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TEST AND EVALUATION  
COMMAND

AD No. \_\_\_\_\_

TECOM Project No. 7-CO-M95-AVD-004

FINAL REPORT

METHODOLOGY INVESTIGATION

GLOBAL POSITIONING SYSTEM (GPS) VEHICLE TRACKING SYSTEM

FOR FLIGHT TESTING OF FIXED- AND ROTARY-WING AIRCRAFT

MR. LARRY MARTIN, TEST DIRECTOR/ENGINEER

UNITED STATES ARMY AVIATION TECHNICAL TEST CENTER  
FORT RUCKER, ALABAMA 36362-5276

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21005-5055

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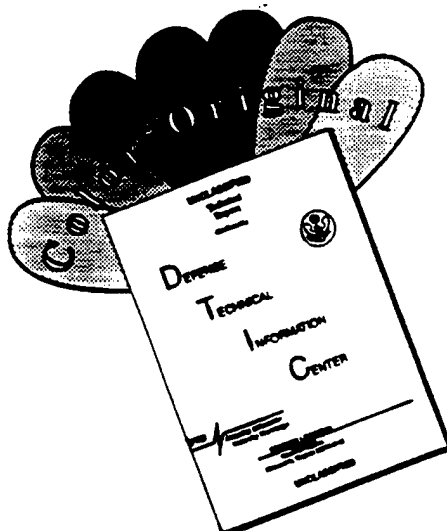
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DEPARTMENT OF THE ARMY  
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REPLY TO  
ATTENTION OF

AMSTE-TM-T (70-10p)

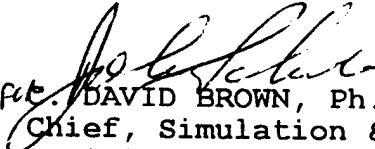
26 Aug 96

MEMORANDUM FOR Commander, U.S. Army Aviation Technical Test  
Center, ATTN: STEAT-TS-D, Fort Rucker, AL  
36362-5276

SUBJECT: Final Report, Methodology Investigation, Global  
Positioning System (GPS) Vehicle Tracking System for Flight  
Testing of Fixed- and Rotary-Wing Aircraft, TECOM Project  
No.7-CO-M95-AVD-004

1. Subject report is approved.
2. The TECOM point of contact is Mrs. Cyndie McMullen,  
AMSTE-TM-T, amstectt@apg-9.apg.army.mil, DSN 298-1469.

FOR THE COMMANDER:

  
Lt. DAVID BROWN, Ph.D.  
Chief, Simulation & Technology  
Division  
Directorate for Technical Mission

**REPORT DOCUMENTATION PAGE**

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<b>6. AUTHOR(S)</b> Mr. Larry Martin, Test Director/Engineer, DSN 558-8276, Commercial (334) 255-8276				
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<b>12a. DISTRIBUTION/AVAILABILITY STATEMENT</b> Approved for public release; distribution is unlimited.			<b>12b. DISTRIBUTION CODE</b>	
<b>13. ABSTRACT (Maximum 200 words)</b> The U.S. Army Aviation Technical Test Center (ATTC) conducted the methodology investigation of the global positioning system (GPS) vehicle tracking system at White Sands Missile Range from June 1995-April 1996. The objectives were to quantify the accuracy of the GPS tracking system throughout the dynamics of normal helicopter flight and ensure that the rotor effect on the GPS signal reception is considered. It was concluded that the system as tested is capable of tracking helicopters through their flight envelope to an accuracy of less than 2 feet spherical error probable in real time, and the rotor system appeared to have little effect on the GPS signals.				
<b>14. SUBJECT TERMS</b> Methodology Investigation Global Positioning System (GPS) Time Space Positioning Information (TSPI) Truth Data Acquisition Recording and Display System (TDARDS)			<b>15. NUMBER OF PAGES</b> 72	
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## FOREWORD

The U.S. Army Aviation Technical Test Center (ATTC) was responsible for planning, execution, and reporting of this methodology investigation.

All data for this report are filed at ATTC under TECOM Project No. 7-CO-M95-AVD-004.

ATTC gratefully acknowledges the contributions of the following personnel to this study:

Mr. Antonio Palomino, White Sands Missile Range  
Mr. Mark Moeglein, Stanford Research Institute

## SECTION 1. SUMMARY

### 1.1 BACKGROUND

The U.S. Army Aviation Technical Test Center (ATTC), jointly with White Sands Missile Range (WSMR), developed a global positioning system (GPS) vehicle tracking system. ATTC uses the tracking system in flight testing to provide time space positioning information (TSPI) of fixed- and rotary-wing aircraft. The GPS tracking system, named the Truth Data Acquisition Recording and Display System (TDARDS), was designed to be a real-time tracking system capable of 1-meter root mean square (RMS) spherical error probable (SEP). TDARDS consists of a vehicle system or systems (up to 10 units), a ground system, and a data link. The TDARDS uses differential GPS technology with both carrier phase and code measurements to provide the very accurate position solution.

### 1.2 PROBLEM

Determine the baseline accuracy of the TDARDS so that ATTC can use the TDARDS in flight testing as a TSPI truth source.

### 1.3 OBJECTIVES

1.3.1 Quantify the accuracy of the TDARDS GPS tracking system throughout the dynamics of normal helicopter flight.

1.3.2 Ensure that the rotor effect on the GPS signal reception is considered.

### 1.4 PROCEDURES

1.4.1 ATTC conducted the accuracy measurement test at WSMR from June 1995 through April 1996. A UH-60L BLACKHAWK helicopter was used as the airborne platform, and the airborne GPS was mounted in the rear of the cargo area of the aircraft. The test was confined to a small area on the WSMR and optical tracking systems at WSMR were used as the truth data. All data produced in the report are with respect to the WSMR truth data.

1.4.2 Mounting of the GPS vehicle unit required mounting the GPS receiver antenna, GPS receiver, and data link antenna. Since the GPS antenna would be the tracking target used by WSMR optics, care was taken to ensure maximum visibility around the helicopter fuselage. The GPS antenna was mounted where the main fuselage and the tailboom meet, approximately 216 inches aft of the main rotor hub on the center line of the aircraft. The mount was a white rectangle 8 inches wide by 8 inches tall that affixed to the top of the tail rotor drive shaft cover. Six white stripes



were painted on each side of the airframe in an arrow shape pointing to the GPS antenna mount (figure (fig.) 1). The GPS receiver was mounted on the aircraft floor in the rear center of the cargo area. The data link antenna was mounted on the bottom of the aircraft on a cover made to fit over the cargo hook hole.

1.4.3 The GPS ground station consisted of two computers that were interconnected, a GPS reference receiver card, a GPS antenna, a data link transmitter, and a data link antenna. One of the computers was used to collect GPS data to correct the vehicle unit GPS, and the other computer was used to control the data link to the vehicle unit GPS.

1.4.3.1 To properly set up the GPS reference receiver computer, the GPS antenna had to be located over a first order surveyed point less than 30 meters away from the GPS reference receiver. The point at WSMR was on the roof of building 300. The location of the point was surveyed just prior to the testing.

1.4.3.2 The data link computer was located in building 300 directly adjacent to the reference receiver computer. The antenna for the data link computer was also located on the roof of building 300.

1.4.4 The optical trackers (cinetheodolites) at WSMR were located on the "Small Missile Range" in a rectangular pattern (fig. 2). There were two parallel rows of 3 trackers each; the rows were separated by approximately 7,000 feet, and the individual trackers in each row were 4,000 feet apart. A 2,500- by 6,000-foot box was centered and overlaid on the area of the trackers in which the aircraft maneuvers were completed.

1.4.5 The test was flown in accordance with (IAW) the test plan (appendix (app) A). Start times and stop times (app B) were determined when the helicopter entered and exited the maneuver box.

1.4.6 The test did not begin until the reference receiver indicated a GPS constellation of at least four satellites.

1.4.7 The GPS data to be collected were the raw measurements data (pseudorange, range rate, integrated carrier cycles, and integrated carrier phase) on board the vehicle and ground station for postmission processing (referred to as method 3) and the navigation solution (latitude, longitude, altitude) generated in the vehicle unit using the differential corrections generated by the ground station (referred to as method 1).

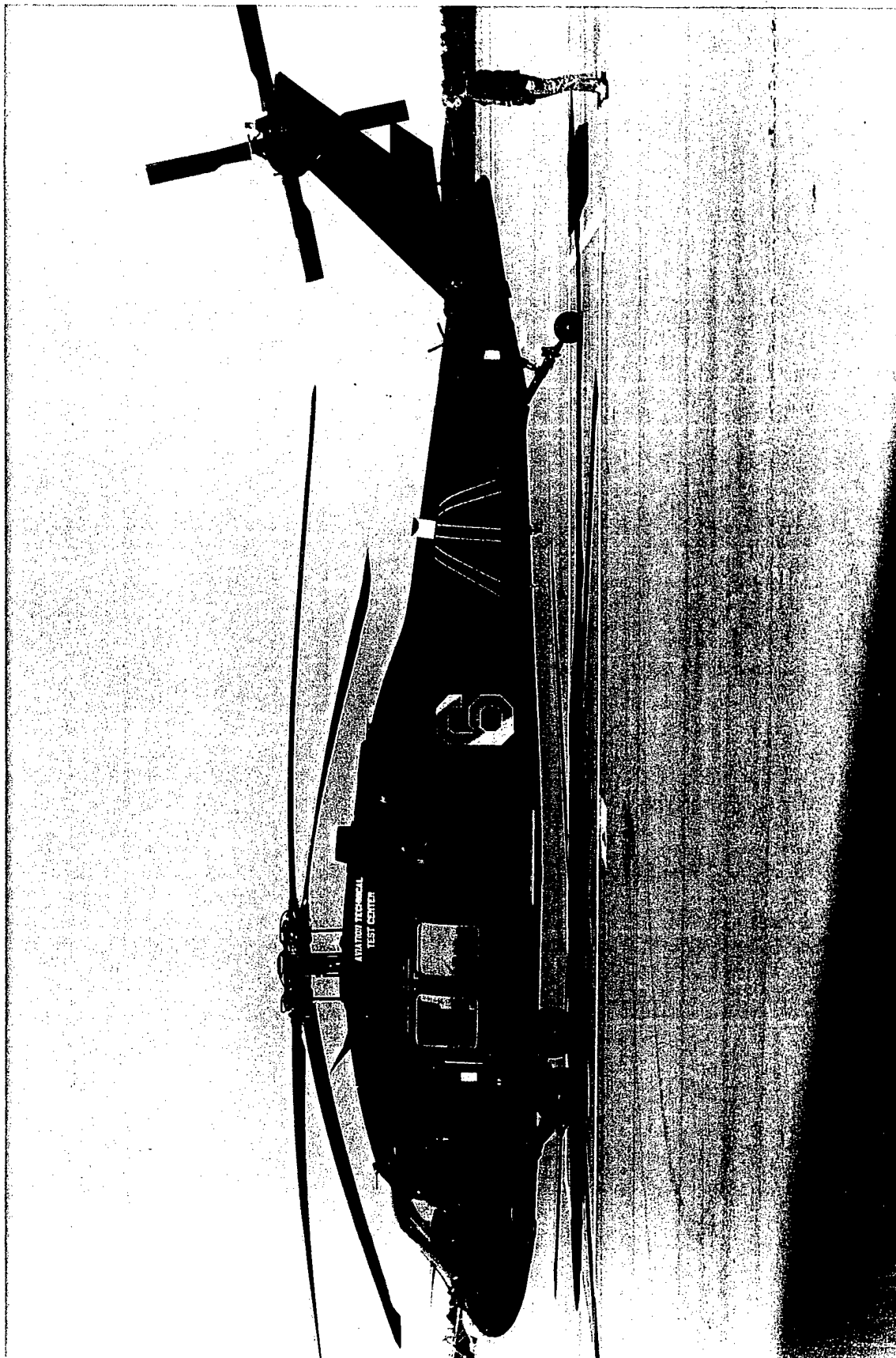


FIGURE 1. WHITE STRIPES POINTING TO WHITE GPS ANTENNA MOUNT

# GPS Baseline Test

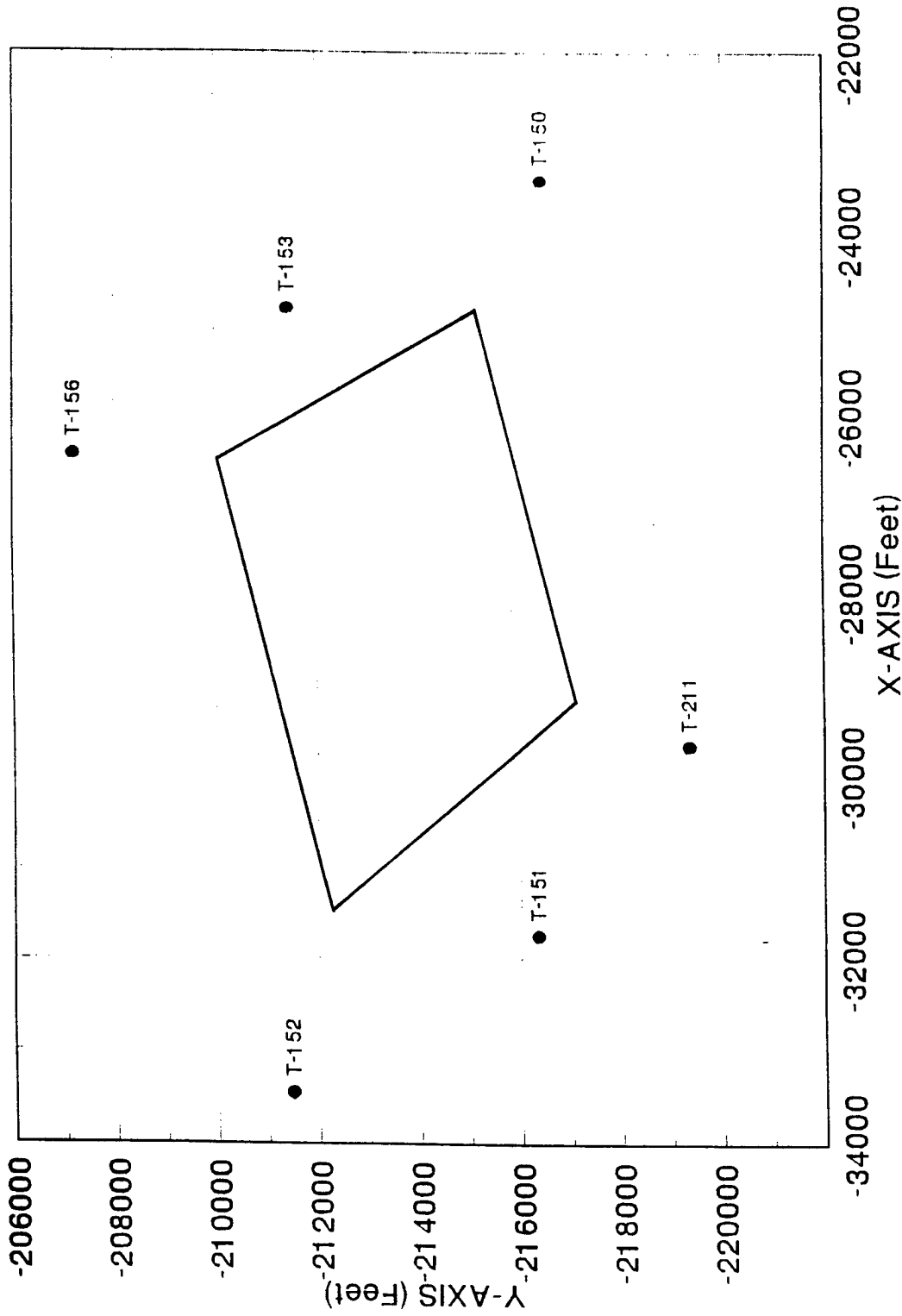


FIGURE 2. PATTERN OF OPTICAL TRACKERS AND MANEUVERING BOX

1.4.7.1 The postmission-processed GPS data used a process referred to as carrier averaging to produce the navigation solution from the raw measurements taken at the vehicle unit and ground station. The carrier averaging process was applied to the GPS receiver channel by channel (or satellite by satellite). Pseudorange and integrated carrier phase corrections were calculated by using the reference receiver data and the first order survey data and were individually applied to the airborne GPS receiver's code and carrier measurements. Once these corrections were applied, the difference between pseudorange and integrated carrier phase measurements was observed. The weighted average of this difference over the entire interval for which the satellite vehicle was in track determined the best estimate for the constant of carrier phase integration. On a second pass through the data, the stored constant of integration was added to the individual integrated carrier phase samples to form the best estimate of pseudorange. This best estimate of pseudorange data was then used in determining position (or a navigation solution) using a weighted least squares filter. Finally, this position solution was smoothed with differentially corrected velocity data, which were also derived from integrated carrier phase data.

1.4.7.2 The real-time navigation solution was calculated by using the pseudorange and integrated carrier phase differential corrections received from the ground station at the airborne GPS and individually applied to the GPS receiver's pseudorange and integrated carrier measurements. Once these corrections were applied, the difference between pseudorange and integrated carrier phase measurements was observed. The weighted average of this difference over the time the satellite vehicle had been in track (past data only) was used as an estimate for the constant of carrier phase integration. This constant was added to the most recent integrated carrier phase sample to form the best estimate of pseudorange. This best estimate of pseudorange data was then used in determining position (or the navigation solution) using a weighted least squares filter. (Note that the real-time (method 1) software does not currently perform the velocity smoothing found in the postmission (method 3) software.)

## 1.5 RESULTS

1.5.1 The GPS antenna installation on the UH-60L tailboom proved to be very effective for the WSMR test. The antenna provided a highly visible target from all aspect angles of the helicopter. The white-painted antenna mount also had a high contrast that was easily identifiable through the optical tracker video. The added stripes painted on the tailboom of the helicopter pointing to the antenna were visually helpful. The GPS antenna was mounted on the tailboom under the rotor, approximately two-thirds of the way down the rotor. This ensured that the GPS data were exposed to the interference problems associated with the rotor.

1.5.2 The reference receiver ground station could not be set up to operate in the method 1 mode of position solution (differential corrections transmitted to the aircraft and the position solution calculated on the aircraft and transmitted to the ground station). This turned out to be caused by a setup problem with the third RS-232 port on the ground station. This port is used to communicate with a graphics system for displaying position. The method 3 mode of GPS position solution (airborne GPS raw measurements are transmitted to the ground station where they are corrected using the reference receiver corrections and a position solution is calculated on the ground station) was used for real-time operation. Data presented in this report as real time used the algorithms that would have been used on the airborne unit for method 1 processing. These data were processed postmission and are a representation of what the data would have been assuming a perfect transmission data link with no data dropouts. For most applications where there is line of sight between the ground station and the airborne unit, this is a safe assumption.

1.5.3 Although some maneuvers were not completed within the smaller prescribed box inside the optical trackers, all were completed within the larger rectangle formed by the trackers (fig. 2).

1.5.4 The helicopter performed the maneuvers IAW the test plan. These maneuvers were increasingly more dynamic and gave a trend of the effects of the dynamics on the GPS solution.

1.5.5 The constellation of GPS satellites viewable by both the ground station and the airborne GPS varied between 6 and 9. The solution switched between satellites during the dynamic maneuvers, but the transitions occurred without dropping below the 6 common satellites.

1.5.6 The data comparing the postmission and real-time processed GPS position solution to the WSMR optics data are summarized in app C and D, respectively. A summary of statistics for the postmission and real-time processed data is in app E.

## 1.6 CONCLUSIONS

1.6.1 The TDARDS is capable of tracking helicopters through their flight envelope to an accuracy of less than 2 feet SEP in real time. The TDARDS solution can be refined in postmission processing to an accuracy of less than 1 foot SEP. It should be noted that the accuracies stated are dependent on having satellite coverage equivalent to the test data or better.

1.6.2 The rotor system appeared to have minimal effect on the GPS signals. There was no difficulty in signal tracking or acquisition, and there was no appreciable carrier-to-noise loss due to the GPS antenna being located under the rotor.

SECTION 2. APPENDIXES

APPENDIX A. METHODOLOGY INVESTIGATION PLAN AND DIRECTIVE

13 JUN 1994

MEMORANDUM FOR SEE DISTRIBUTION

SUBJECT: Internal Test Plan (Support), Global Positioning System (GPS), TECOM Project No. 4-CO-210-000-068, XO 399

1. REFERENCES

a. Memorandum, Department of the Air Force, Aeronautical Systems Center, 5 May 1994, subject: Customer Test Request, U.S. Army Aviation Technical Test Center.

b. Telephone Conversation, Mr. Rigler, AMSTE-TA-L, Headquarters, U.S. Army Test and Evaluation Command (HQ TECOM), and Mr. Hamilton, STEAT-TS-P, U.S. Army Aviation Technical Test Center (ATTC), 31 May 1994, subject: Support for GPS Test.

c. Technical Manual (TM) 55-1520-237-10, Operator's Manual for UH-60A through UH-60L Helicopters, 15 February 1993.

2. TEST OBJECTIVES

Support the helicopter GPS test program conducted by the Eglin Air Force Base (AFB), Florida (FL), Range Applications Joint Program Office (RAJPO) to:

a. Quantify the effect of rotor blade interference with GPS receiver operation.

b. Determine a suggested location of the GPS antenna for future helicopter use.

3. TESTING AUTHORITY

a. On 5 May 1994, the U.S. Air Force (USAF) Aeronautical Systems Center requested HQ TECOM to direct ATTC to support the Eglin AFB RAJPO as required for the GPS test (reference (ref) paragraph (para) 1a).

b. On 31 May 1994, HQ TECOM directed ATTC to support the GPS test as requested (ref 1b).

4. SYSTEM DESCRIPTION

The instrumentation to be installed on the UH-60A consists of the GPS Coarse Acquisition Code Receiver (CACR), a GPS antenna, a High Dynamics Instrumentation System (HDIS) GPS receiver with solid-state recorder, a RAJPO Data Link System (DLS), a DLS antenna, and a radar tracking transponder and antenna.



STEAT-FS-B

SUBJECT: Internal Test Plan (Support), Global Positioning System (GPS), TECOM Project No. 4-CO-210-000-068, XO 399

5. TEST CONCEPT/PROCEDURE

a. The flight testing will be conducted at Eglin AFB, FL, from 13 June to approximately 17 June 1994. One UH-60A helicopter will be ferried from Cairns Army Airfield (AAF), Fort Rucker, Alabama (AL), to Eglin AFB, FL. Upon arrival at Eglin AFB, the test equipment for the GPS project will be ground checked. DynCorp will provide aircraft staging and maintenance support at Eglin AFB which is several miles from the test site at Eglin range B70.

b. The test will be conducted in approximately 6 flight-hours under day visual meteorological conditions (VMC). Ferry flights to and from the test site (if required) may be completed during day or night VMC or instrument meteorological conditions (early takeoffs and late returns).

c. The flight portion of the test will be conducted at the Eglin AFB test range. The profiles consist of standard maneuvers, shown in table 1, in a specified area of the range. As the helicopter flies the profiles and GPS signal data are acquired and recorded, cinetheodolites and ground-based range radars will track the helicopter location and provide truth data.

