenna array is designed to minimize, but not eliminate, this problem by providing more power to the outside elements, which are aimed less directly at the Earth and whose signal will pass through a greater portion of the atmosphere before reaching a user near the surface.

From a system design standpoint, the GPS satellites have been optimized for use at elevation angles above 5°; this is currently the minimum angle which the military plans to use. However, many potential users and manufacturers have expressed the opinion that any satellite in view may be considered for use under certain conditions. For example, in some cases only three satellites will be in view above 10° while another will be available below this elevation. In this case it is felt that the advantage of adding a fourth satellite measurement to the position solution outweighs the disadvantage of resultant degraded performance.

A receiver generally incorporates some limiting mechanism so that satellites below a particular elevation angle will not be used. This angle is called the "mask angle" for that receiver. As noted above, the mask angle for military receivers is currently 5°. The mask angle which the FAA currently anticipates to implement is not greater than 10°, although this number is advisory in nature as certification criteria have not yet been established.

Navigational system accuracy requirements are currently defined in Advisory Circular (AC) 90-45A. That document sets forth the 95 percent (2-sigma) levels of performance in nautical miles (nmi) of error for area navigation systems in each of three phases of flight: en route, terminal, and nonprecision approach. The Federal Radionavigation Plan (FRP) identifies the anticipated requirements in meters (m) for future navigation systems. Table 1 shows the limits established in each of these documents.

TABLE 1. NAVIGATIONAL ACCURACY REQUIREMENTS

	En Route	Terminal	NonPrecision Approach
AC 90-45A	1.5 nmi	1.1 nmi	0.3 nmi
FRP	1000 m	500 m	100 m

EQUIPMENT

Flight tests were conducted in a Convair-580 twin-turboprop aircraft equipped with various navigation systems, instrumentation, and data collection equipment. Equipment onboard includes two GPS receivers, a data collection computer with aircraft interface unit and tape drive, as well as various navigational sensors, such as Loran, and air data sensors.

The data collection computer is a Norden militarized PDP-11/34M. It directs collection of all aircraft and project data and stores them on 9-track tape. Interface to aircraft signals is accomplished through an aircraft system coupler which takes a variety of signals and converts them to a format suitable for input to the computer. These parameters include aircraft altitude, airspeed, and attitude, as well as navigational system parameters and steering signals.

The Litton LTN-700 is a fast sequencing C/A code receiver which utilizes a single channel front end to track up to four satellites simultaneously. This type of design attempts to minimize hardware costs without sacrificing performance. The design also trades off signal strength for dynamic performance because of its hardware multiplexing technique. Approximately 6 decibels (dB) of signal strength available at the antenna are lost through the use of this architecture. The receiver provides serial data outputs through an RS-232 interface and an ARINC-429 port. It may also be controlled through the RS-232 interface.

The LTN-700 used for this flight test was specially modified by the manufacturer to eliminate the software mask angle. The receiver in this configuration will attempt to track the four satellites with the best geometry, regardless of elevation angle. This can lead to cases where a satellite low to the horizon is selected for use even if it is shaded or has poor signal strength. For this reason the results of this test should not be considered as a measure of performance for the LTN-700 production receiver.

The Magnavox Z-set is a Phase I prototype C/A code receiver which uses a single channel and sequential scanning. In this design the receiver tracks each

satellite continuously for approximately 1 second at a time. It sequentially tracks up to four satellites which are included in the navigation solution. This design also minimizes hardware at the expense of software. No signal strength is lost, but the receiver will not perform as well in a dynamic environment as one that tracks multiple satellites simultaneously. The Z-set interfaces to the PDP-11 UNIBUS™ to provide position and satellite tracking data.

A modified Nike-Hercules tracking radar at the FAA Technical Center was used as a position reference to determine actual aircraft position throughout the flight. The radar interrogates a transponder in the aircraft and measures time delay to resolve position. It produces a tape containing the aircraft's position at a selected rate; in this case, 10 times per second. Records are time stamped with the output of a clock synchronized to Universal Coordinated Time. This time is used to merge, during post-flight processing, airborne data with radar data collected on the ground. Overall accuracy of the radar system is approximately 20 meters throughout the flight test area.

FLIGHT TEST PROCEDURE

Flights were conducted in the vicinity of the FAA Technical Center at the Atlantic City International Airport. A total of approximately 12 hours of the flight test data collected to date are presented in this report. During this time the LTN-700 was operated with a mask angle of 0°, with satellite selection based on geometry only.

A representative flight route is shown in figure 1. It shows radar tracked position of the aircraft as determined by the Nike-Hercules tracking radar. The pattern crosses over the Atlantic City International Airport to produce a cloverleaf. This pattern was generally flown at 3000 to 4000 feet.

Approaches were flown to each of the available runways at Atlantic City International Airport to observe any direction-dependent characteristics, and to measure performance during vertical maneuvering.

TEST RESULTS

Test results available to date are presented statistically in tables 2 and 3 and graphically in figures 2 through 8. These tables show the accuracy of the modified LTN-700 for position solutions when satellites at various elevation angles are included in the solution. Z-set accuracy data are presented for all elevation angles.

TABLE 2. LTN-700 ACCURACY RESULTS IN METERS

Date	Samples	North Error Mean	North Error SD	East Error Mean	East Error SD	Up Error Mean	Up Error SD
All satellites above 7.5°							
1/13/87	4692	3.37	27.40	-6.11	8.09	-25.56	120.63
1/14/87	4692	6.24	42.44	-4.17	12.59	-8.51	162.81
1/20/87	3070	-1.58	59.94	-2.45	5.43	-13.89	80.86
1/22/87	3406	-1.74	57.32	-19.91	37.62	134.47	212.25
at least one satellite below 7.5°							
1/13/87	389	10.13	38.40	-13.53	10.08	-167.11	345.78
1/14/87	196	-15.48	52.10	4.83	6.80	12.50	42.08
1/20/87	1438	-4.15	33.01	-3.53	8.34	11.95	200.52
1/22/87	1075	-29.16	28.08	-22.66	16.14	244.76	250.20
at least one satellite below 5°							
1/13/87	162	-26.41	51.99	-6.07	5.55	23.14	55.02
1/20/87	878	-3.12	36.45	-1.92	9.19	49.49	193.79
1/22/87	635	-33.68	30.70	-23.77	19.11	275.33	308.26

TABLE 3. Z-SET ACCURACY RESULTS IN METERS

Date	Samples	North Error Mean	North Error SD	East Error Mean	East Error SD	Up Error Mean	Up Error SD
1/13/87	1671	9.31	93.55	2.55	6.91	2.59	24.60
1/14/87	1365	14.66	48.28	0.66	12.39	6.20	26.79
1/22/87	1260	13.71	25.69	0.87	5.17	-1.58	33.75

The three conditions identified for the LTN-700 in table 2 are for four-satellite solutions in which: all satellites are above 7.5°, at least one satellite is between 5° and 7.5°, and at least one satellite is below 5°. Also, accuracy of the Z-set is provided in table 3 for comparison purposes. The Z-set uses only satellites at least 5° above the horizon. In all cases HDOP was less than 3.2 for the LTN-700.

Both tables follow the same format. Flight dates are shown with the mean and standard deviation (SD) in north, east and up directions, as well as sample size.

The plots show errors as compared to radar in all three spatial dimensions. Plot units on the vertical scales are meters of error in the north, east and up directions shown versus time in minutes on the horizontal scale. The time axis is based on a 24-hour clock. The time 1310, for example, is 10 minutes after 1 p.m.

The data in the plots are generally well behaved. However there are several instances of errors due to radar tracking characteristics. Errors introduced by the radar tracking process have been deleted from the statistics, although they are presented in the plots. They result in the ramping effect evident during several periods in the plots.

One radar characteristic is a large bias in all three traces occurring at the beginning of the flight. This is due to the fact that the aircraft is at or below the radar horizon as it taxis for takeoff. Once the aircraft is airborne and within radar coverage, the radar begins tracking. At that point the radar system performs at its specified accuracy level.

A second characteristic is one in which the radar track position becomes invalid for some reason (lost target, data anomalies, tracker reset, etc.) and "freezes" at the last valid position. The result is the ramping effect, noted above, which is evident in the plots in the north and east directions. This occurs most frequently when the aircraft is near the limits of radar coverage and at low altitude.

The plots also show several gaps in the data which are the result of aircraft acceleration and shielding during turns. This can cause the receiver to break its signal lock on the satellite. The trace resumes once the aircraft levels off and all satellites are once again in view. The LTN-700 will very quickly detect this condition and annunciate it to the pilot or operator, indicating that the receiver cannot provide accurate navigation for a temporary period.

Statistical data (see tables 2 and 3) show that error levels do not vary significantly as elevation angle decreases. The effect of signal behavior from day to day is more pronounced than the effect of satellites moving toward the horizon during a flight. A gradual trend may be discerned in which error increases as elevation angle decreases. This is most likely due to effects of modeling the ionosphere and varying signal performance.

Representative plots of signal-to-noise ratio (SNR) versus elevation angle are shown in figures 9 and 10. In one case SNR is constant through all elevation angles, while in the second there is a pronounced degradation of SNR as elevation angle decreases. The amount of data are limited and no broad conclusions can be drawn from them.

CONCLUSIONS

The results presented in this report show that accuracy performance does not degrade significantly as satellites low to the horizon are included in the position solution. The worst case situation observed was well within the limits established in Advisory Circular 90-45A (AC) for all phases of flight, and was within the the limits contained in the Federal Radionavigation Plan (FRP) for en route and terminal operations.

Performance of the modified LTN-700 was generally comparable to the Z-set in the horizontal plane.

Changing the mask angle in the receiver may affect the number of satellites available when the possibility of shielding is taken into account. Satellite elevation angle should be considered in the satellite selection process. Further study must be conducted to determine the nature of tradeoffs between signal quality and geometry, and the possibility of deselecting satellites which may be temporarily shielded by aircraft structure.

From the data available to date it appears that four-satellite position solutions using low-elevation satellites meet the requirements of AC 90-45A for all phases of flight. They also meet the requirements of the FRP for the en route and terminal phases of flight. The receiver generally failed to meet the requirements of the FRP for nonprecision approach when satellites below 7.5° were in use.

Use of low angle satellites does not preclude derivation of accurate horizontal navigational information. In some cases the receiver performed as well using satellites at low elevations as it did with all satellites above 7.5°. Although use of these low elevation satellites may cause difficulty in tracking the signal because of blockage, there appears to be no significant degradation of accuracy when the signal is available.

SNR results are inconclusive with respect to low angle satellites due to the limited amount of data available. Signals from satellites between 0° and 10° may exhibit lower SNR which varies with elevation angle. Further study is required to determine SNR performance requirements.