Table 1. Flight Maneuvers for GPS Test

MANEUVERS	Altitudes (ft AGL)	Airspeed (KIAS)	Bank Angle (Deg)	Load Factor (g)
1. Racetrack	500	70	30-45	<2.0
2. Figure-8	500	70	30-45	<2.0
3. Vertical takeoff (100-ft increments)	500	TBD	0	<2.0
4. Maximum vertical climb	500	TBD	0	<2.0
5. Medium vertical climb	500	TBD	0	<2.0
6. High speed run	500	120-130	0	<2.0
7. Rapid altitude change in flight	100-300	100-110	0	<2.0

STEAT-FS-B

SUBJECT: Internal Test Plan (Support), Global Positioning System (GPS), TECOM Project No. 4-CO-210-000-068, XO 399

Notes: AGL - above ground level  
Deg - degrees  
ft - feet  
g - gravity  
KIAS - knots indicated airspeed  
TBD - to be determined

6. ADMINISTRATION AND SUPPORT REQUIREMENTS

- a. ATTC will provide one UH-60 helicopter and flightcrew.
- b. DynCorp will provide maintenance support at Eglin AFB and Cairns AAF as required. If this test is done on a TDY basis, the DynCorp support crew will consist of a flight mechanic, an electrician, and a technical inspector.
- c. The 46th Test Wing (46TW) at Eglin AFB will provide test management and coordination of the overall test effort.
- d. The test equipment suite (para 4) will be provided by RAJPO and installed by Dyncorp technicians at Cairns AAF. ATTC will conduct flight release inspections and provide a flight release for the internal sensor package installation.
- e. USAF personnel and contractor personnel from Eglin AFB will be flying in the aircraft during the test as test instrumentation operators.
- f. The aircraft will be flown without the external stores support system. Crew will consist of two pilots, one crew chief, and up to two instrumentation technicians. With the test equipment installed, the takeoff gross weight will be approximately 15,000 pounds.
- g. The aircraft will be flown within the limitations of the UH-60 Operator's Manual (ref 1c) and the flight release.
- h. Labor and flight-hours will be charged to XO 399.
- i. ATTC will submit a test record within 35 days of test completion.
- j. The overall level of risk for this test support is LOW (III-E).

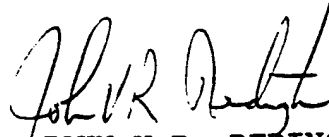
STEAT-FS-B

SUBJECT: Internal Test Plan (Support), Global Positioning System (GPS), TECOM Project No. 4-CO-210-000-068, XO 399

7. POINT OF CONTACT

Point of contact is CW5 William R. Murphy, Test Director, DSN 558-8167, commercial (205) 255-8167, or FAX (205) 255-8174, Fort Rucker.

FOR THE COMMANDER:



JOHN V.R. REDINGTON

LTC, AV

Director, Flt Sys Test Directorate

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REPLY TO  
ATTENTION OF

AMSTE-CT-T (70-10p)

MEMORANDUM FOR Commander, U.S. Army Aviation Technical Test  
Center, ATTN: STEAT-TS-P, Fort Rucker, AL  
36362-5276

SUBJECT: Amendment 2 to Test Execution Directive, FY95  
Methodology Program

1. Reference HQ TECOM Memo, AMSTE-CT-T, 12 Sep 94, subject:  
Test Execution Directive, FY95 Methodology Program.
2. This memorandum, with list of projects at enclosure 1, amends  
reference 1.
3. Point of contact at this headquarters is Ms. Cyndie McMullen,  
AMSTE-CT, amstect@apg-9.apg.army.mil, DSN 298-1469.

FOR THE COMMANDER:

Encl

FREDERICK D. MABANTA  
Chief, Technology Development Division  
Directorate for Corporate Information  
and Technology

CF:

Cdr, USAATTC, ATTN: STEAT-TS-D (Larry Eagerton)

FY95 METHODOLOGY PROGRAM		INITIAL FUNDING	REVISED FUNDING	AMEND #1	AMEND #2
AVIATION TECHNICAL TEST CENTER				24 JAN 95	15 JUN 95
7-CO-M95-AVD-001	FY95 Quick Reaction Methodology	20.0	5.0	-15.0	0.0
7-CO-M95-AVD-002	FY95 Technical Committee Support	5.0	5.0	0.0	0.0
7-CO-M95-AVD-003	Common Airborne Instrumentation Testing	100.0	0.0	-100.0	0.0
7-CO-M95-AVD-004	GPS System Investigation	0.0	80.0	65.0	15.0
TOTAL ATTC PROGRAM		125.0	90.0	-50.0	15.0

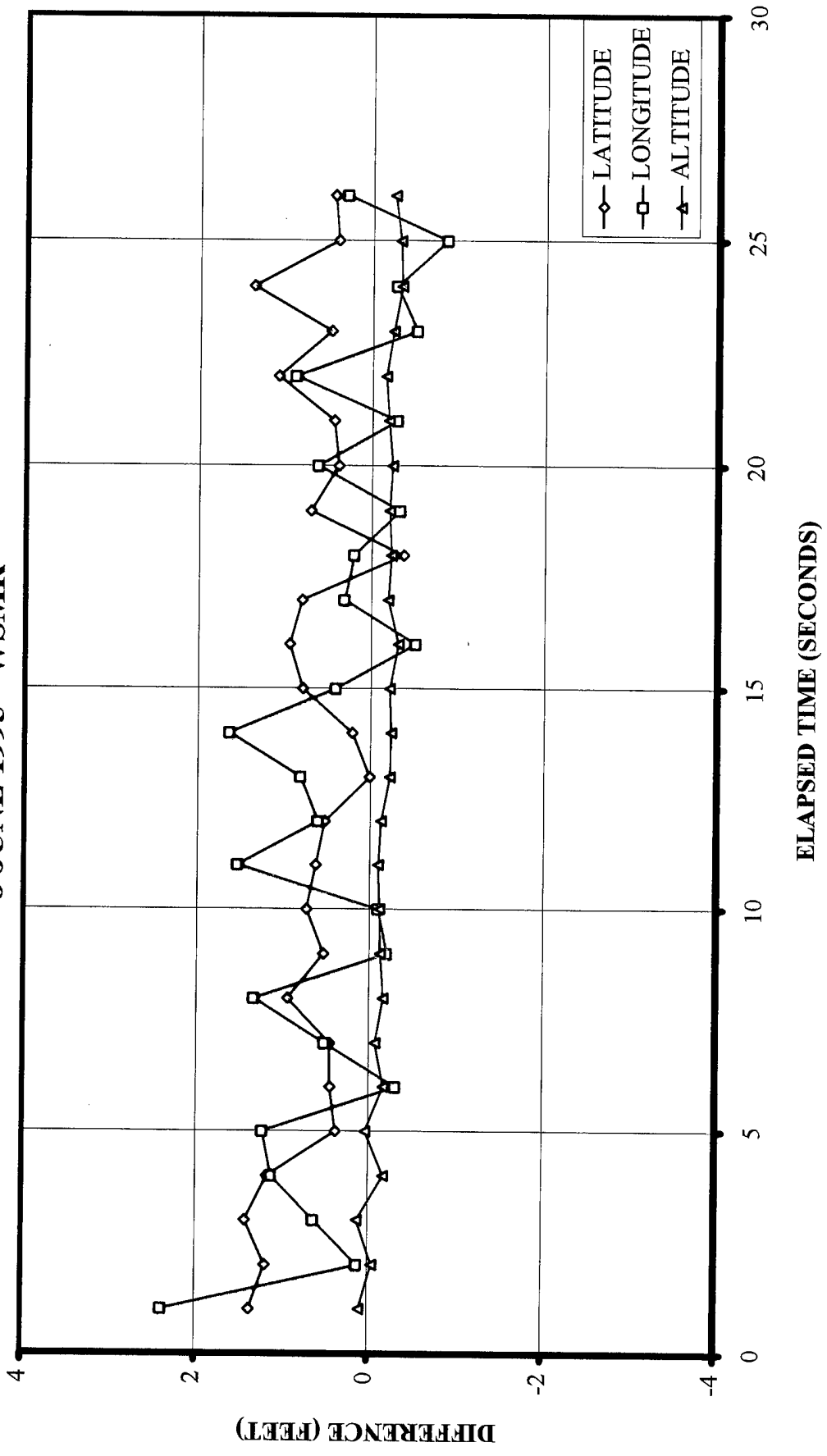
APPENDIX B. START AND STOP TIMES

Following are the start and stop times (Greenwich mean time (GMT)) for each data pass on 8 June 1995. Times are shown in the following sequence: Julian date:hours:minutes:seconds.

PASS	MANEUVER	START	END
1	Level Flight	5159:18:18:50	5159:18:19:17
2	Rapid Altitude Change	5159:18:20:21	5159:18:21:12
3	15° Bank	5159:18:23:14	5159:18:25:21
4	30° Bank	5159:18:26:34	5159:18:28:10
5	45° Bank	5159:18:29:22	5159:18:30:40
6	60° Bank	5159:18:31:48	5159:18:32:53
7	Figure 8	5159:18:34:12	5159:18:36:00
8	Level Flight	5159:18:37:16	5159:18:37:48
9	Rapid Altitude Change	5159:18:39:13	5159:18:39:51
10	Level Flight	5159:18:41:16	5159:18:41:43
11	15° Bank	5159:18:43:12	5159:18:44:55
12	30° Bank	5159:18:46:48	5159:18:48:05
13	45° Bank	5159:18:49:47	5159:18:50:47
14	60° Bank	5159:18:52:02	5159:18:53:00
15	Figure 8	5159:18:54:11	5159:18:55:09
16	Level Flight	5159:18:57:02	5159:18:57:29
17	Rapid Altitude Change	5159:18:59:15	5159:18:59:58
18	Level Flight	5159:19:01:34	5159:19:02:03
19	15° Bank	5159:19:04:31	5159:19:06:19
20	30° Bank	5159:19:08:20	5159:19:09:41

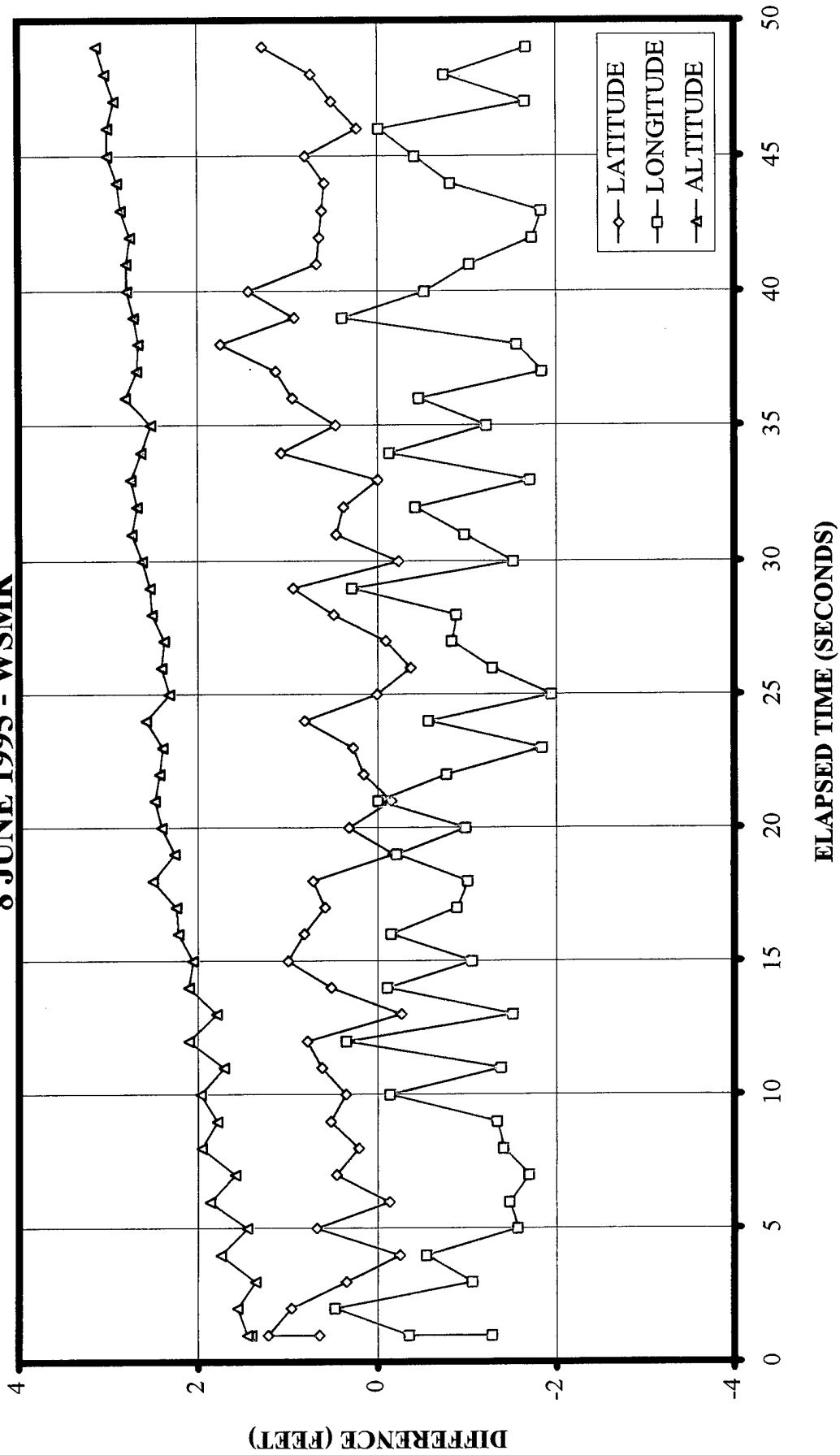
APPENDIX C. COMPARISON OF POSTMISSION GPS POSITION SOLUTION  
TO WSMR OPTICS DATA

**GPS vs OPTICS  
PASS # 1 - LEVEL FLIGHT  
8 JUNE 1995 - WSMR**

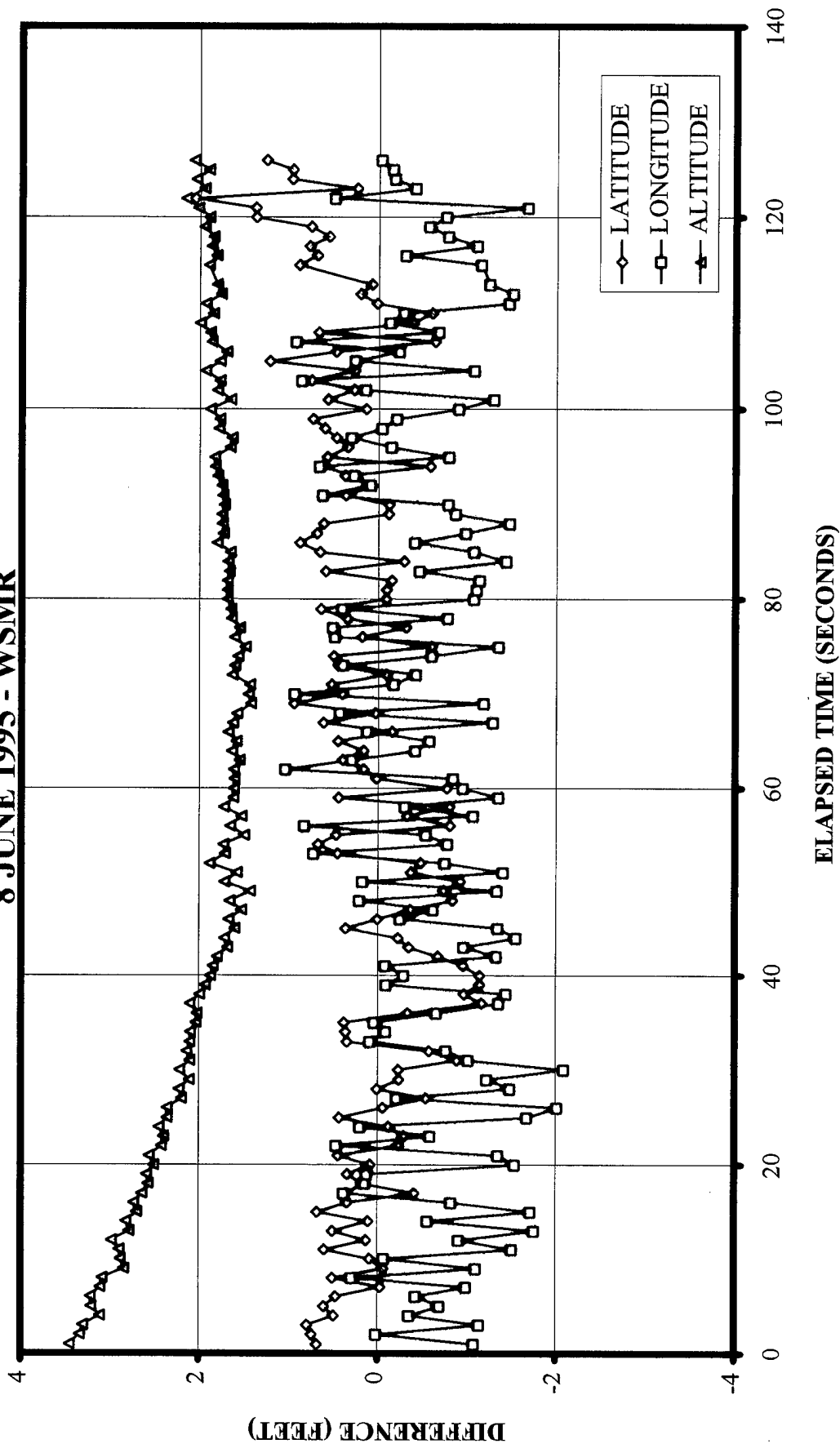




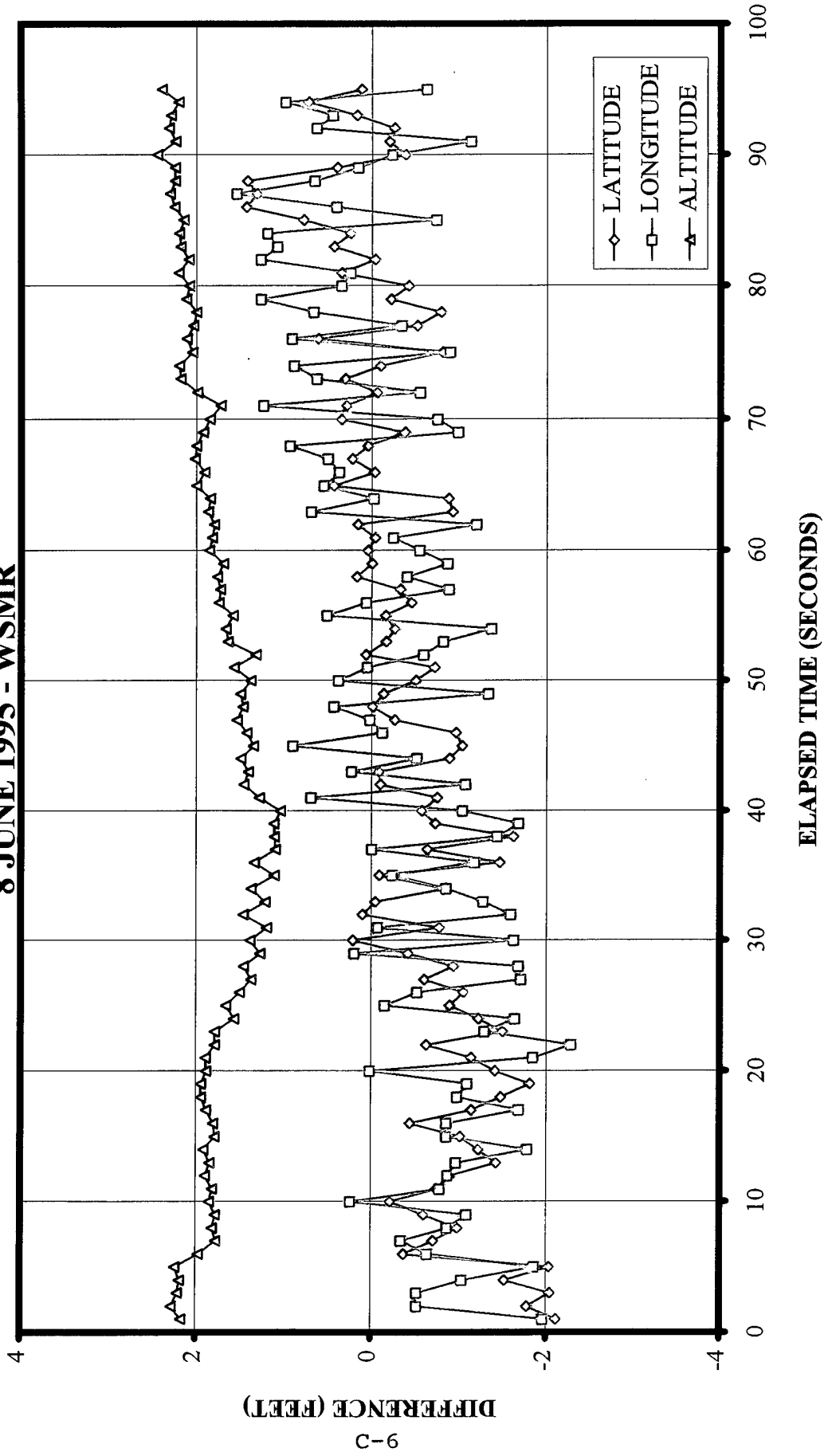
**GPS vs OPTICS**  
**PASS # 2 - RAPID ALTITUDE CHANGES**  
**8 JUNE 1995 - WSMR**