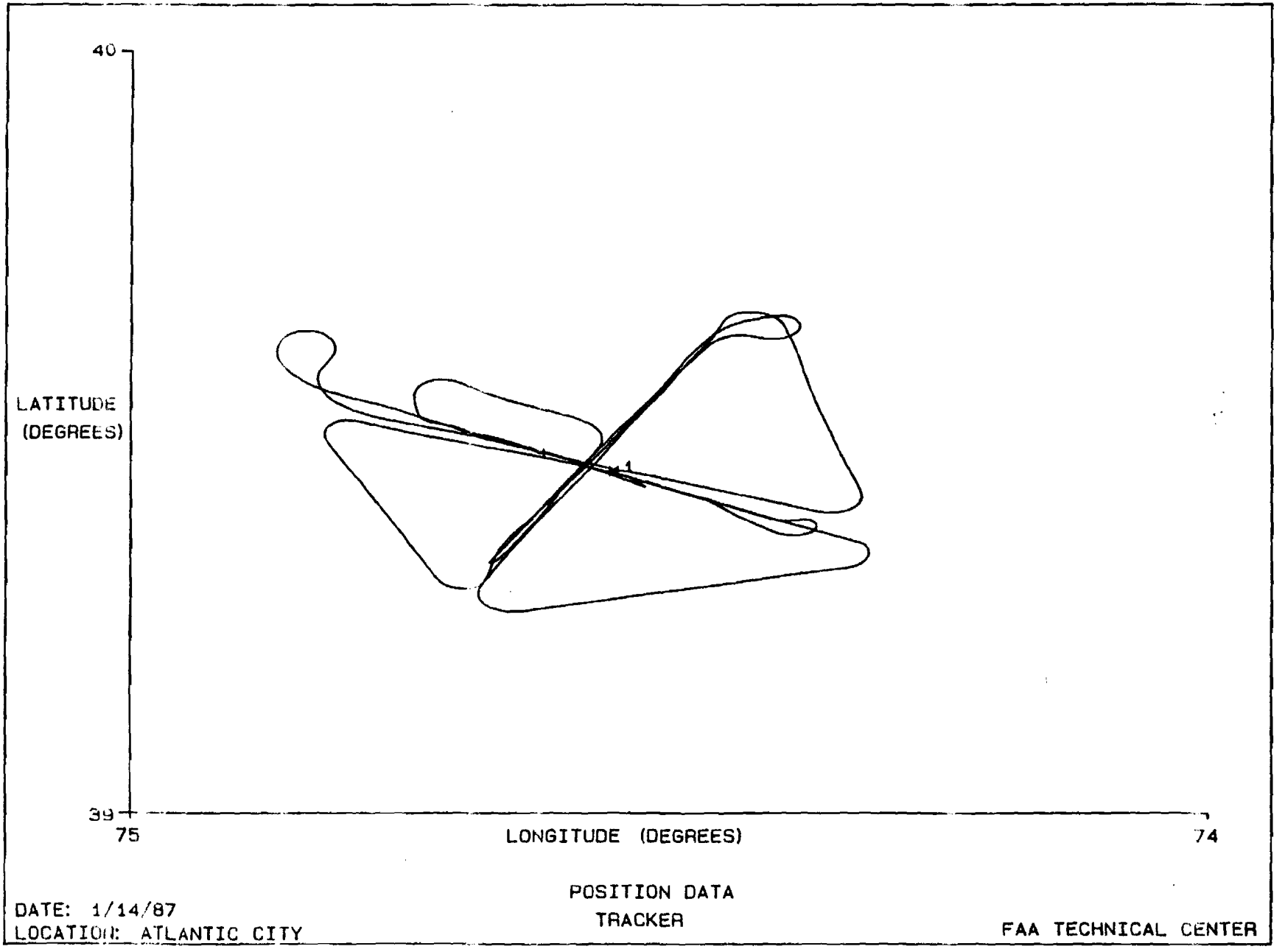


FIGURE 1. POSITION DATA - TRACKER

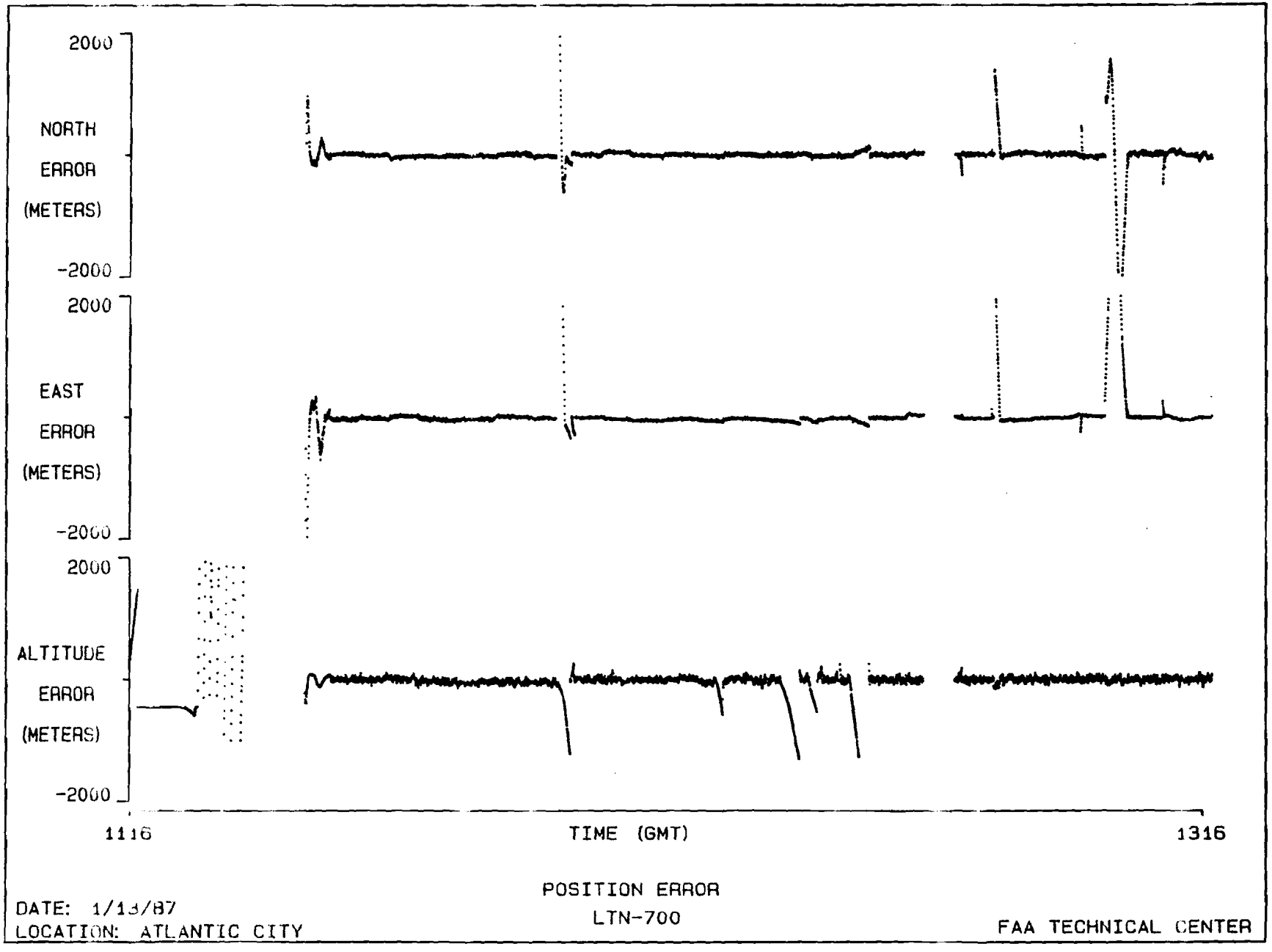


FIGURE 2. POSITION ERROR - LTN-700 1/13/87

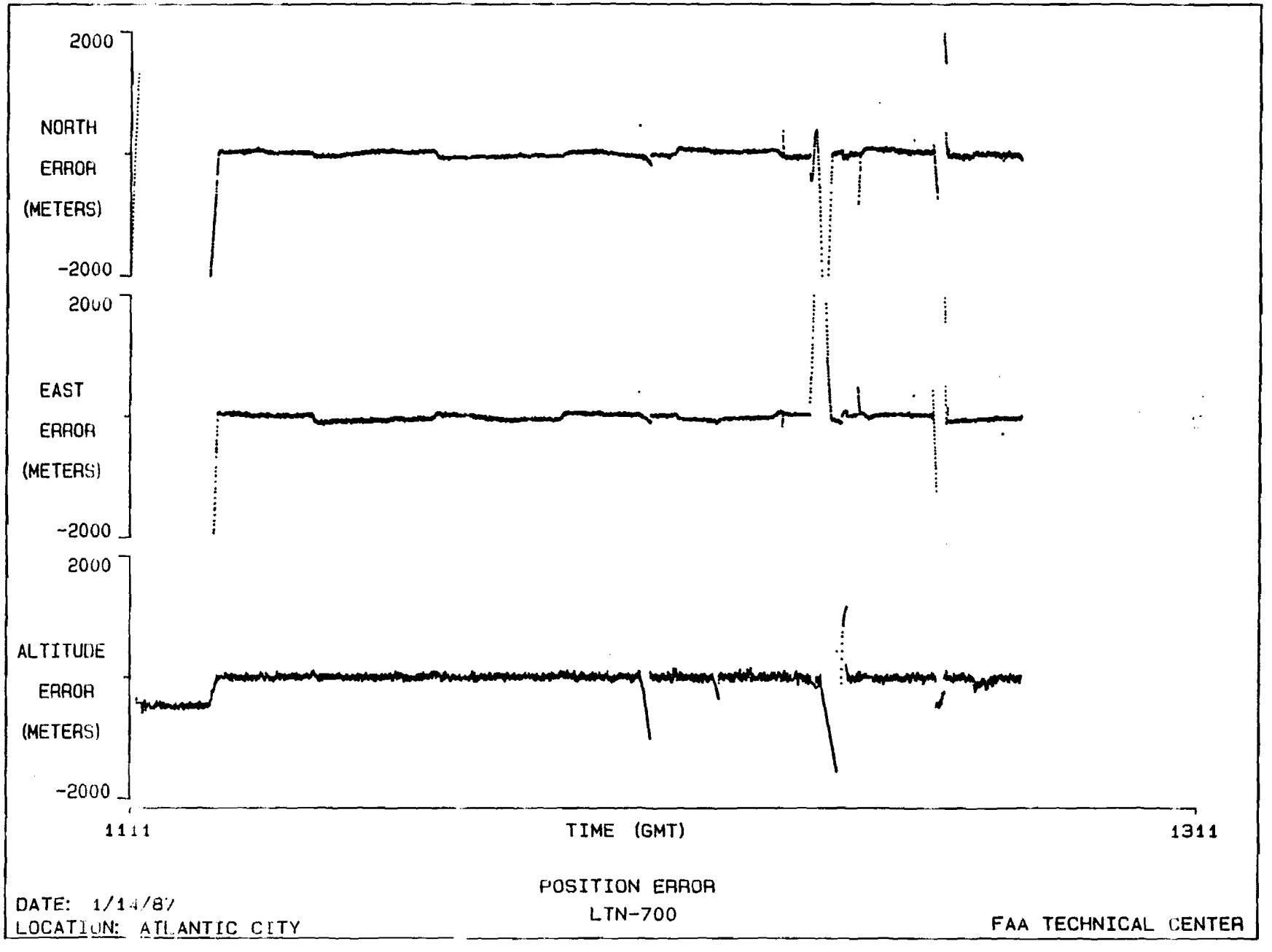


FIGURE 3. POSITION ERROR - LTN-700 1/14/87