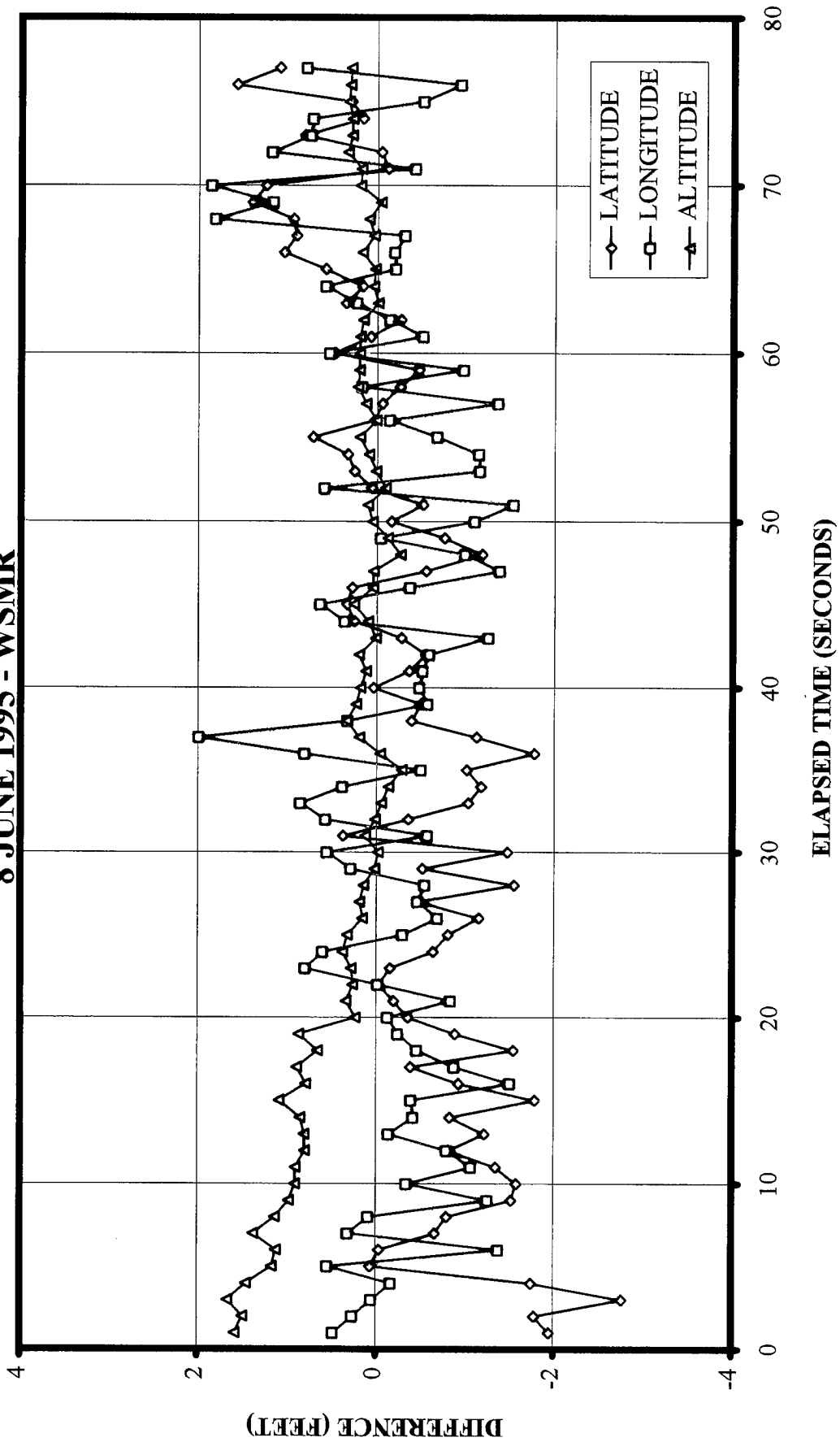
**GPS vs OPTICS  
PASS # 3 - 15 DEGREE BANK  
8 JUNE 1995 - WSMR**



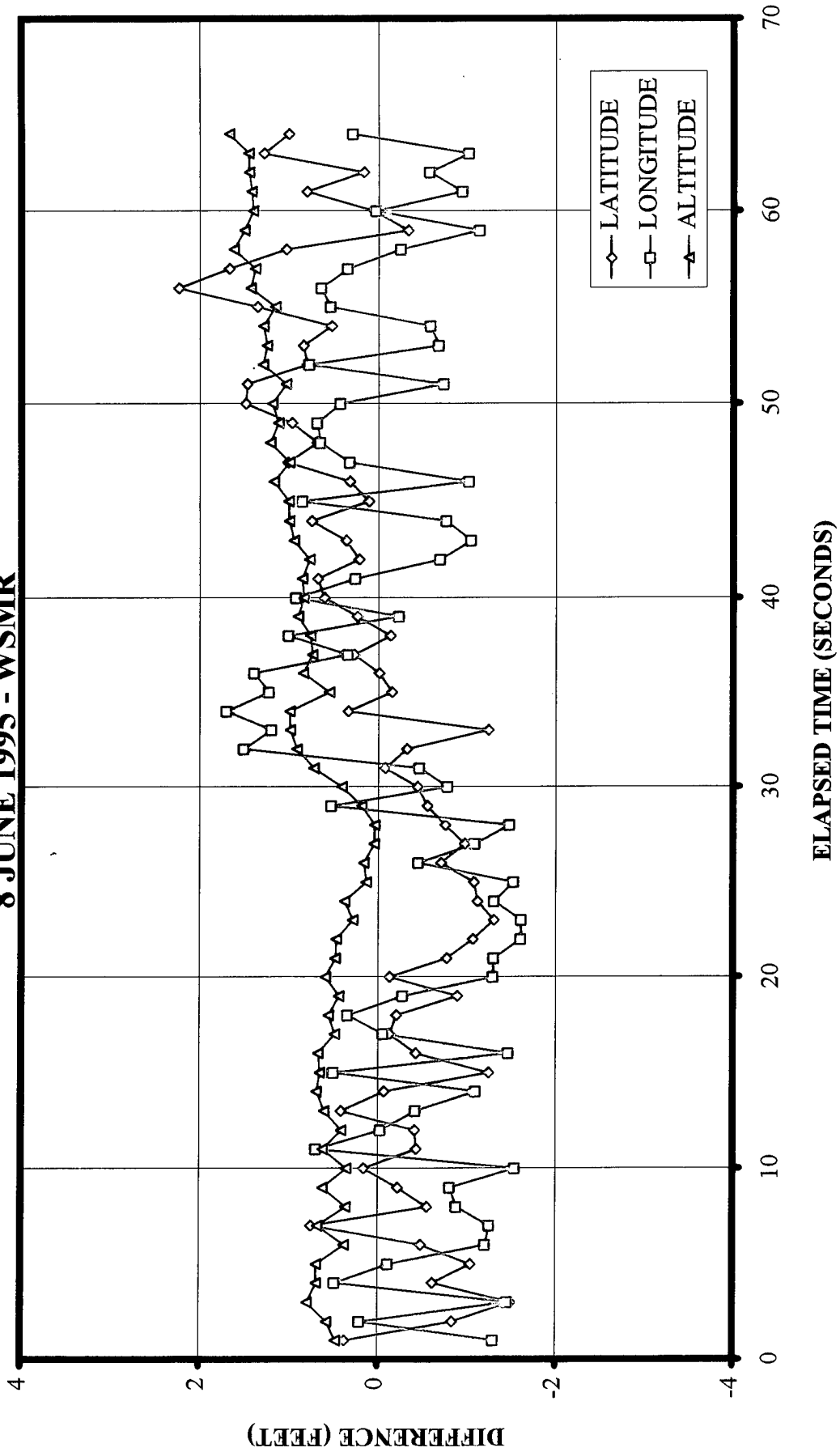
**GPS vs OPTICS  
PASS # 4 - 30 DEGREE BANK  
8 JUNE 1995 - WSMR**



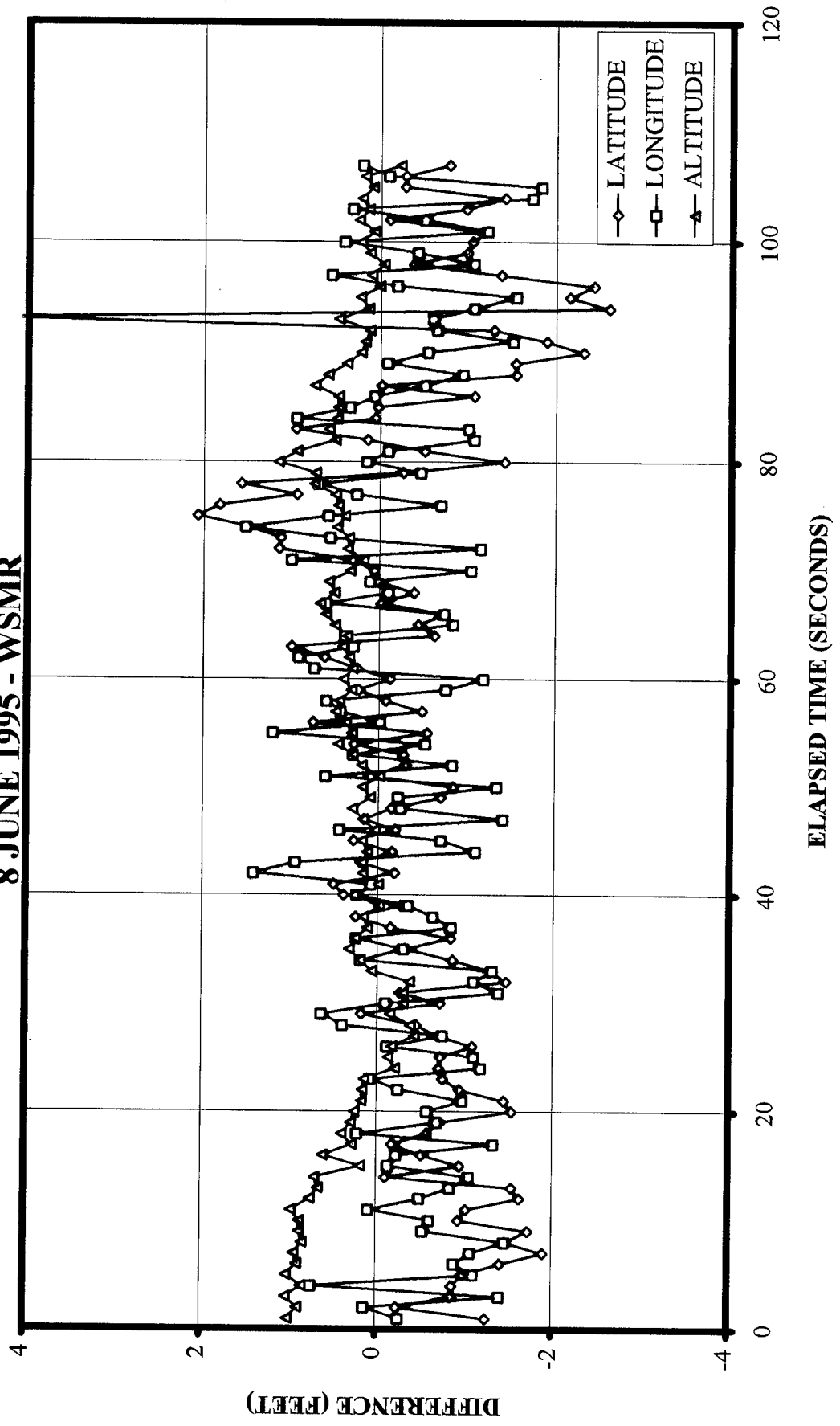
**GPS vs OPTICS  
PASS # 5 - 45 DEGREE BANK  
8 JUNE 1995 - WSMR**



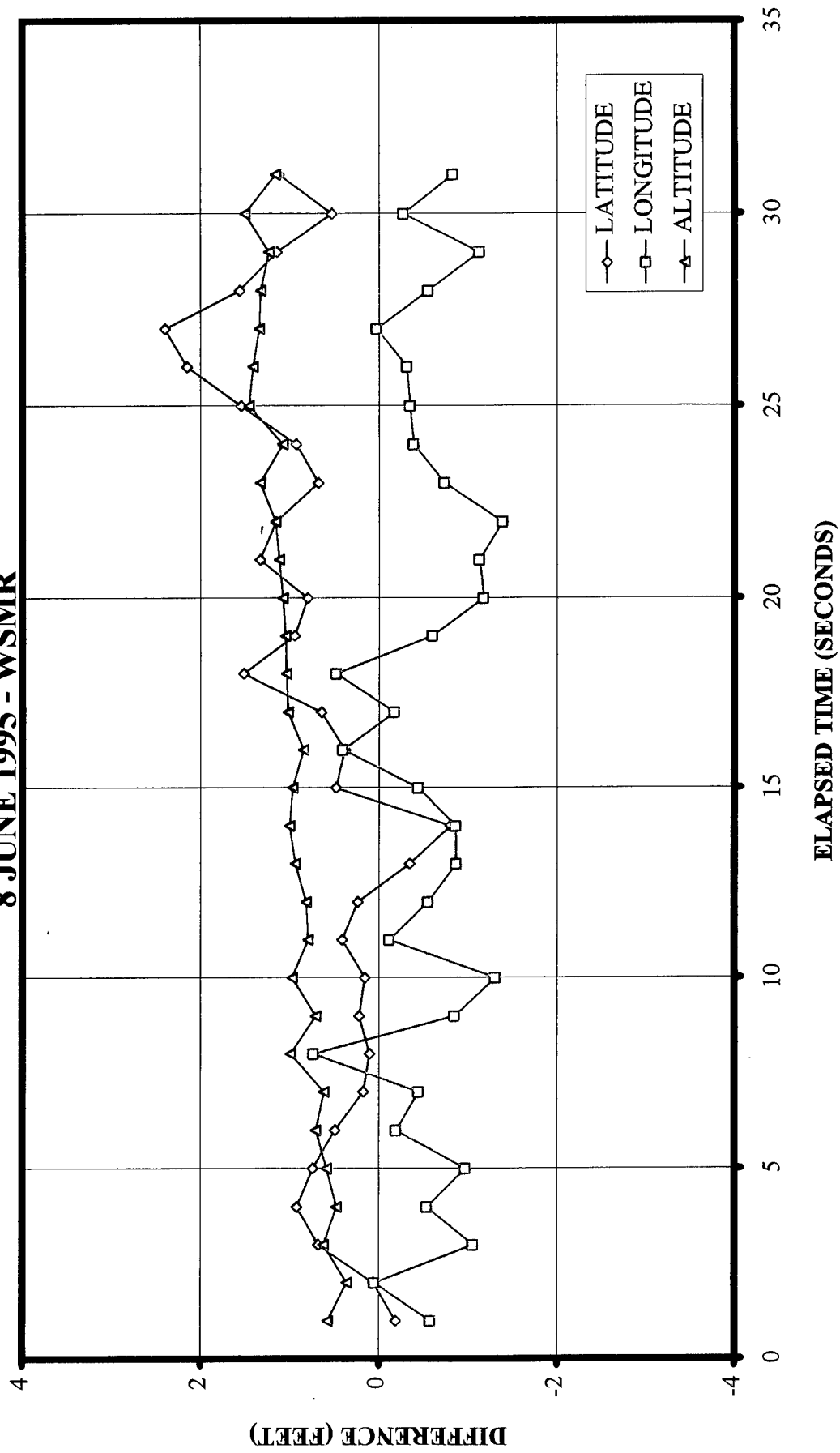
**GPS vs OPTICS  
PASS # 6 - 60 DEGREE BANK  
8 JUNE 1995 - WSMR**



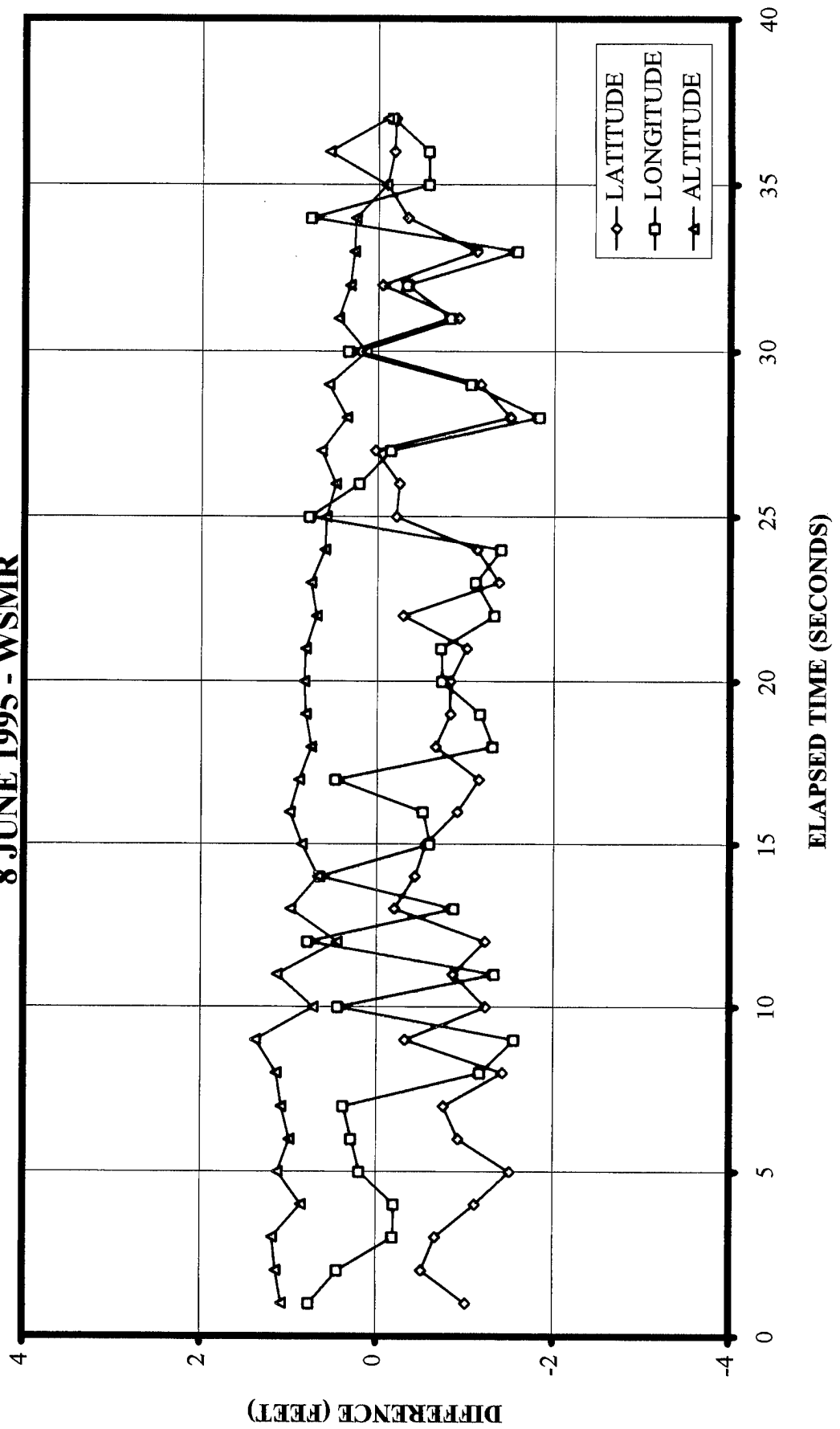
**GPS vs OPTICS  
PASS # 7 - FIGURE EIGHT  
8 JUNE 1995 - WSMR**