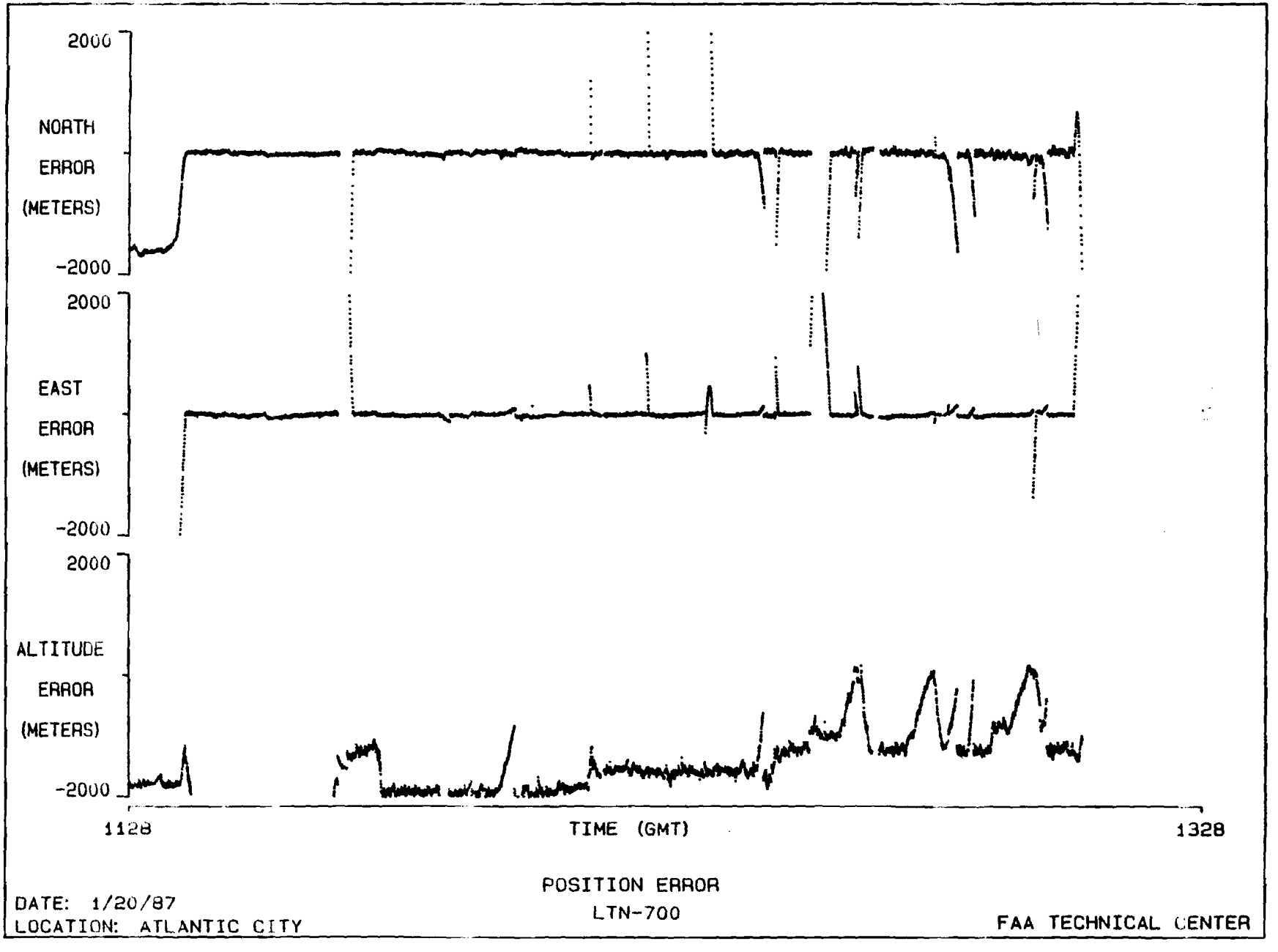


FIGURE 4. POSITION ERROR - LTN-700 1/20/87

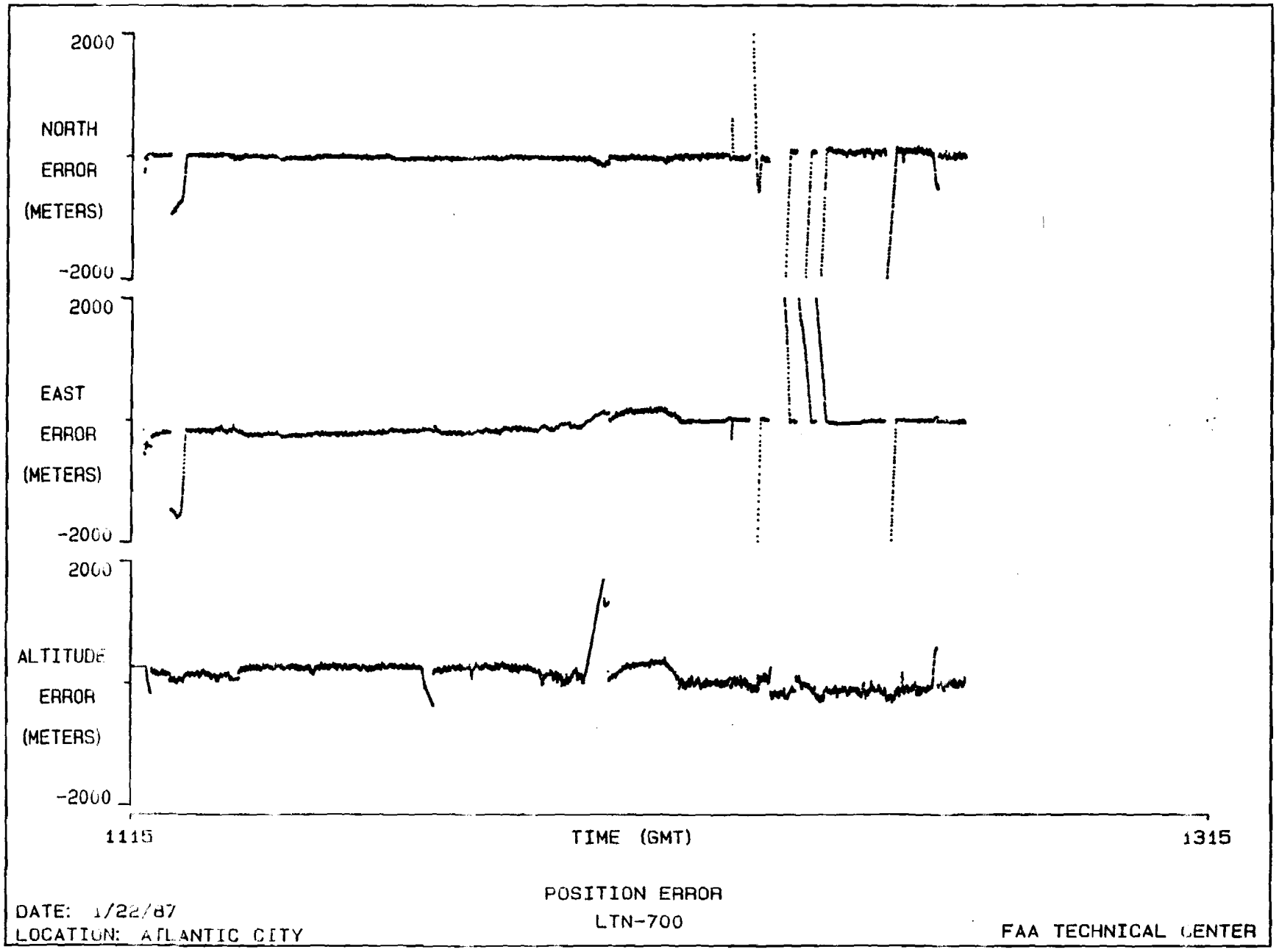


FIGURE 5. POSITION ERROR - LTN-700 1/22/87

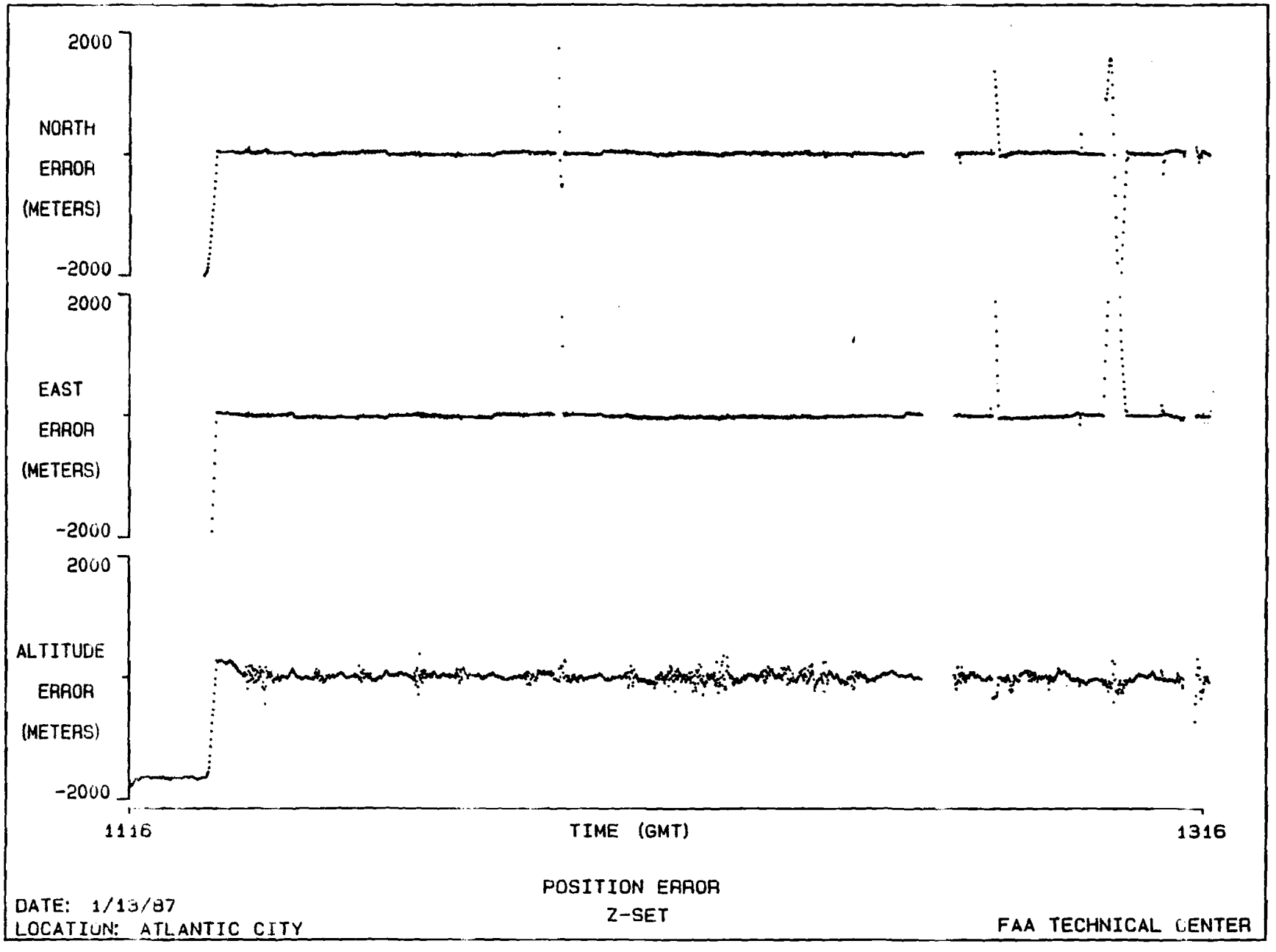
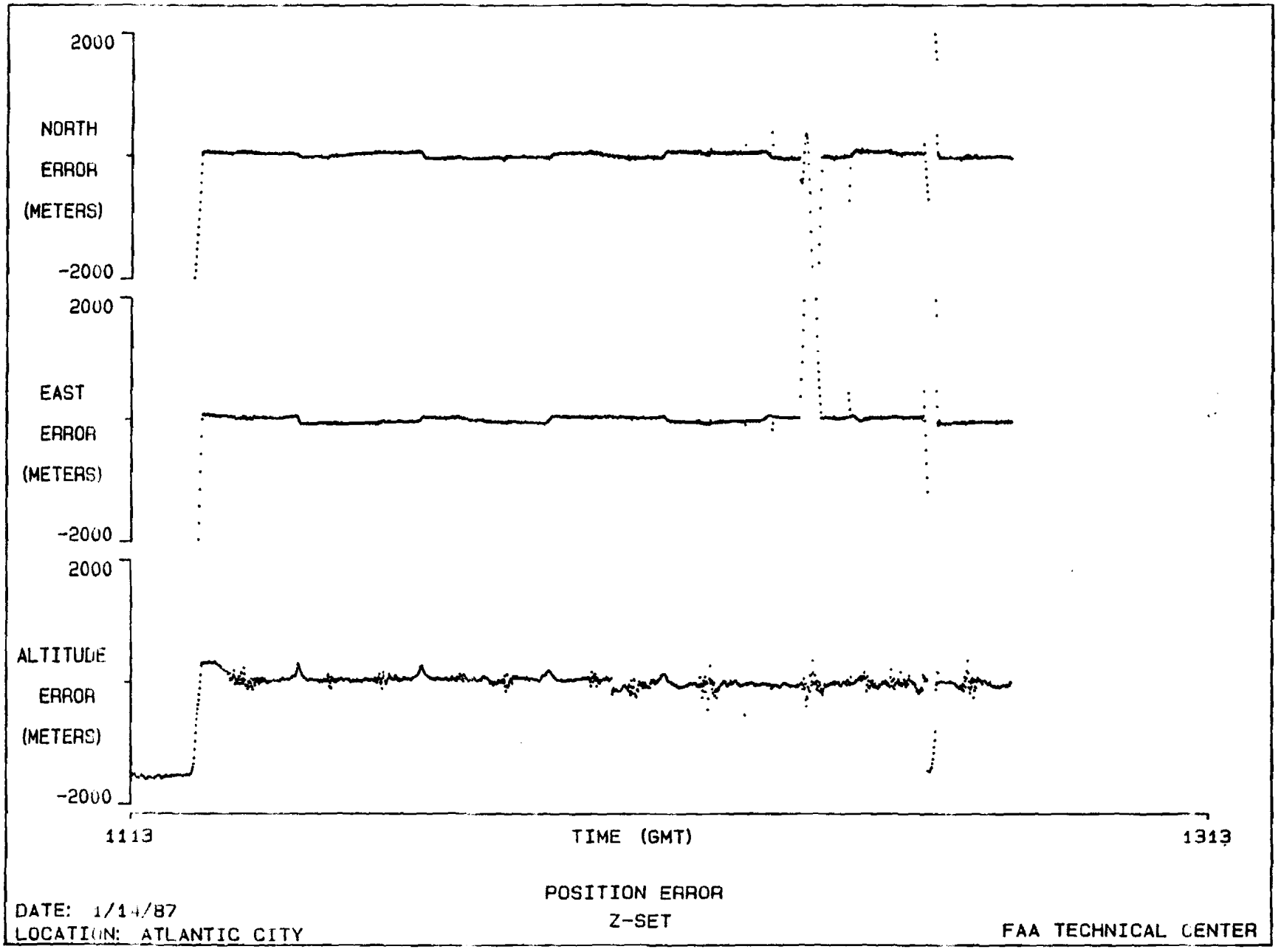