**GPS vs OPTICS  
PASS # 8 - LEVEL FLIGHT  
8 JUNE 1995 - WSMR**

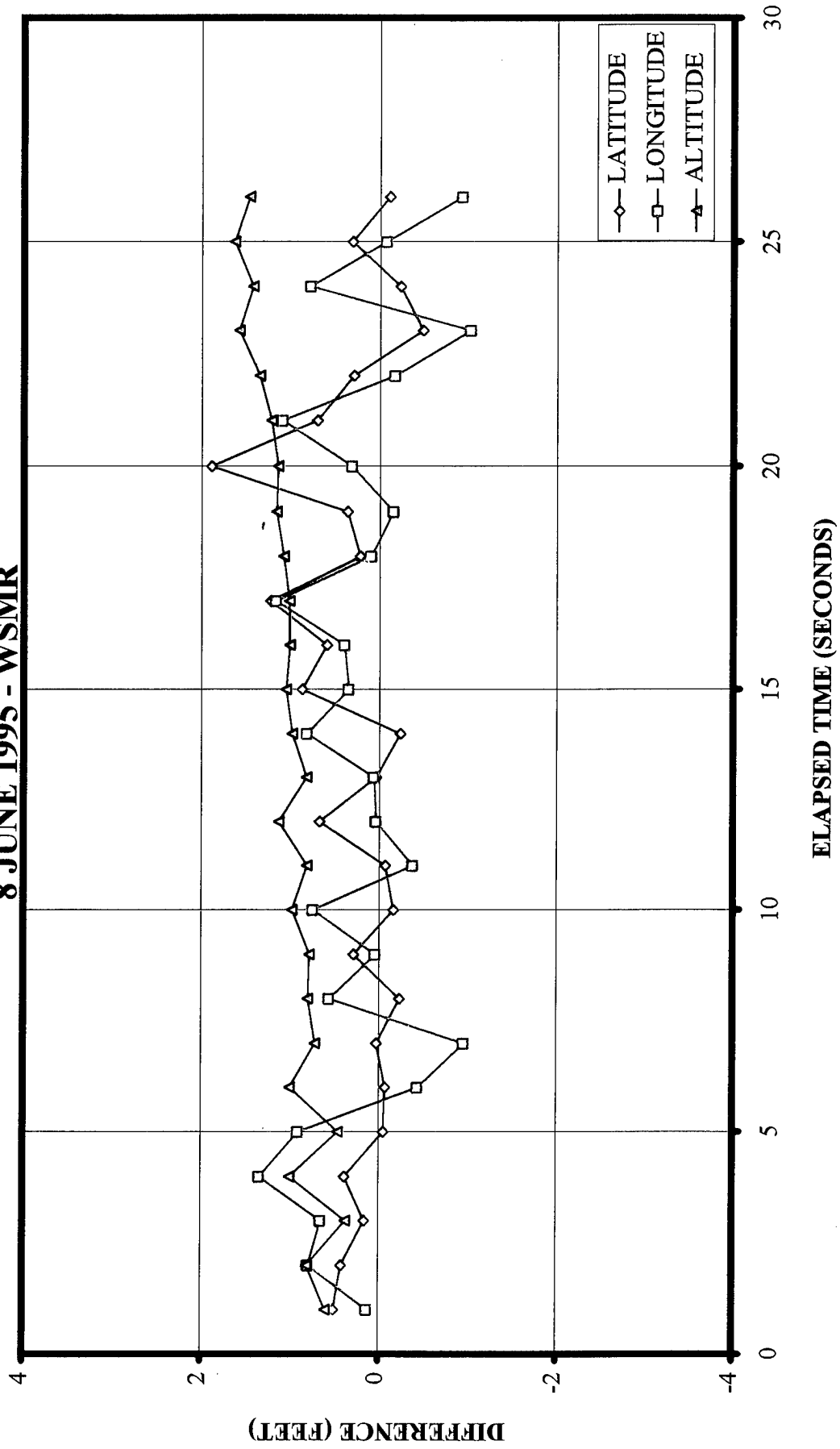


**GPS vs OPTICS**  
**PASS # 9 - RAPID ALTITUDE CHANGES**  
**8 JUNE 1995 - WSMR**

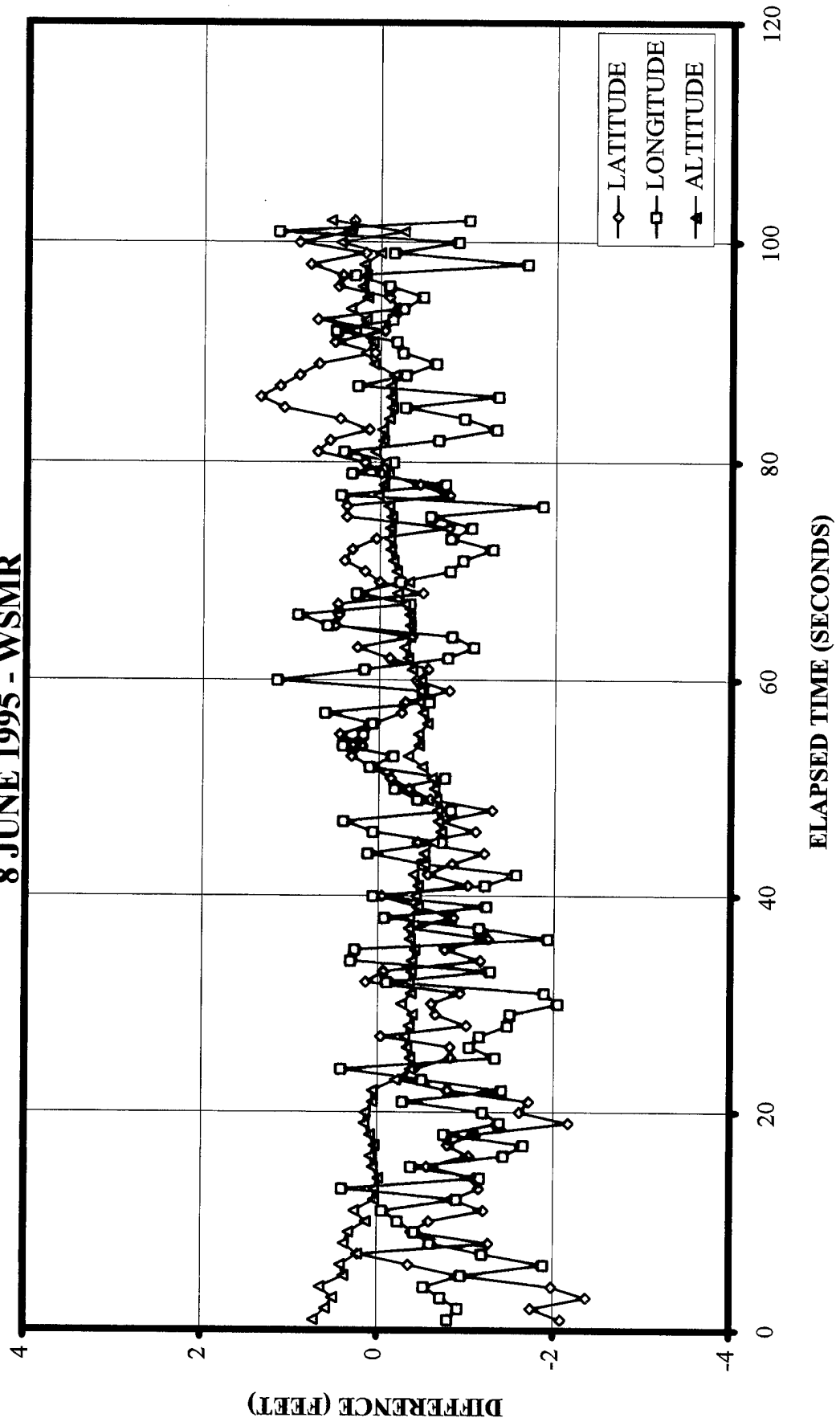




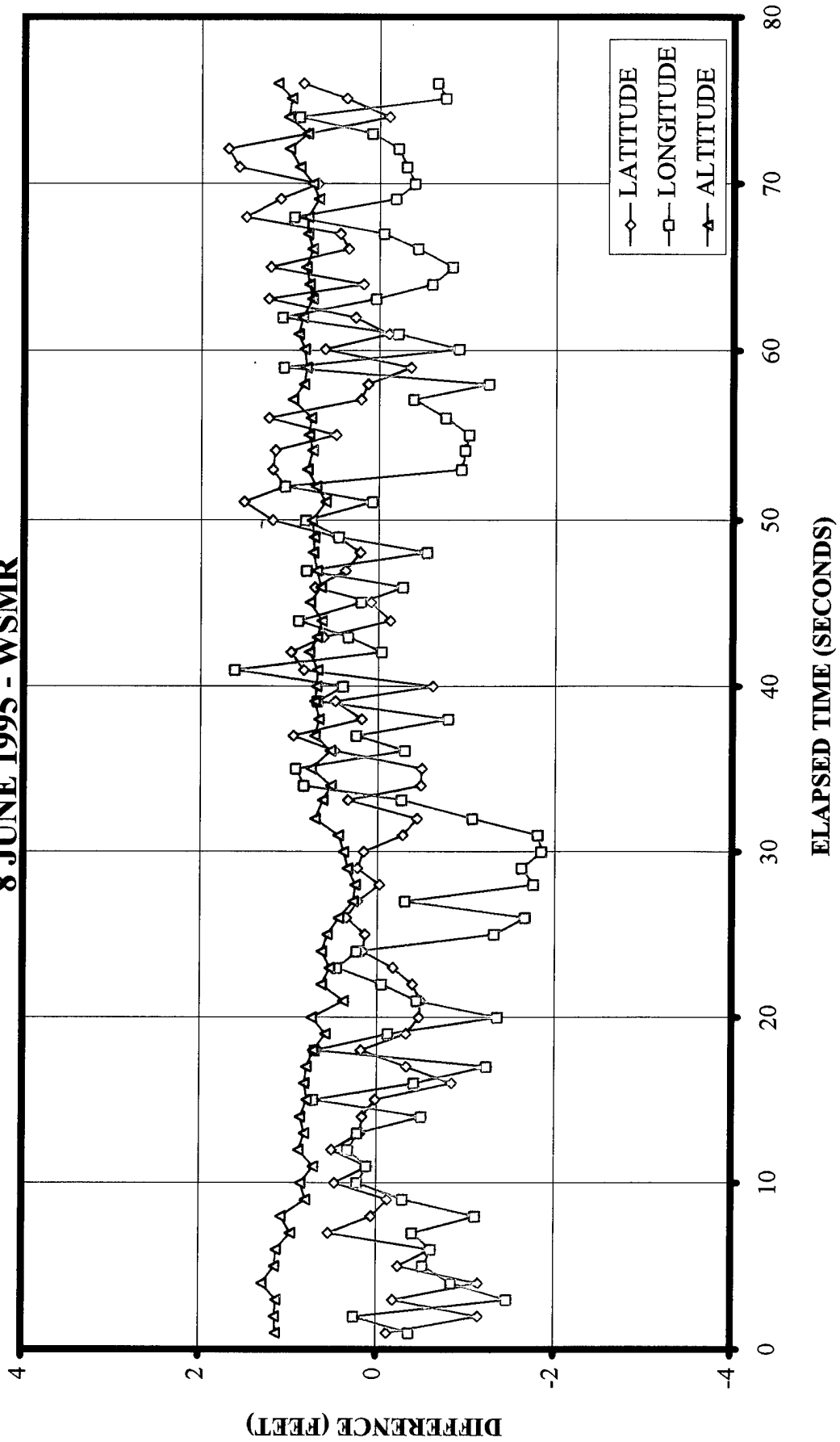
**GPS vs OPTICS  
PASS # 10 - LEVEL FLIGHT  
8 JUNE 1995 - WSMR**



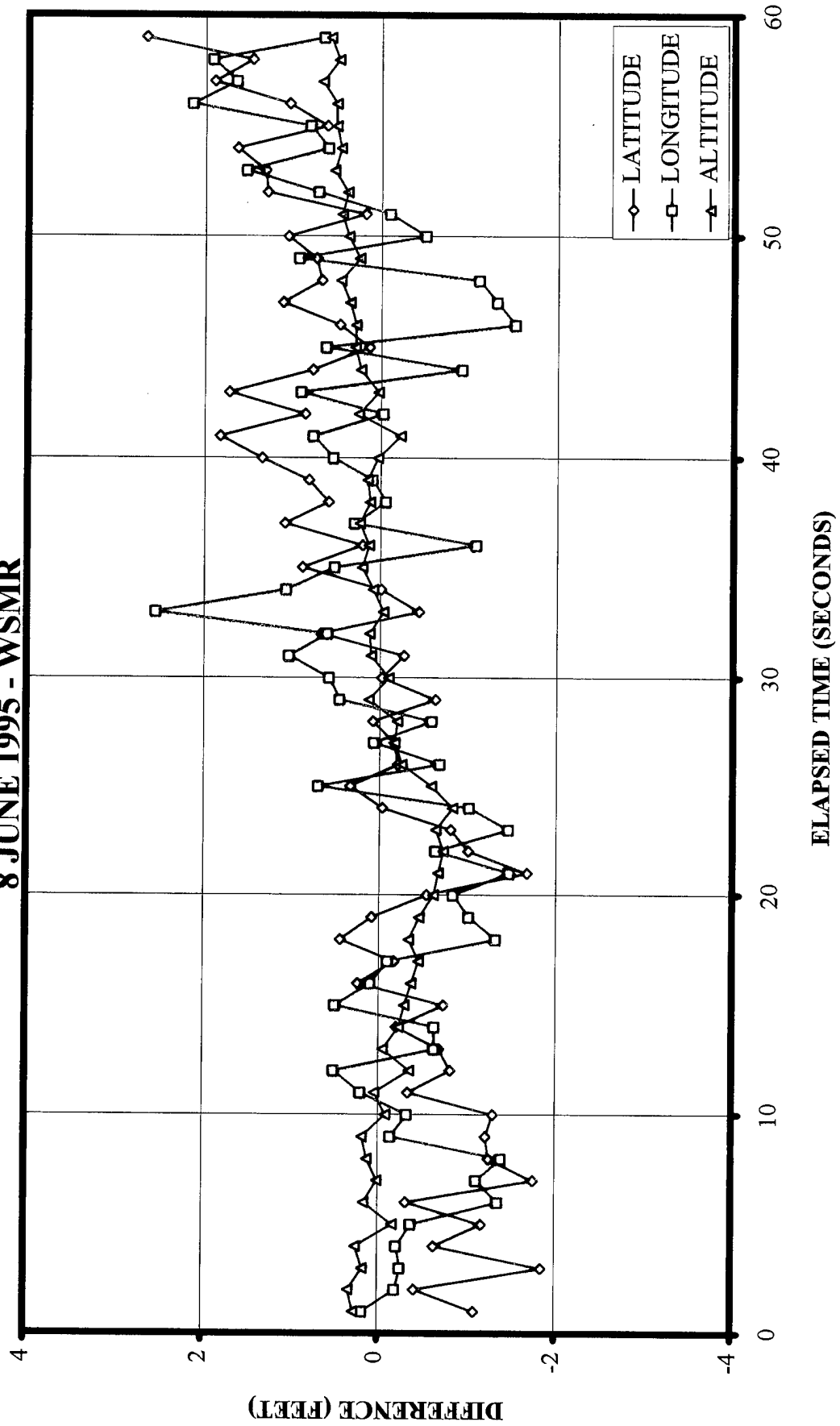
**GPS vs OPTICS  
PASS # 11 - 15 DEGREE BANK  
8 JUNE 1995 - WSMR**



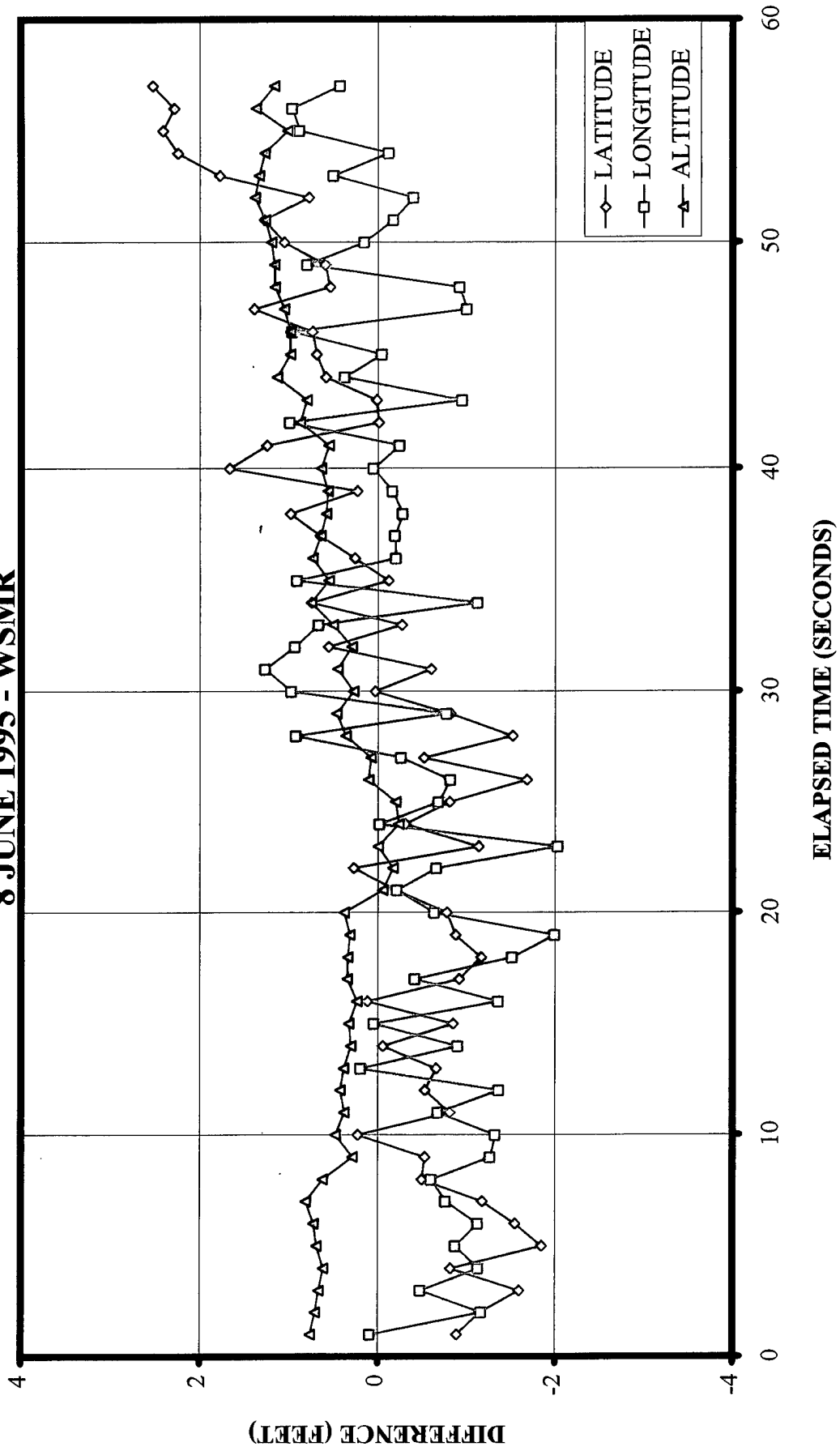
**GPS vs OPTICS  
PASS # 12 - 30 DEGREE BANK  
8 JUNE 1995 - WSMR**



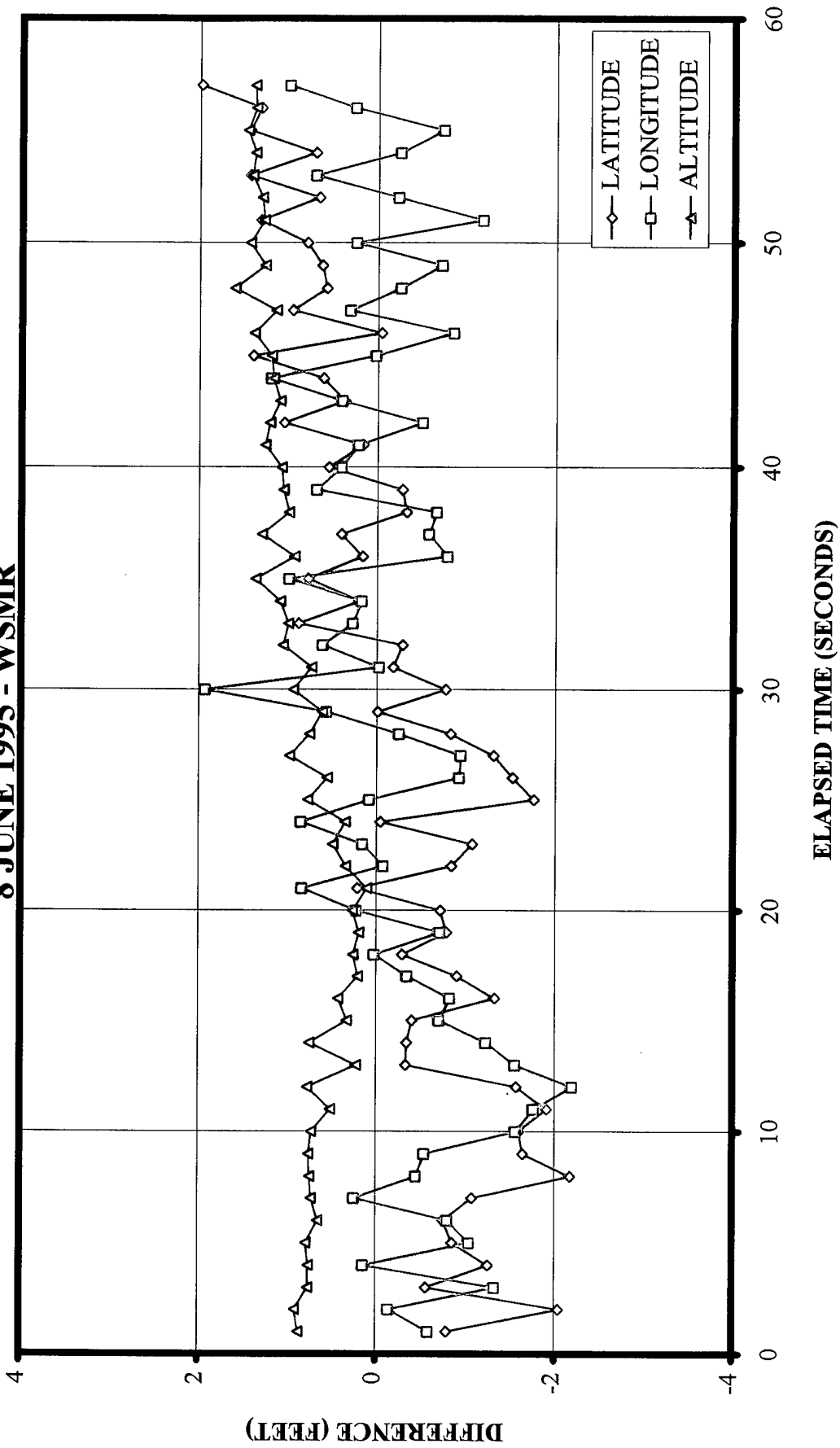
**GPS vs OPTICS  
PASS # 13 - 45 DEGREE BANK  
8 JUNE 1995 - WSMR**



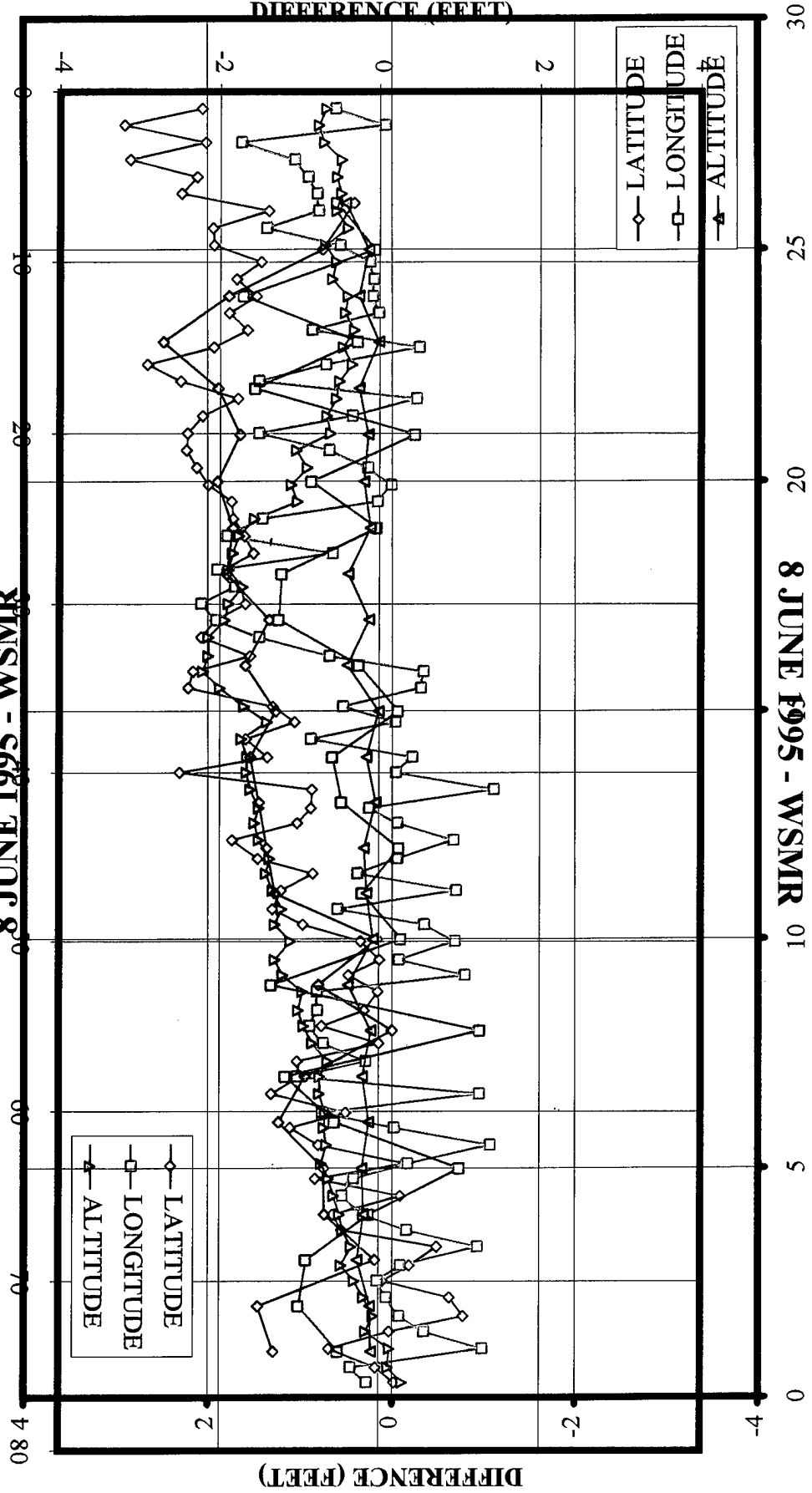
**GPS vs OPTICS  
PASS # 14 - 60 DEGREE BANK  
8 JUNE 1995 - WSMR**