FIGURE 6. POSITION ERROR - Z-SET 1/13/87



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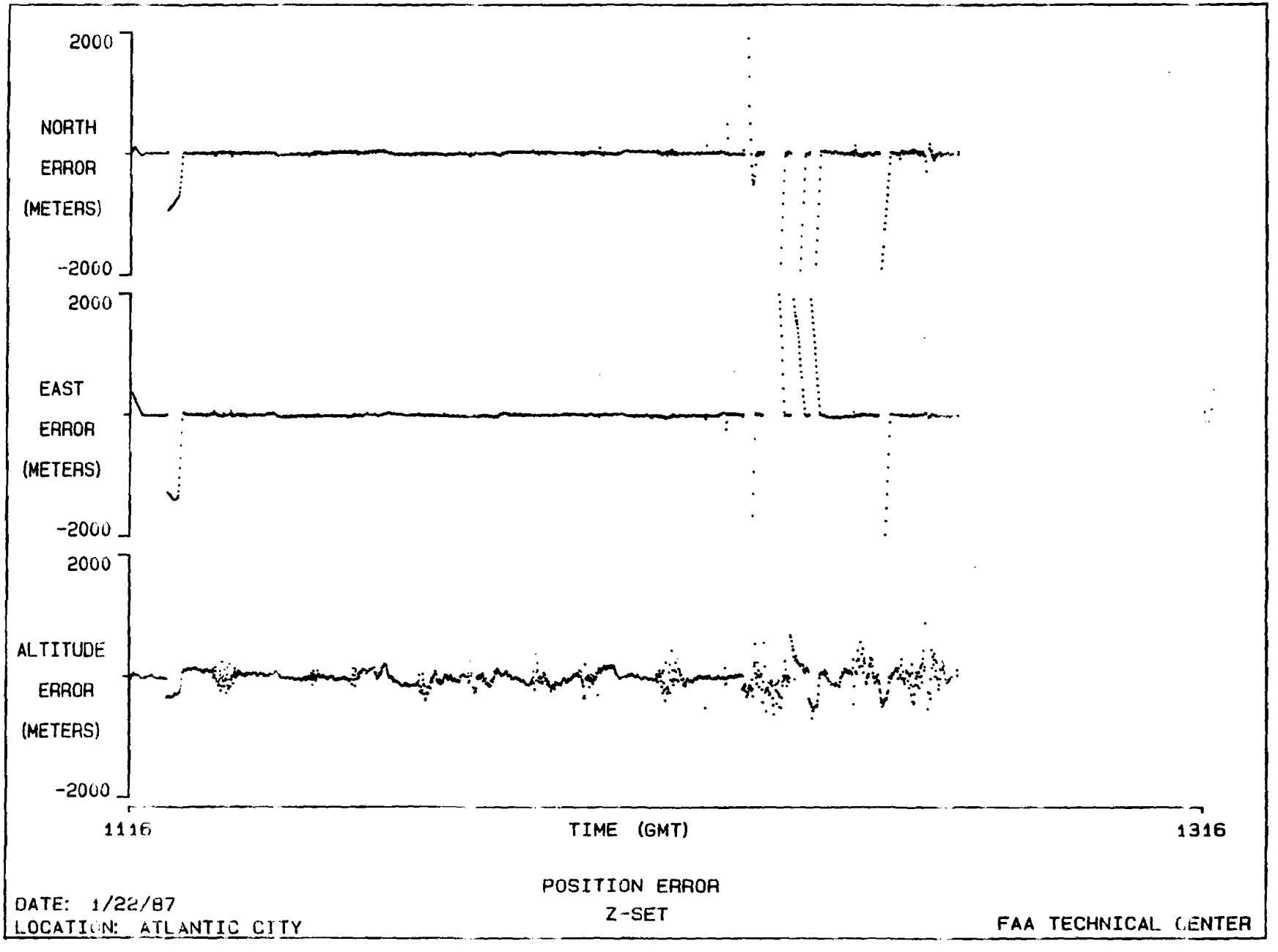