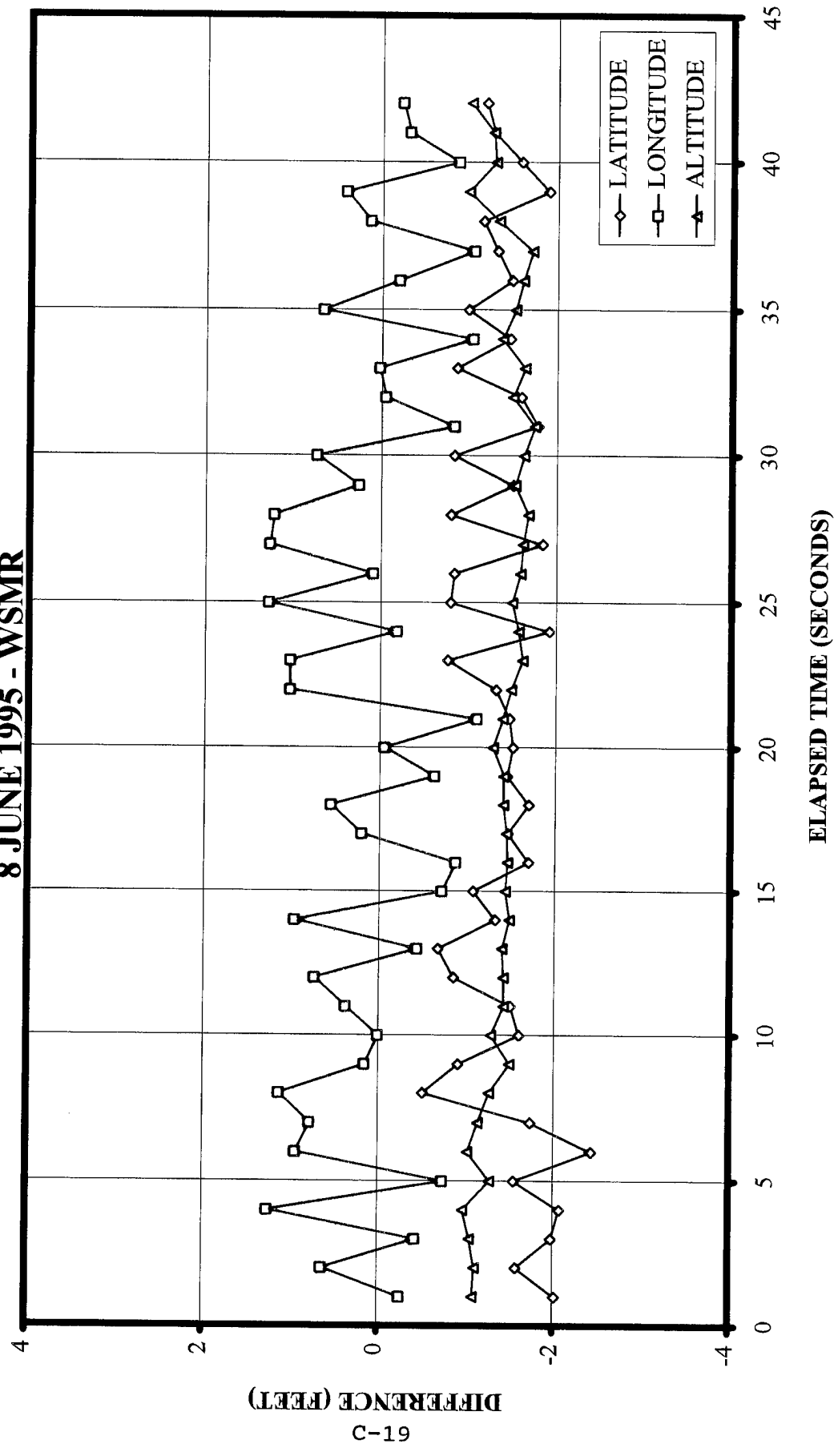
**GPS vs OPTICS  
PASS # 15 - FIGURE EIGHT  
8 JUNE 1995 - WSMR**



**GPS vs OPTICS**  
**PASS # 16 (S) LEVEL 1 FLIGHT**  
**8 JUNE 1995 - WSMR**

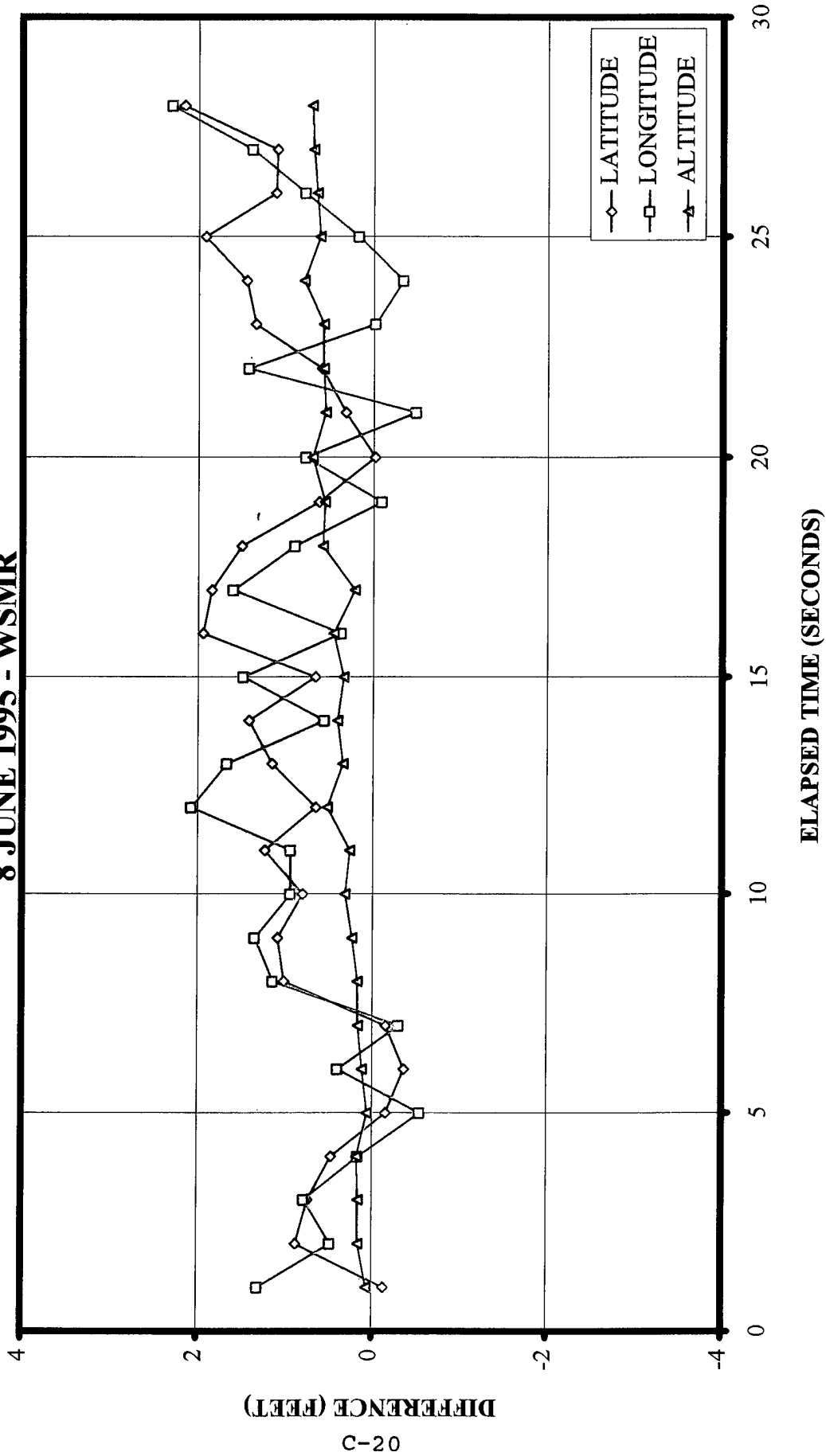


**GPS vs OPTICS**  
**PASS # 17 - RAPID ALTITUDE CHANGES**  
**8 JUNE 1995 - WSMR**

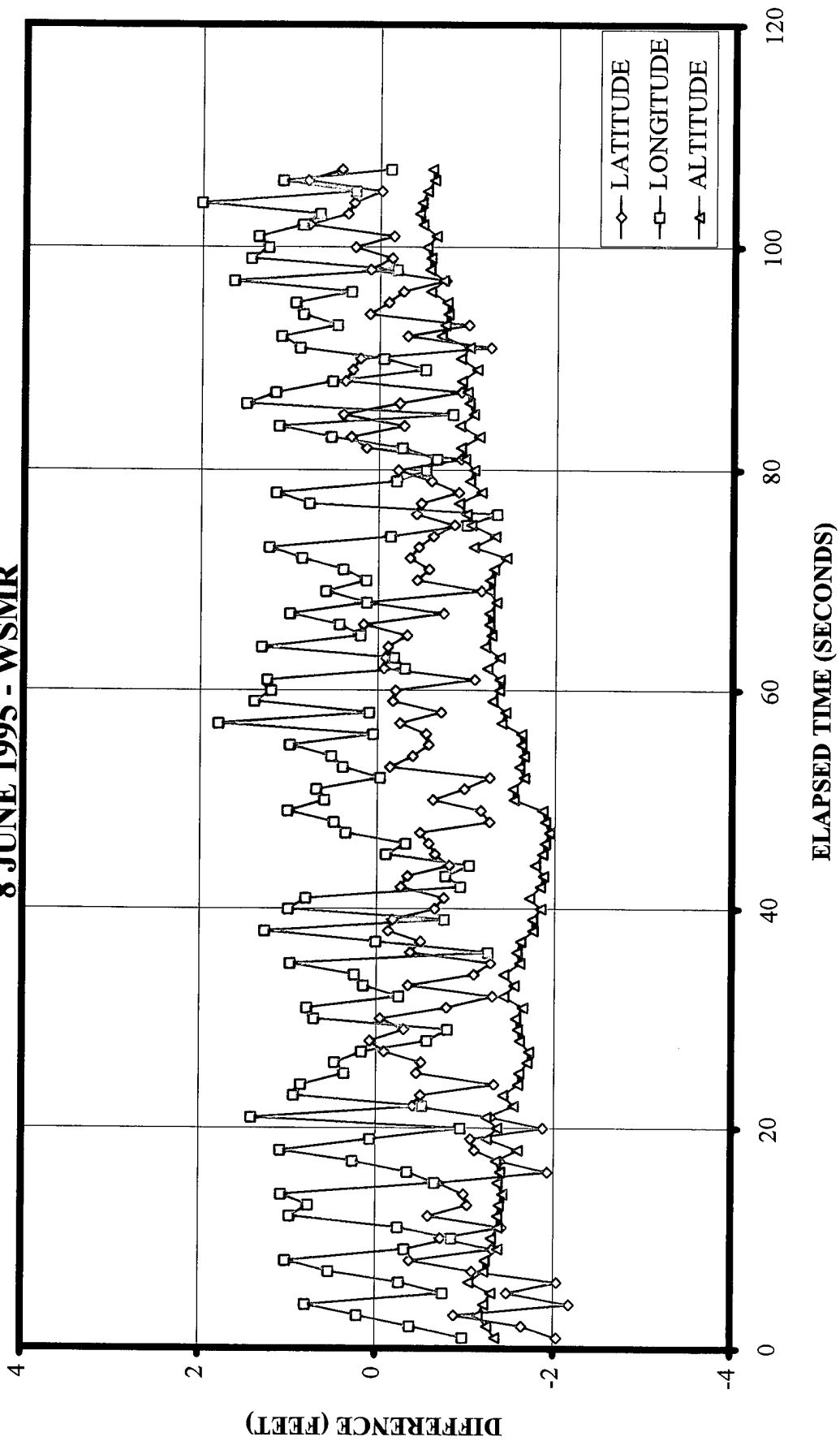




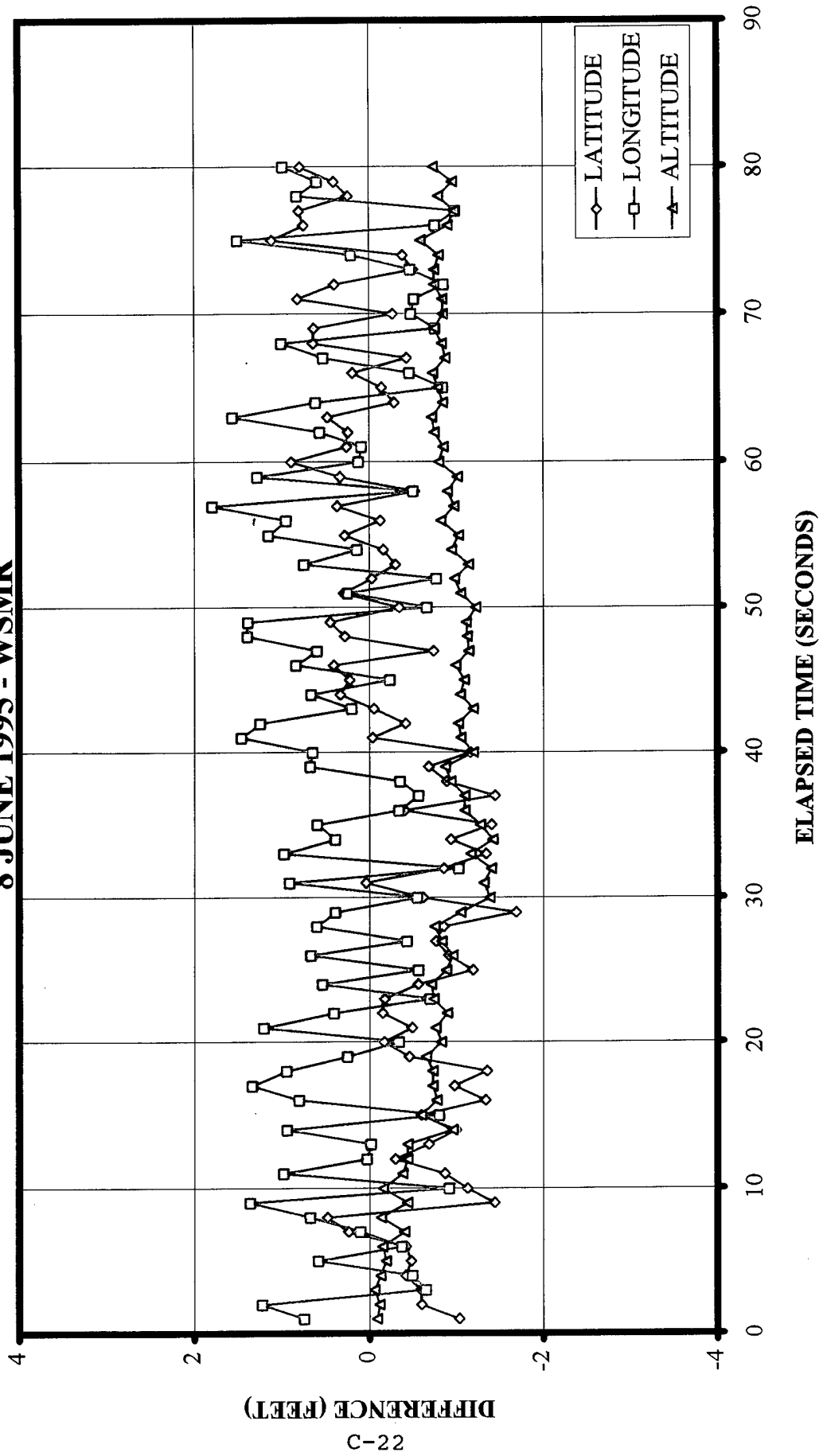
**GPS vs OPTICS  
PASS # 18 - LEVEL FLIGHT  
8 JUNE 1995 - WSMR**



**GPS vs OPTICS  
PASS # 19 - 15 DEGREE BANK  
8 JUNE 1995 - WSMR**

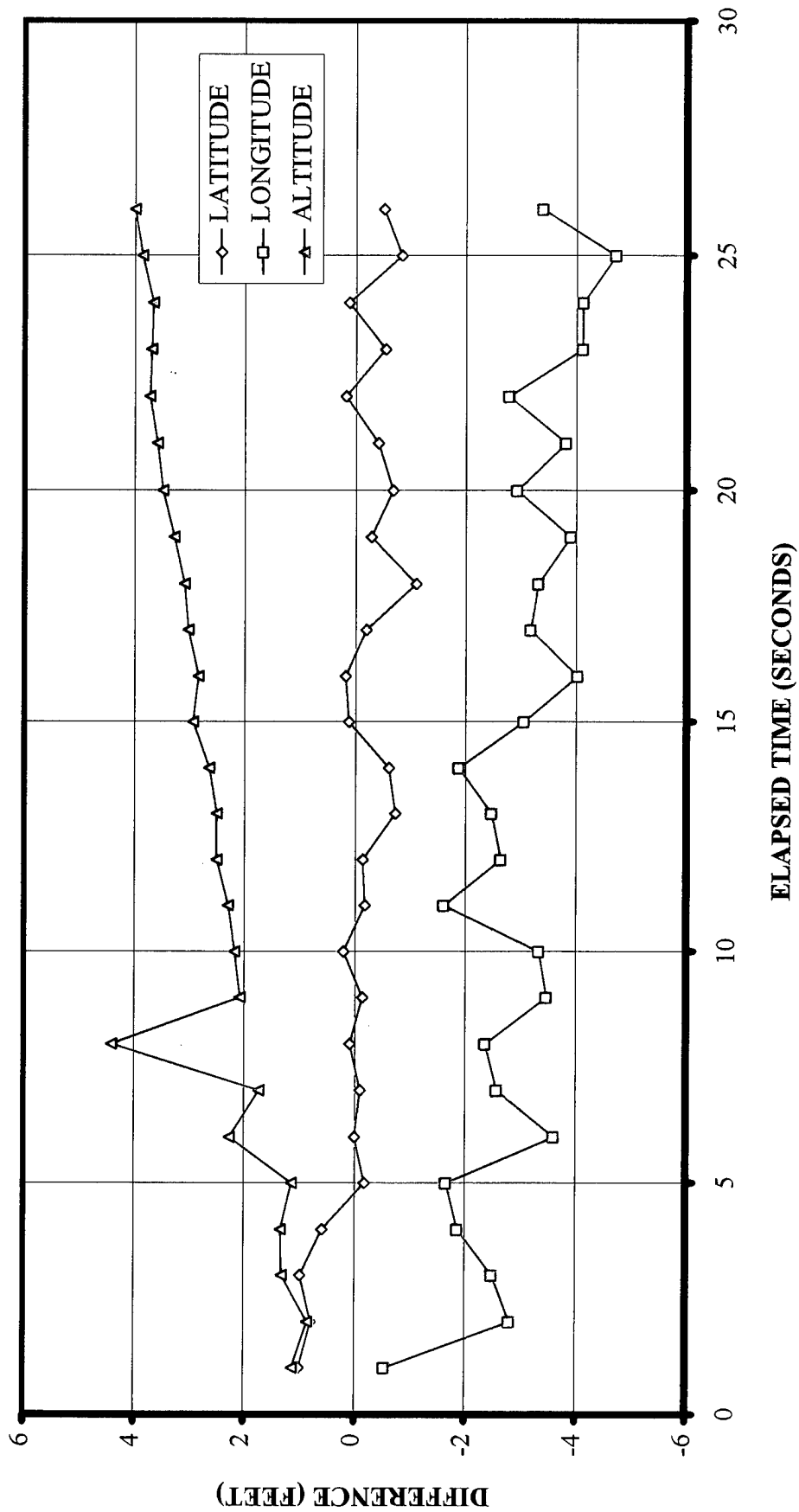


**GPS vs OPTICS  
PASS # 20 - 30 DEGREE BANK  
8 JUNE 1995 - WSMR**

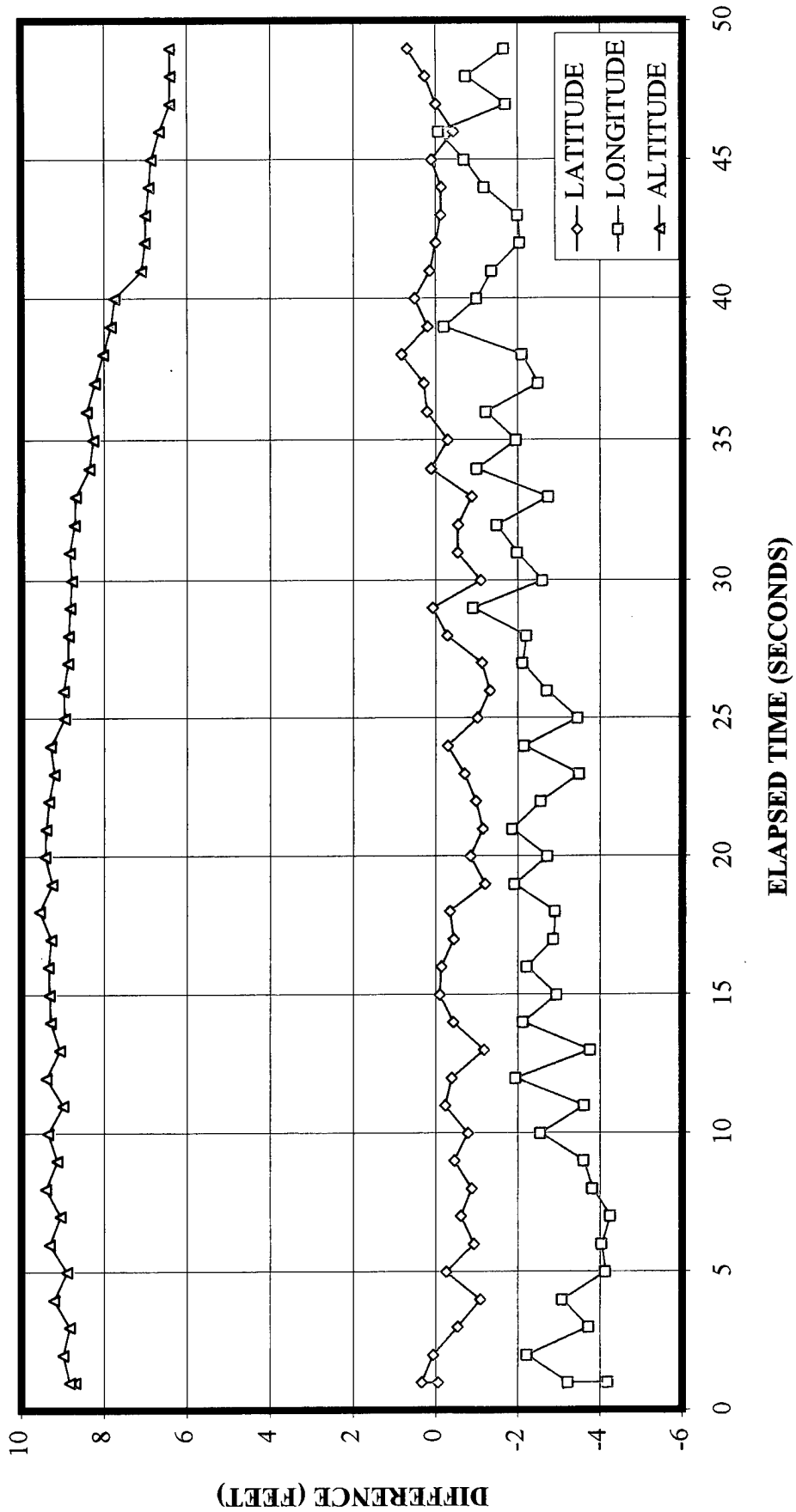


APPENDIX D. COMPARISON OF REAL-TIME GPS POSITION SOLUTION  
TO WSMR OPTICS DATA

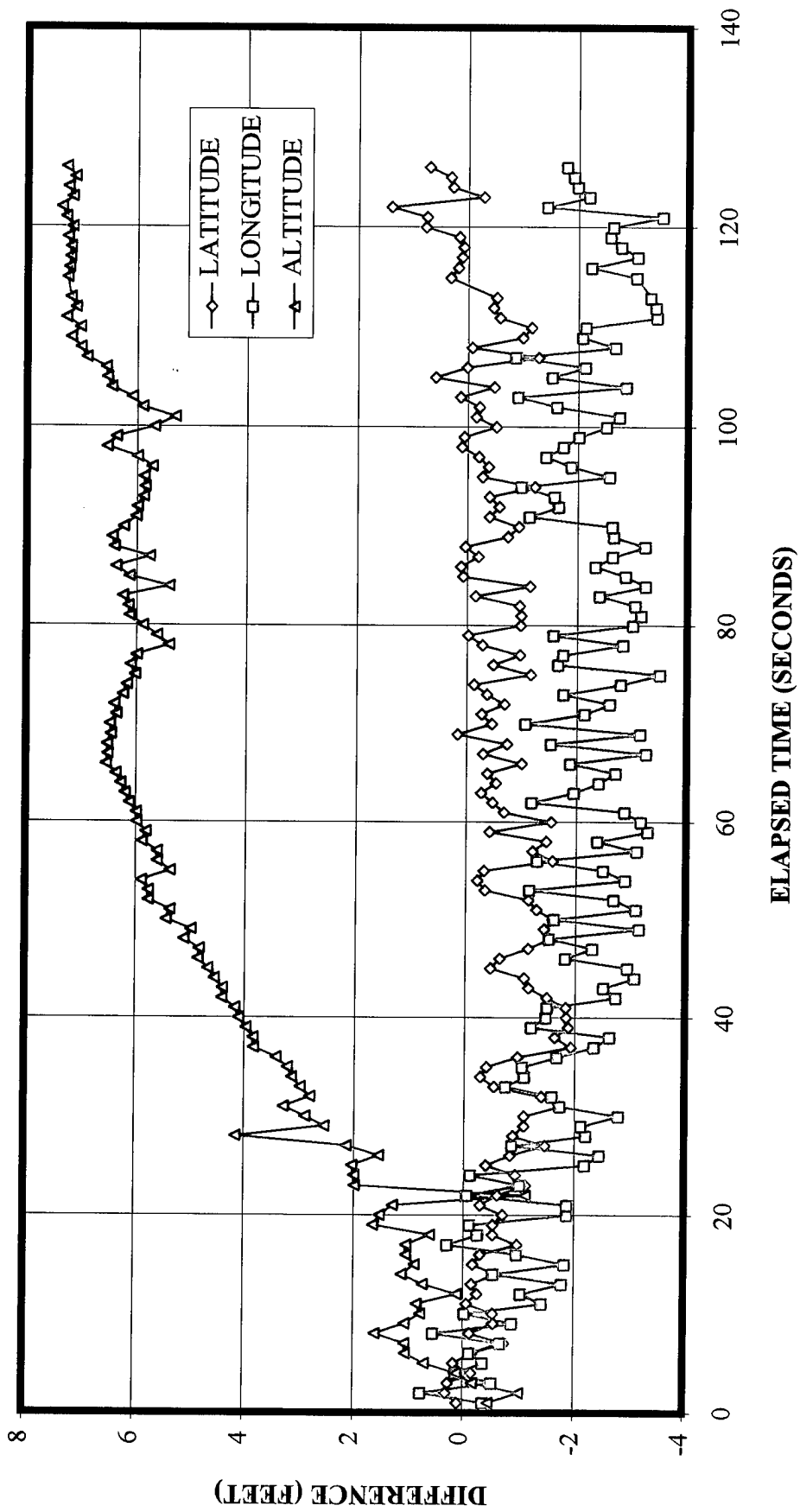
**REAL-TIME GPS vs OPTICS  
PASS # 1 - LEVEL FLIGHT  
8 JUNE 1995 - WSMR**



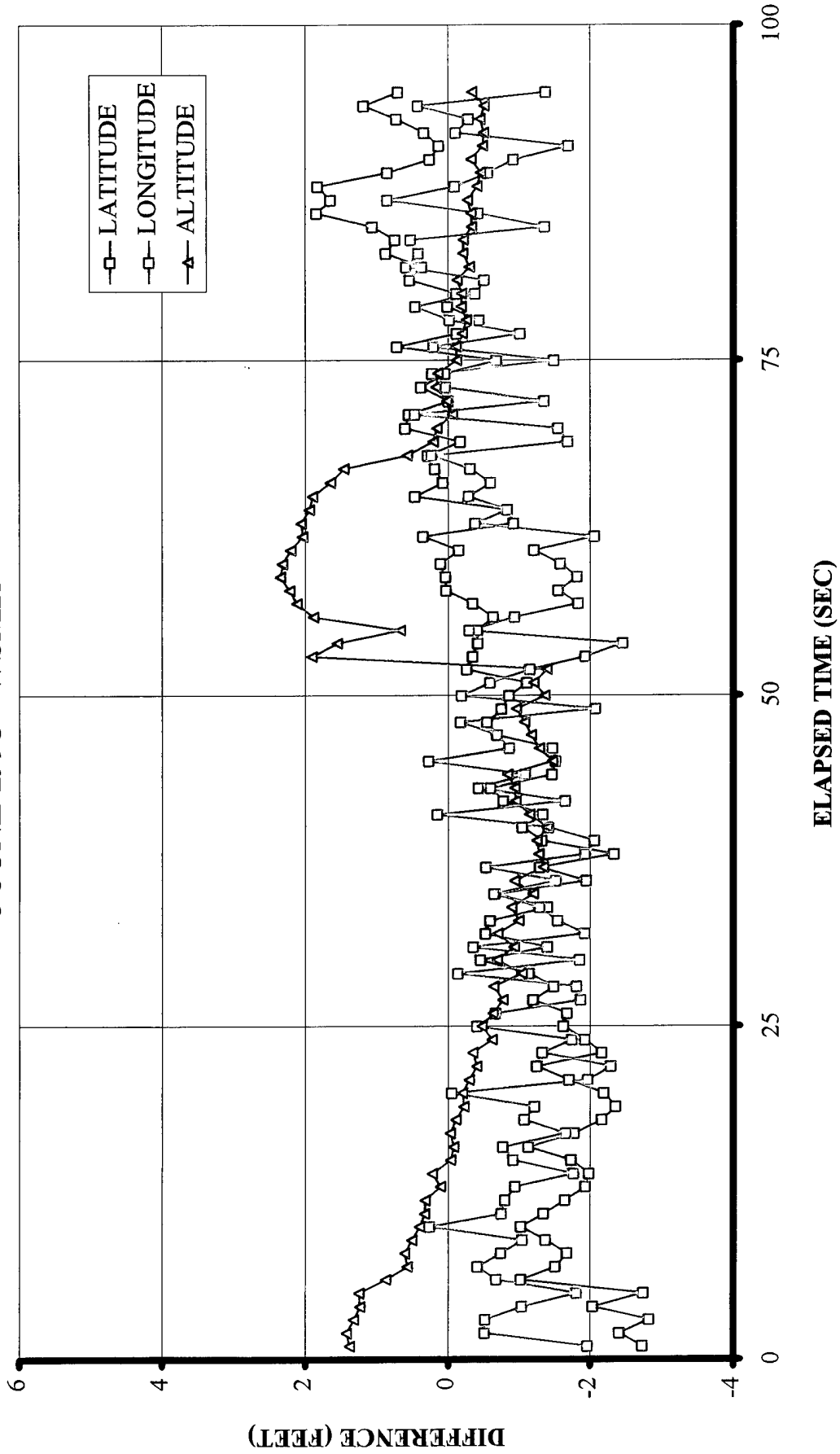
**REAL-TIME GPS vs OPTICS  
PASS # 2 - RAPID ALTITUDE CHANGES  
8 JUNE 1995 - WSMR**



**REAL-TIME GPS vs OPTICS  
PASS # 3 - 15 DEGREE BANK  
8 JUNE 1995 - WSMR**

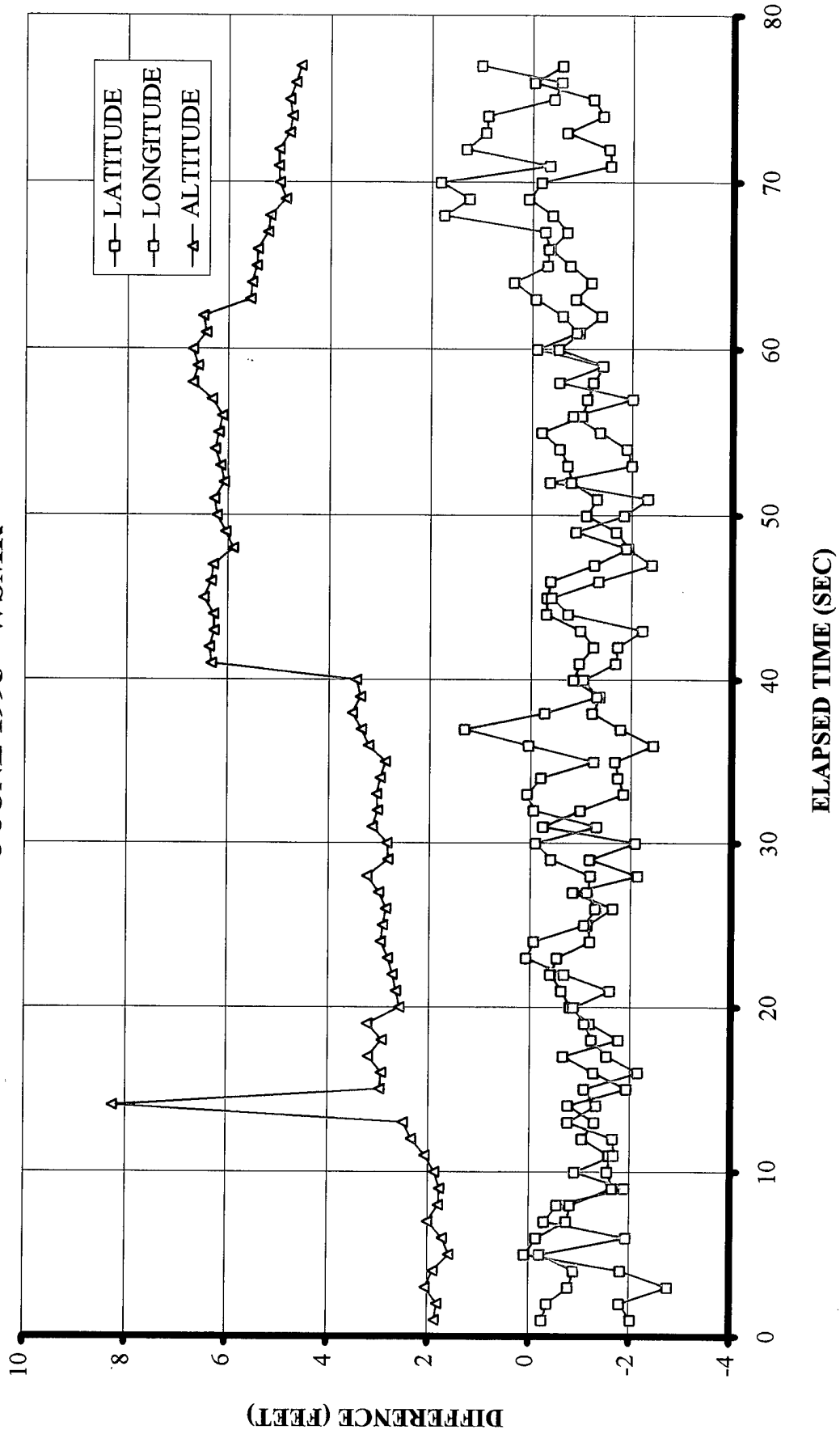


**REAL-TIME GPS vs OPTICS  
PASS # 4 - 30 DEGREE BANK  
8 JUNE 1995 - WSMR**

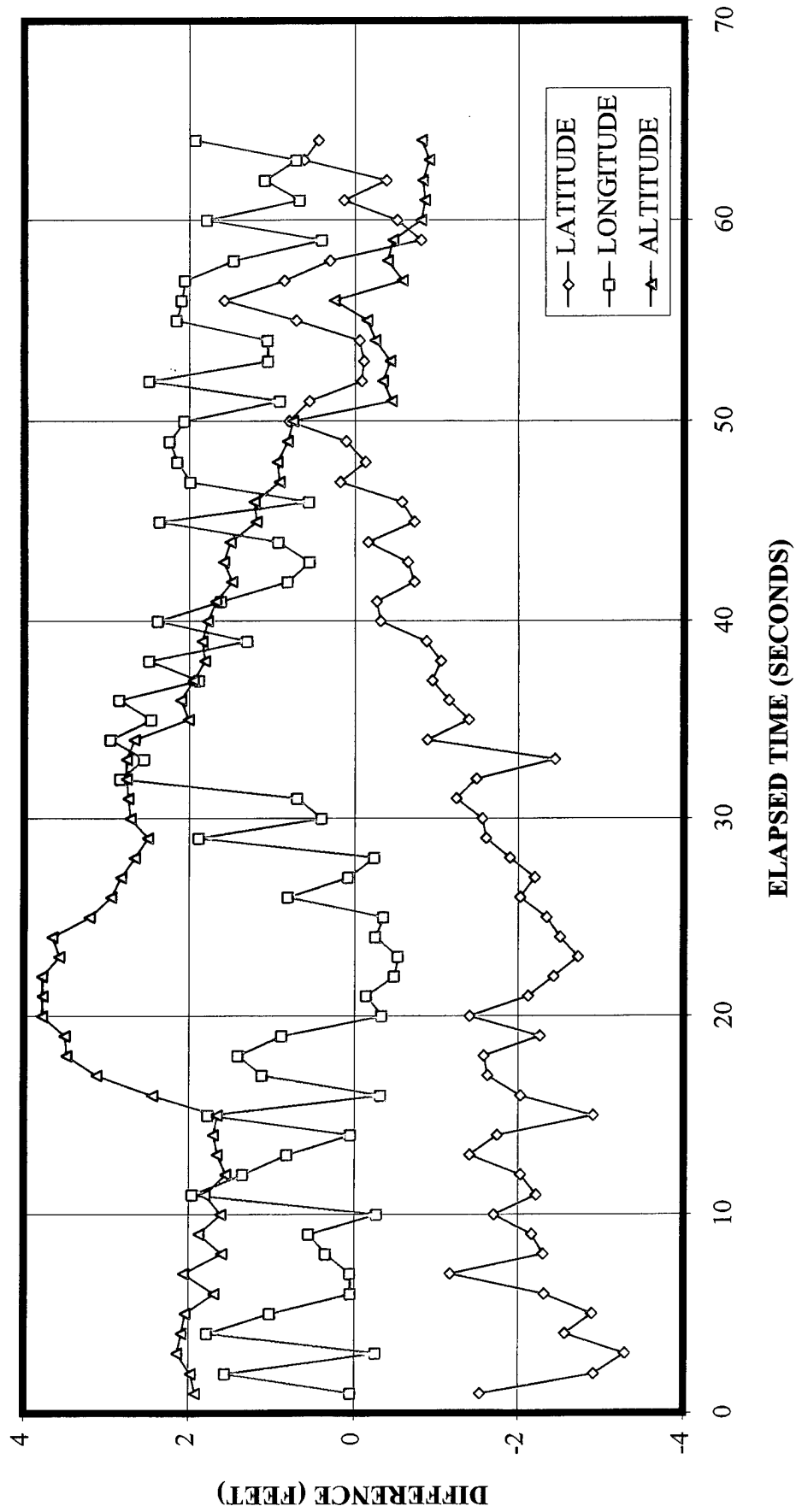




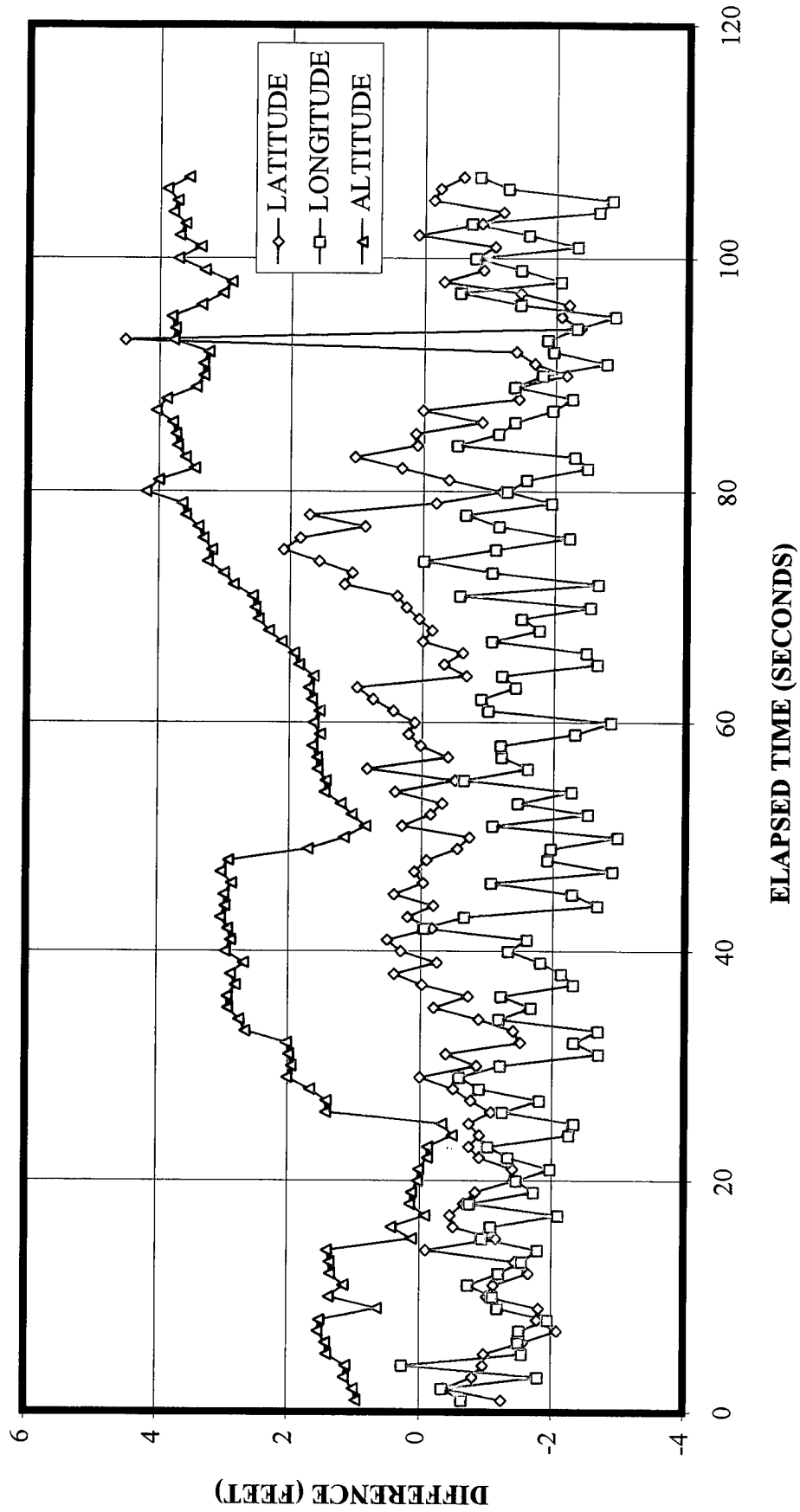
**REAL-TIME GPS vs OPTICS  
PASS # 5 - 45 DEGREE BANK  
8 JUNE 1995 - WSMR**