FIGURE 8. POSITION ERROR - Z-SET 1/22/87

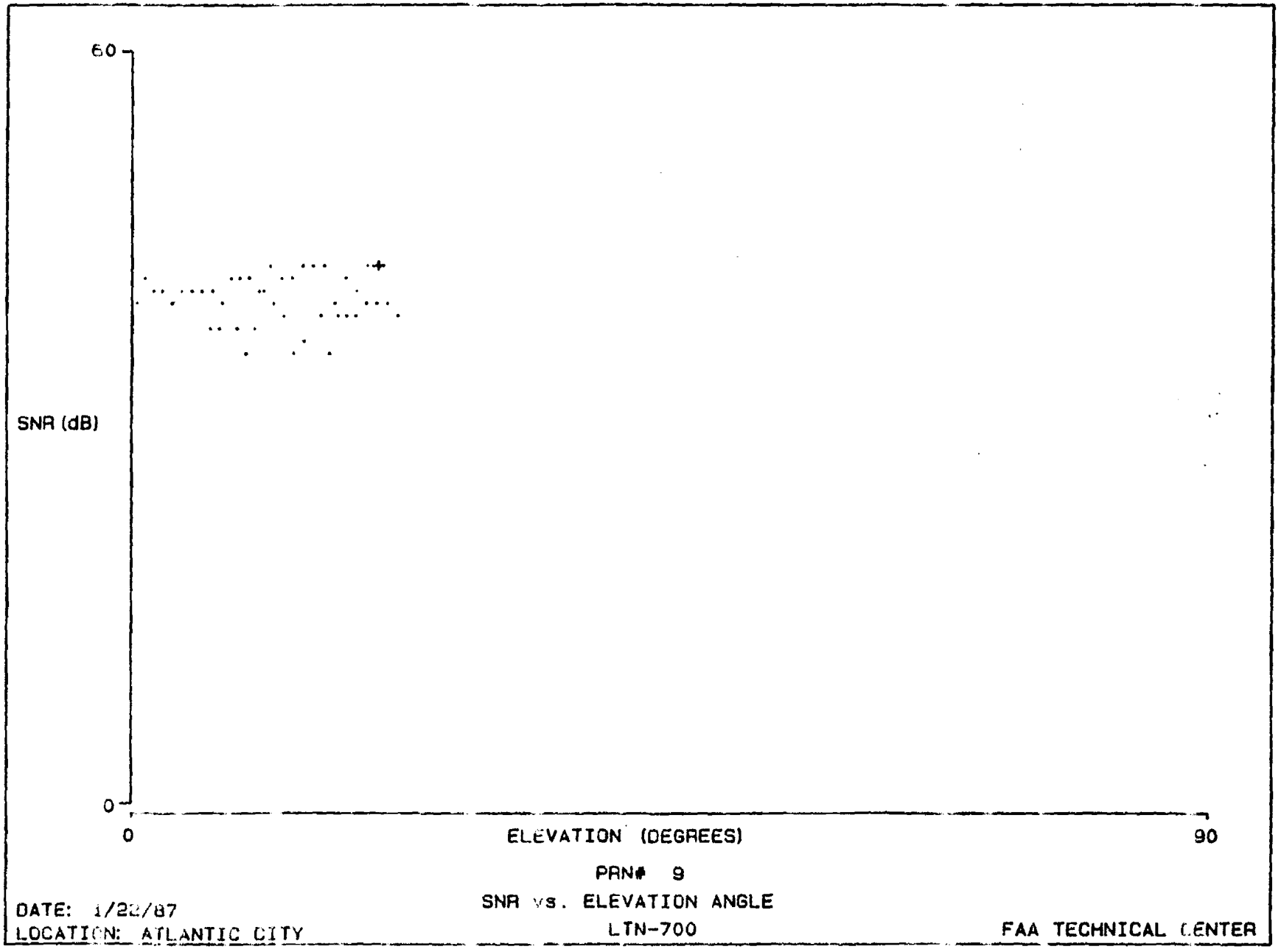

FIGURE 9. SNR VS ELEVATION ANGLE - LTN-700 PRN NO. 9

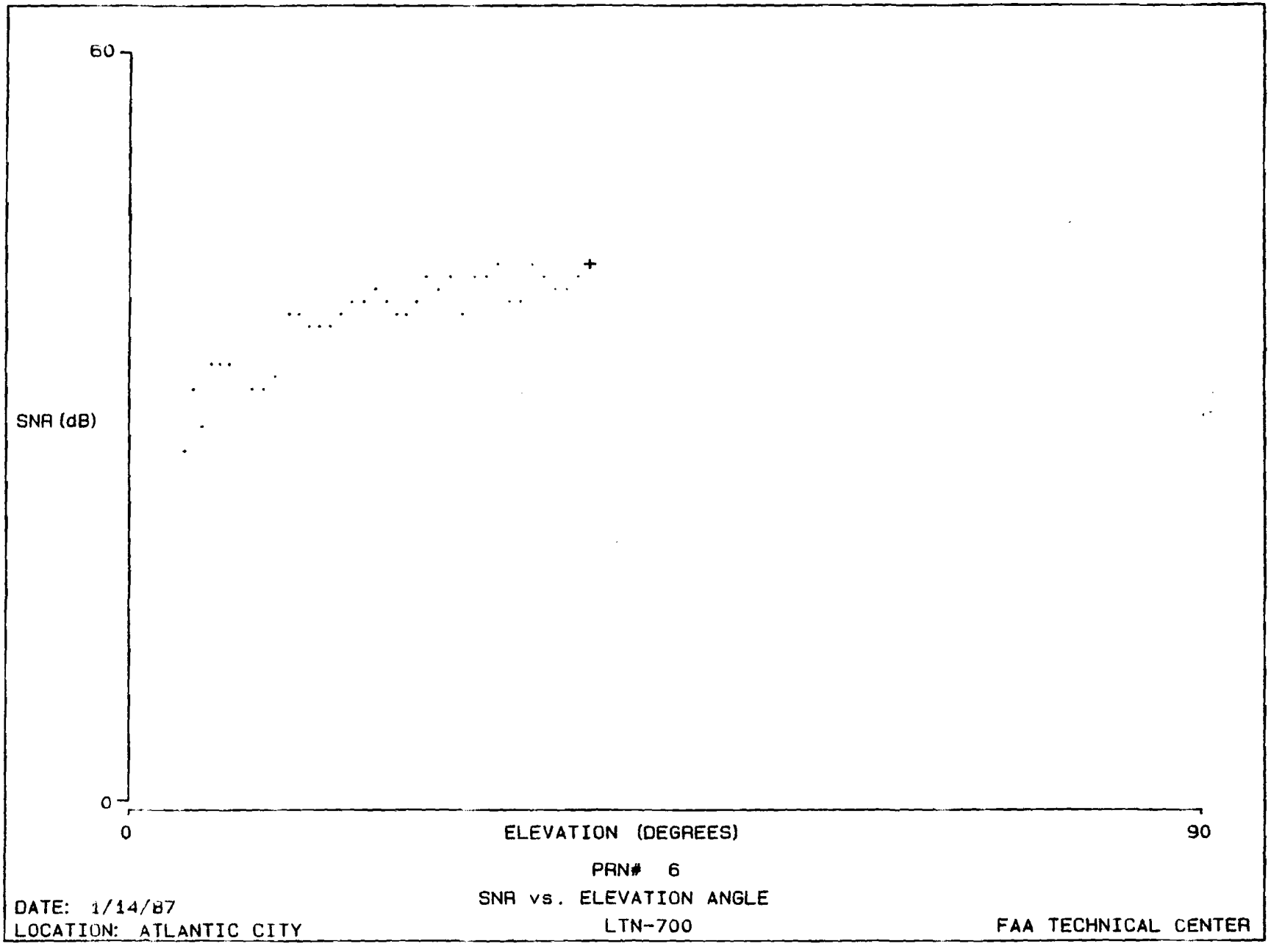

FIGURE 10. SNR VS. ELEVATION ANGLE - LTN-700 PRN No. 6