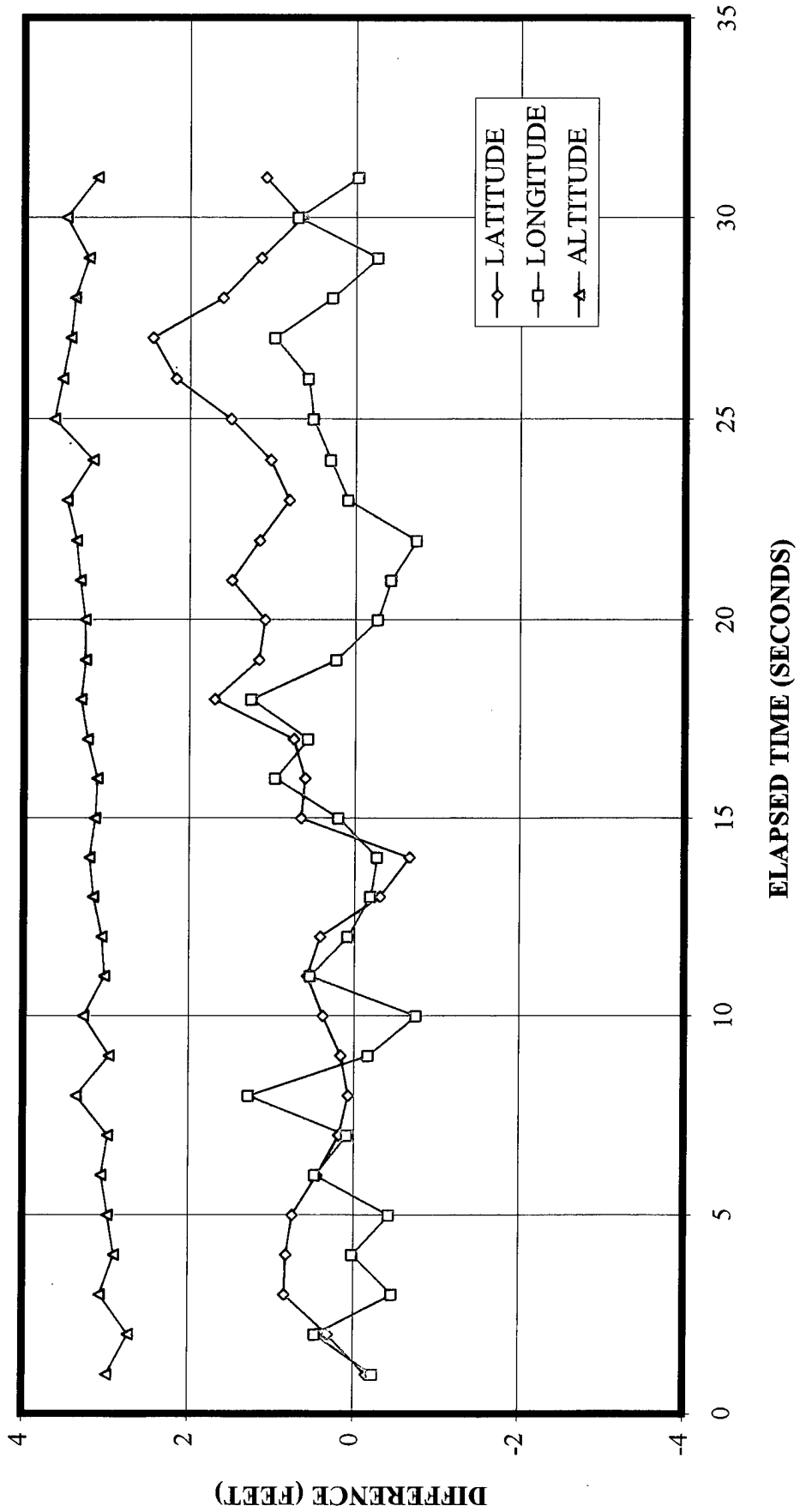
**REAL-TIME GPS vs OPTICS  
PASS # 6 - 60 DEGREE BANK  
8 JUNE 1995 - WSMR**



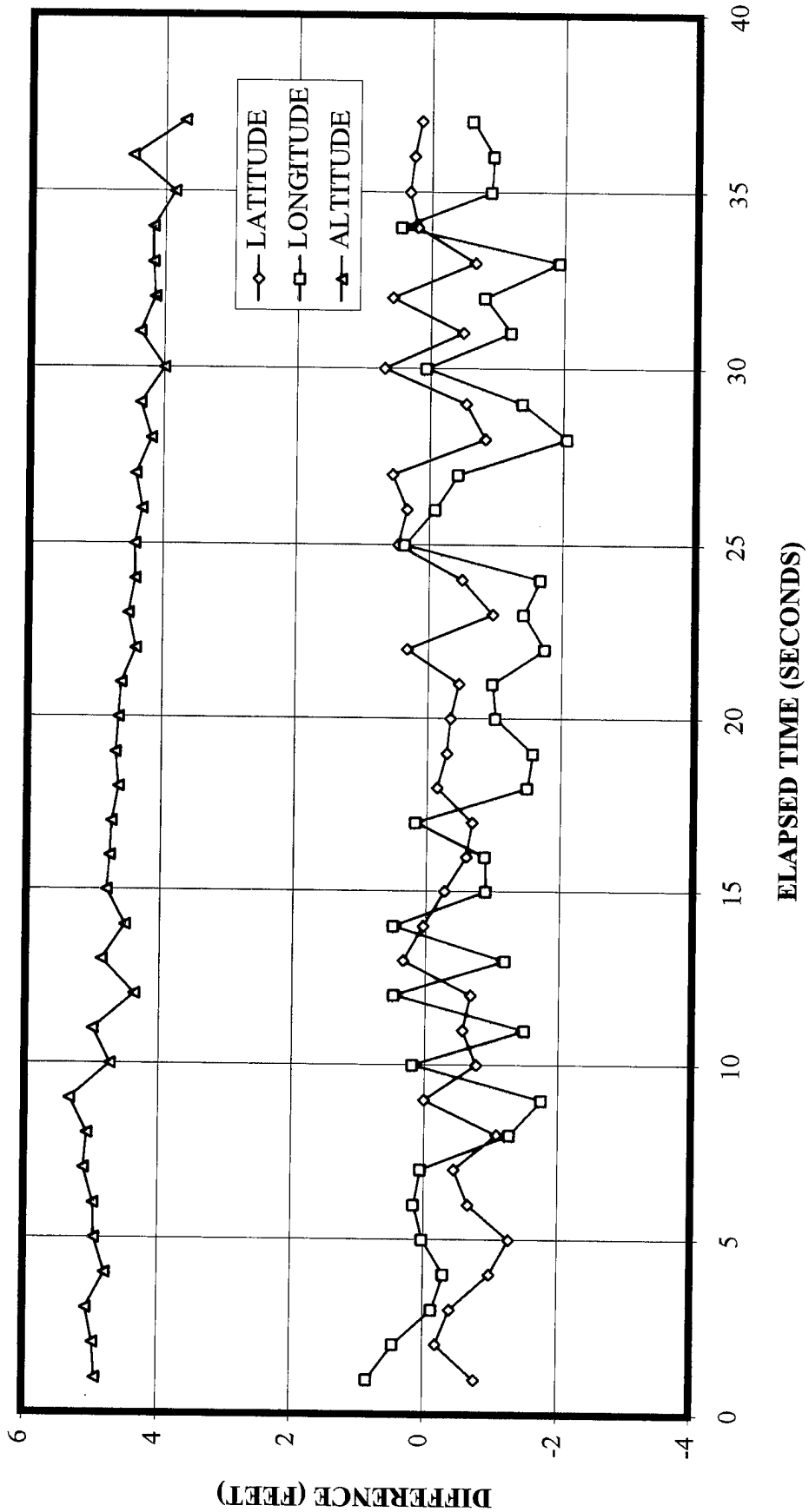
**REAL-TIME GPS vs OPTICS  
PASS # 7 - FIGURE EIGHT  
8 JUNE 1995 - WSMR**



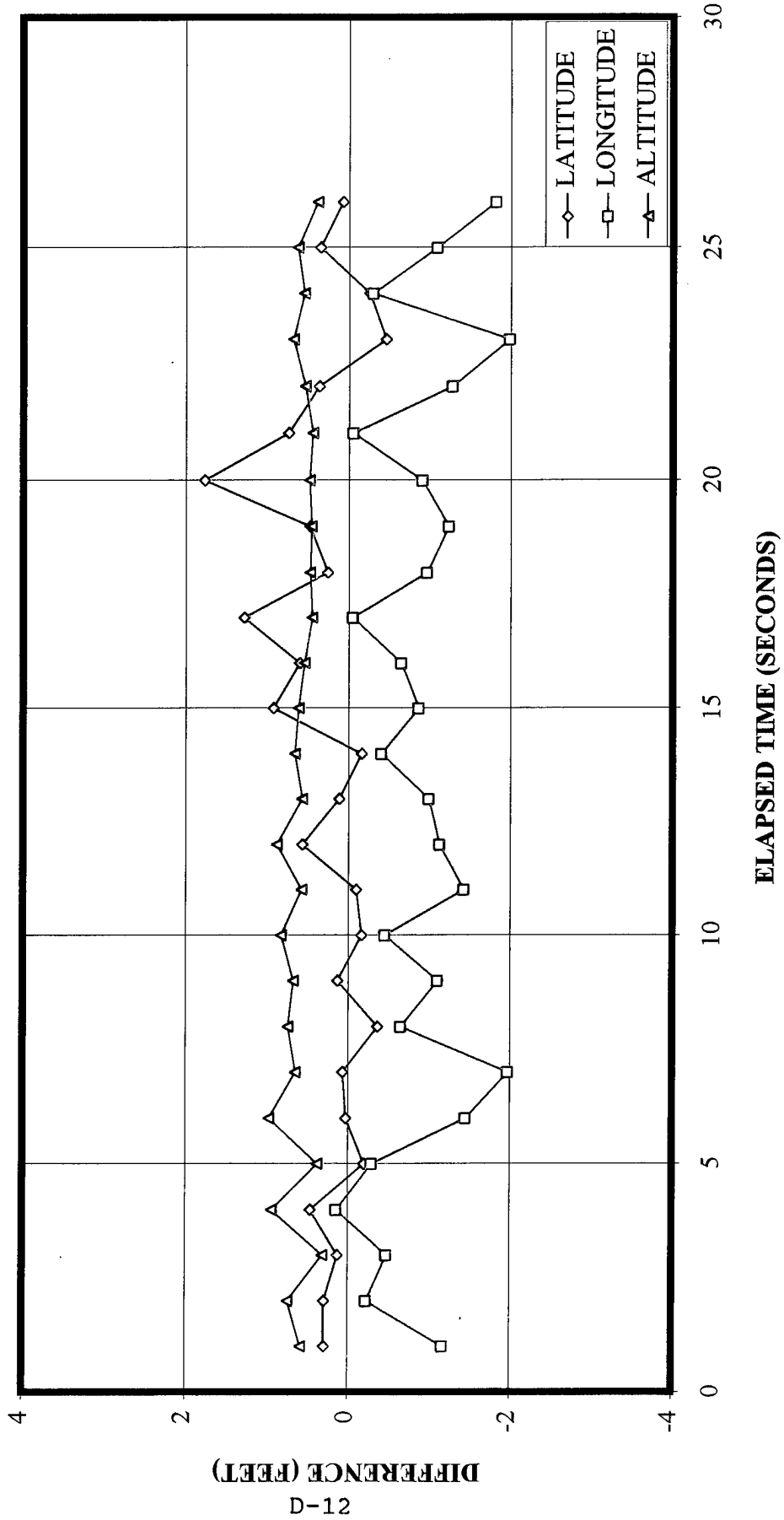
**REAL-TIME GPS vs OPTICS  
PASS # 8 - LEVEL FLIGHT  
8 JUNE 1995 - WSMR**



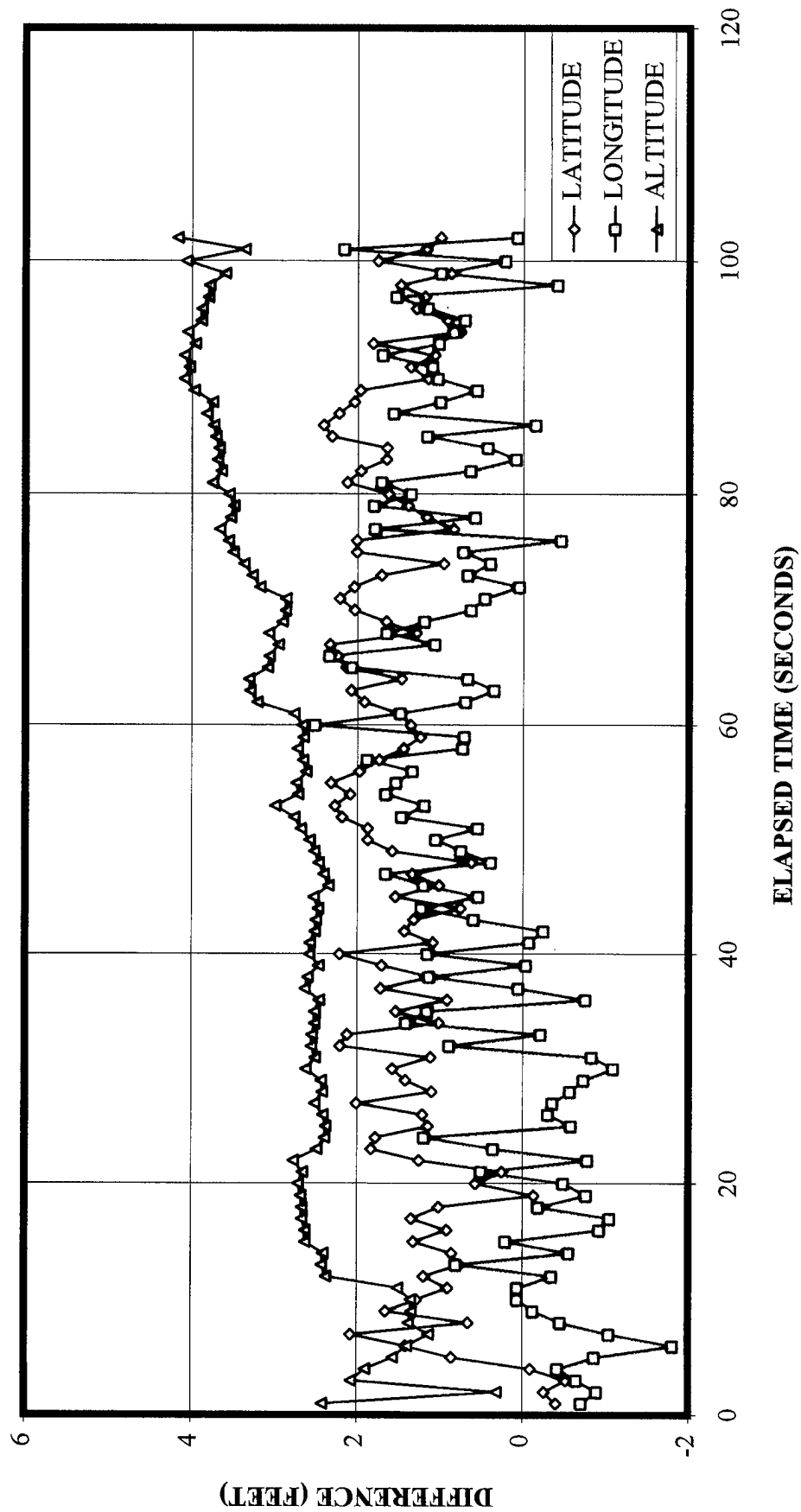
**REAL-TIME GPS vs OPTICS  
PASS # 9 - RAPID ALTITUDE CHANGES  
8 JUNE 1995 - WSMR**



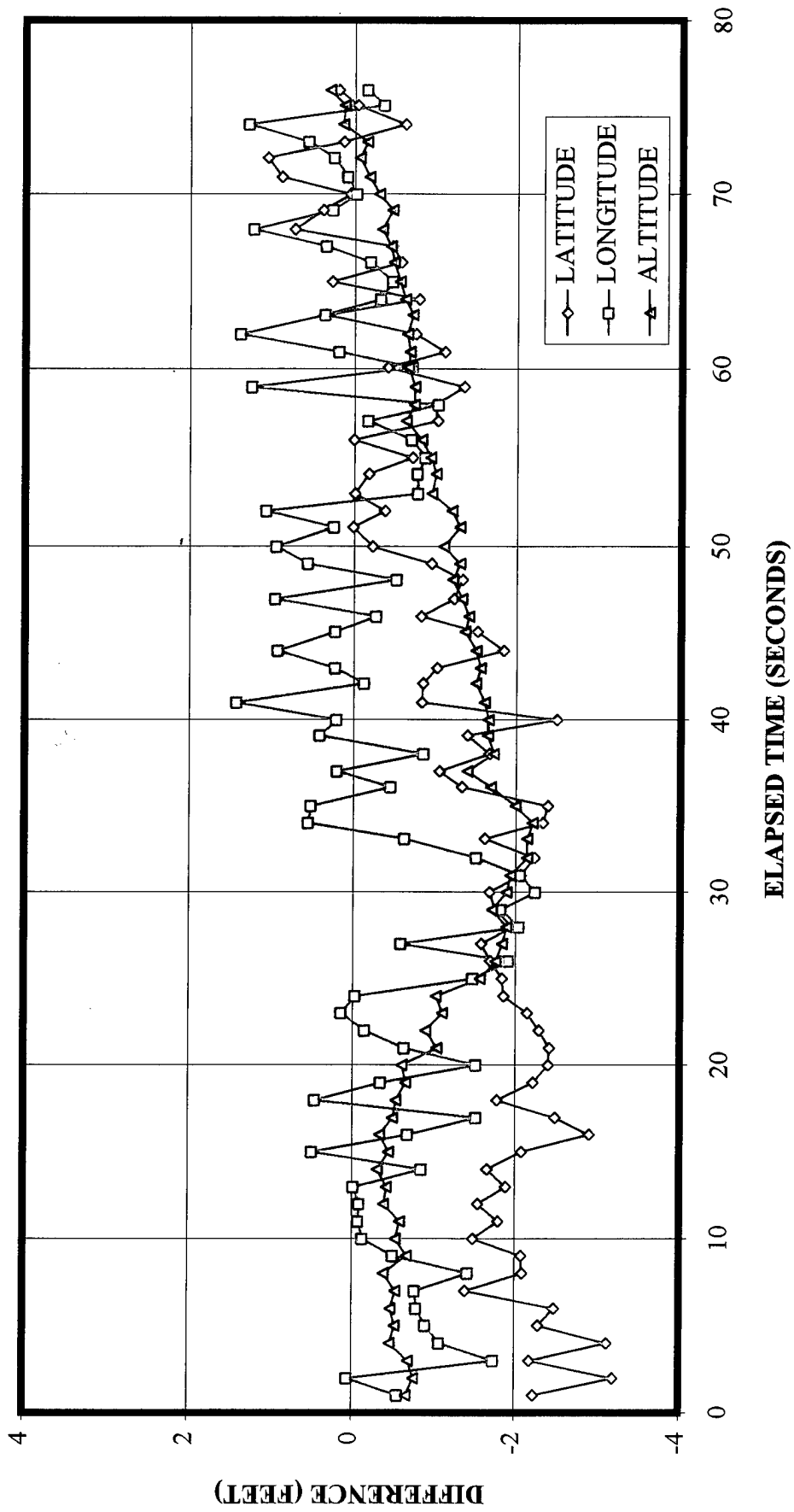
**REAL-TIME GPS vs OPTICS  
PASS # 10 - LEVEL FLIGHT  
8 JUNE 1995 - WSMR**



**REAL-TIME GPS vs OPTICS  
PASS # 11 - 15 DEGREE BANK  
8 JUNE 1995 - WSMR**

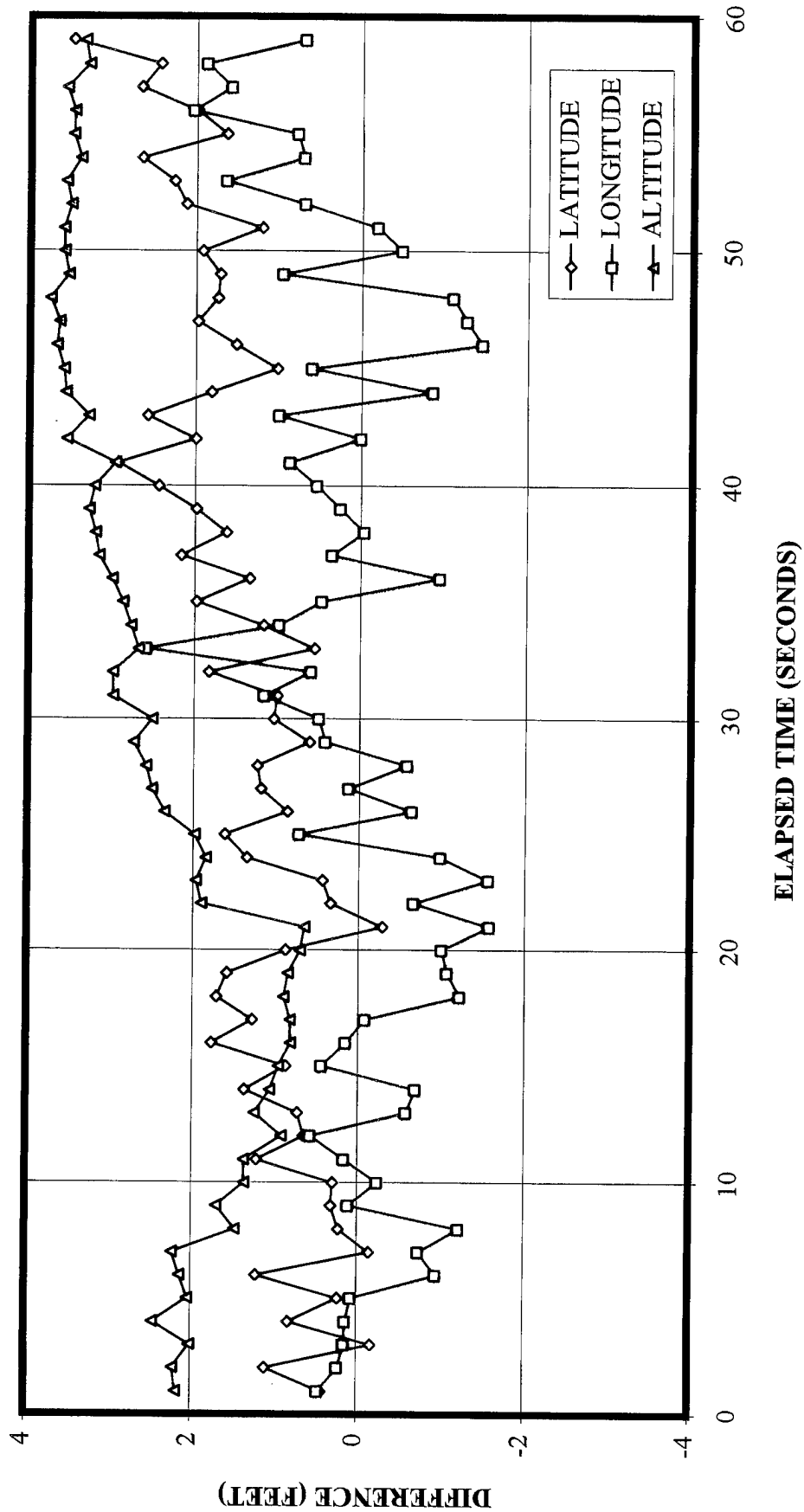


**REAL-TIME GPS vs OPTICS  
PASS # 12 - 30 DEGREE BANK  
8 JUNE 1995 - WSMR**

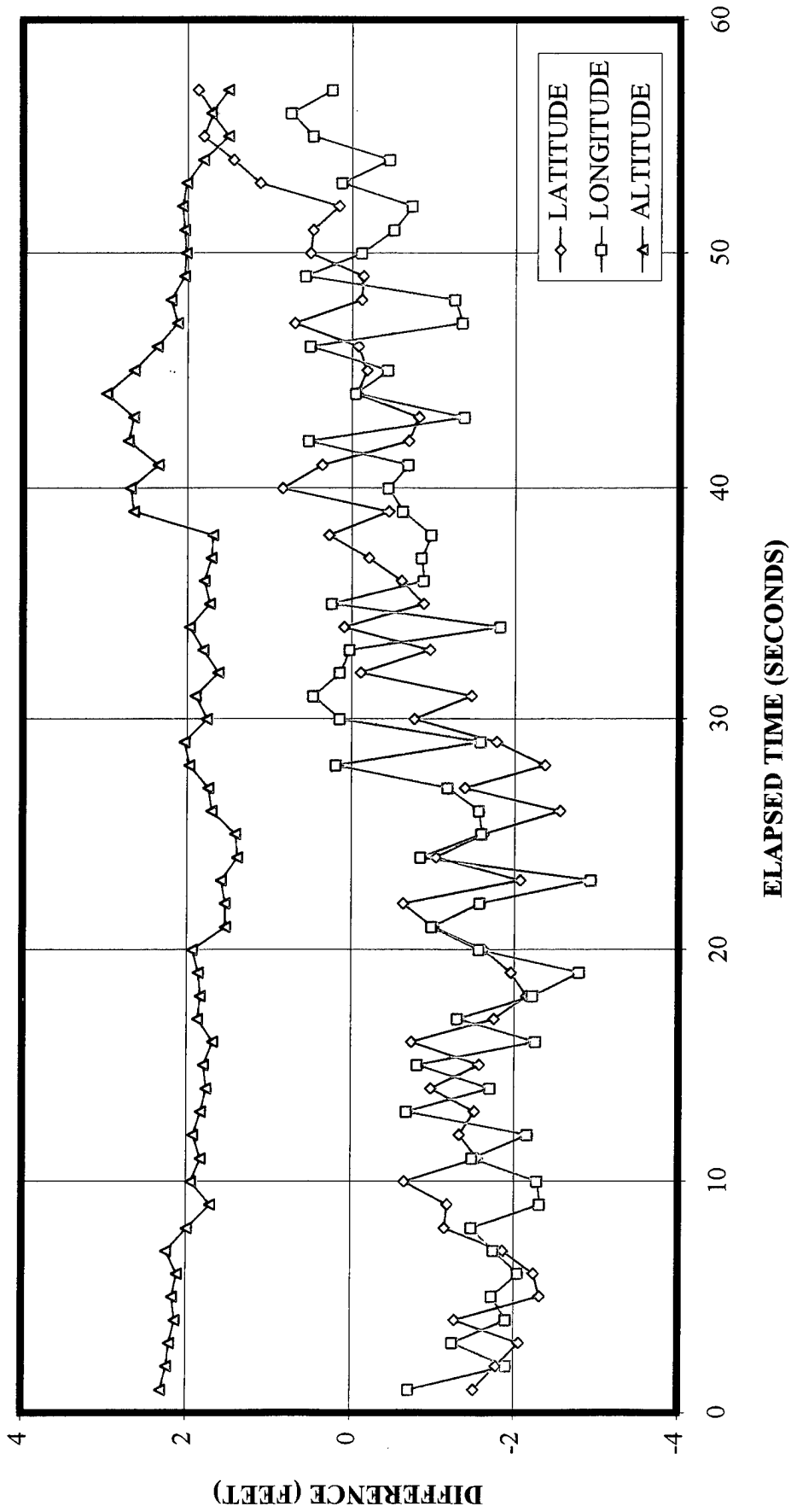




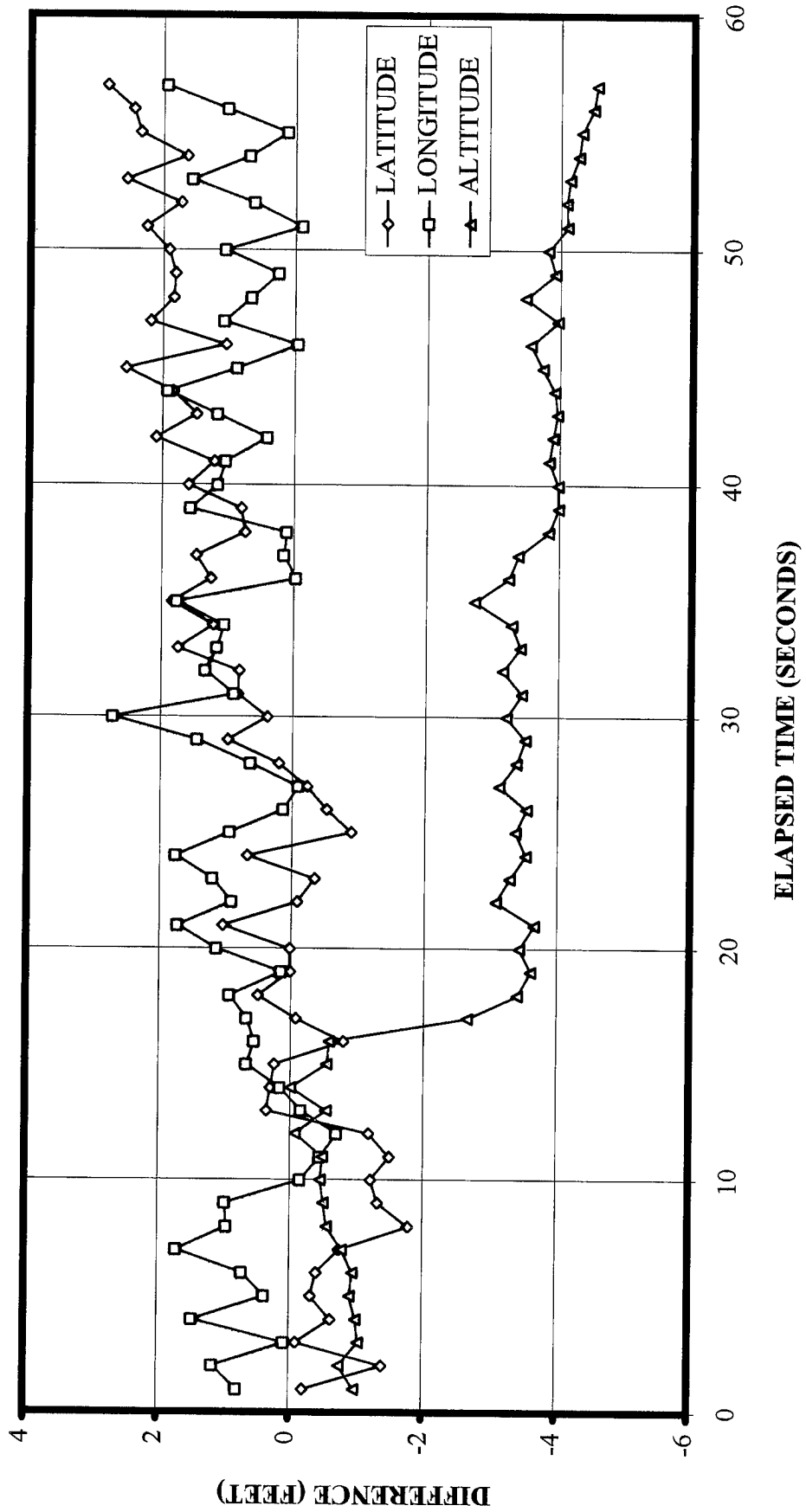
**REAL-TIME GPS vs OPTICS  
PASS # 13 - 45 DEGREE BANK  
8 JUNE 1995 - WSMR**



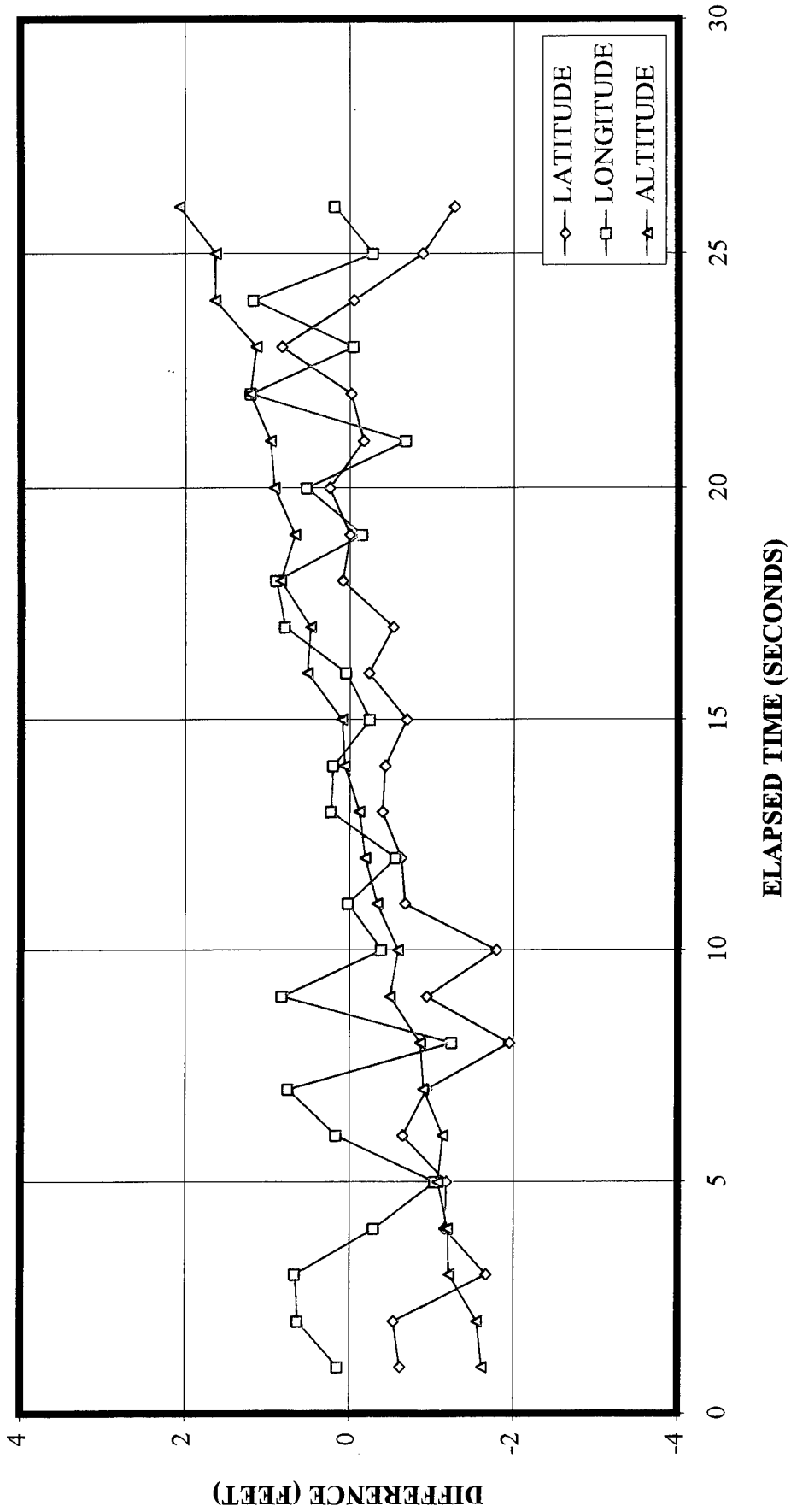
**REAL-TIME GPS vs OPTICS  
PASS # 14 - 60 DEGREE BANK  
8 JUNE 1995 - WSMR**



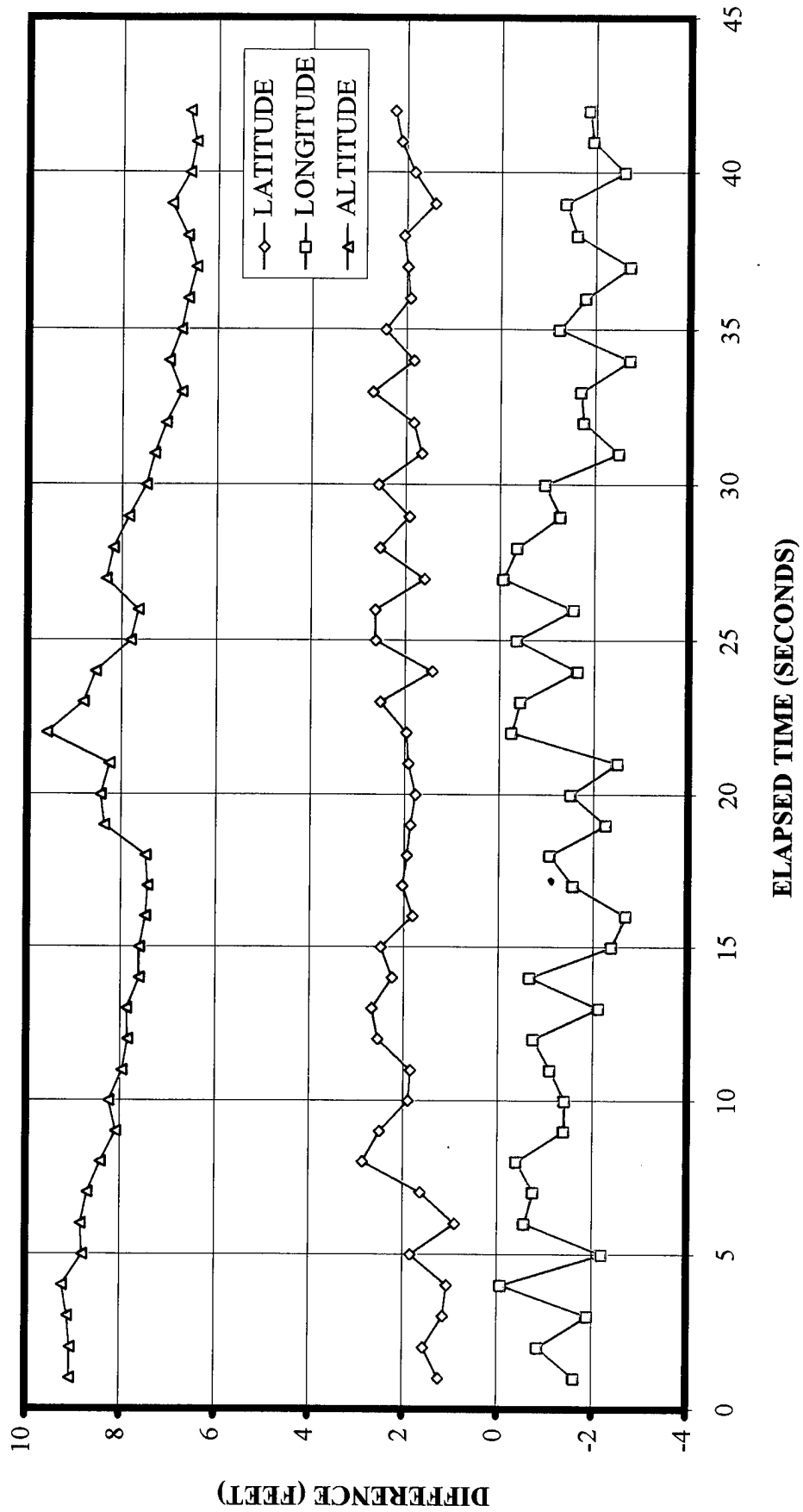
**REAL-TIME GPS vs OPTICS  
PASS # 15 - FIGURE EIGHT  
8 JUNE 1995 - WSMR**



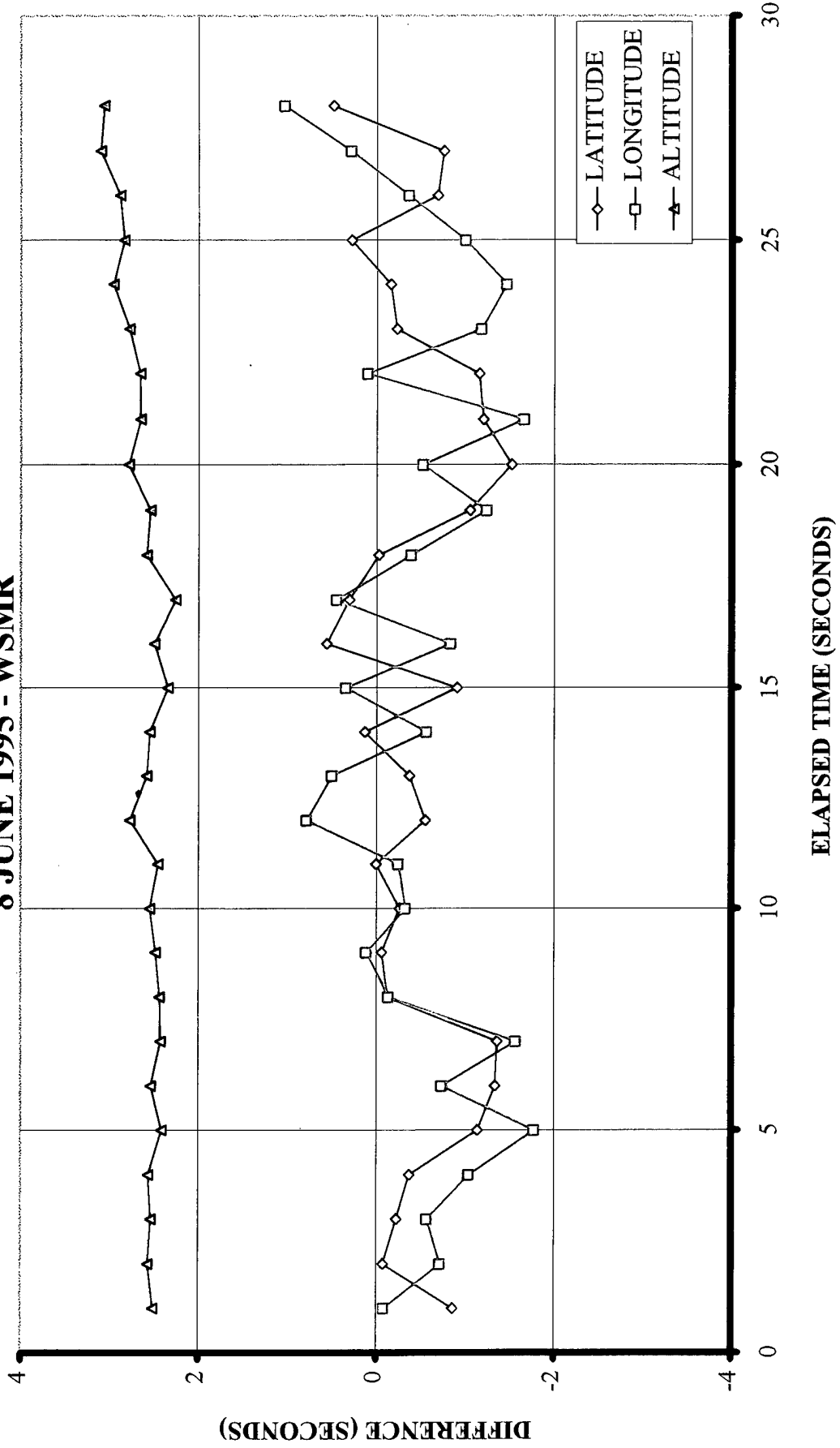
**REAL-TIME GPS vs OPTICS  
PASS # 16 - LEVEL FLIGHT  
8 JUNE 1995 - WSMR**



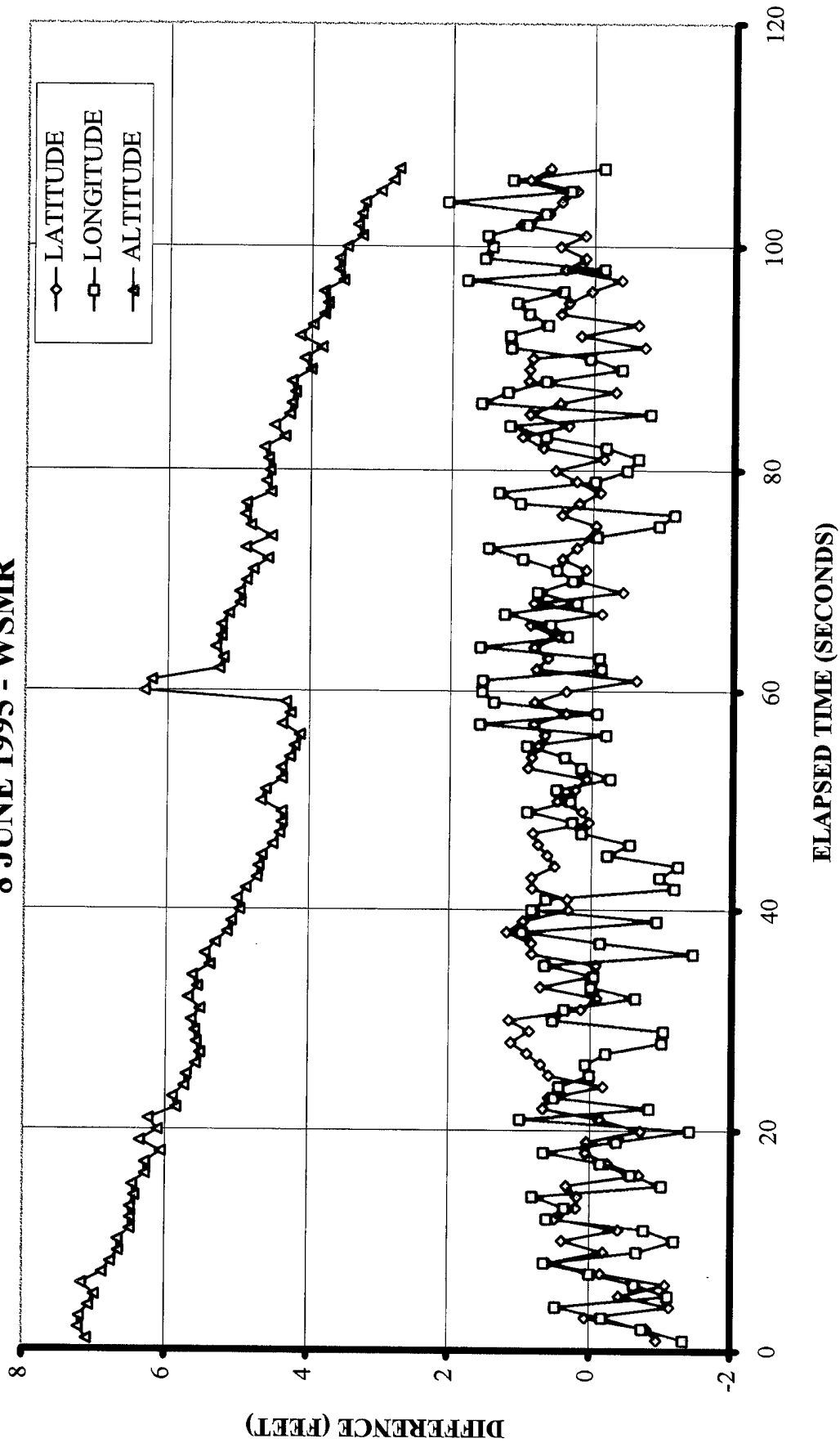
**REAL-TIME GPS vs OPTICS  
PASS # 17 - RAPID ALTITUDE CHANGES  
8 JUNE 1995 - WSMR**



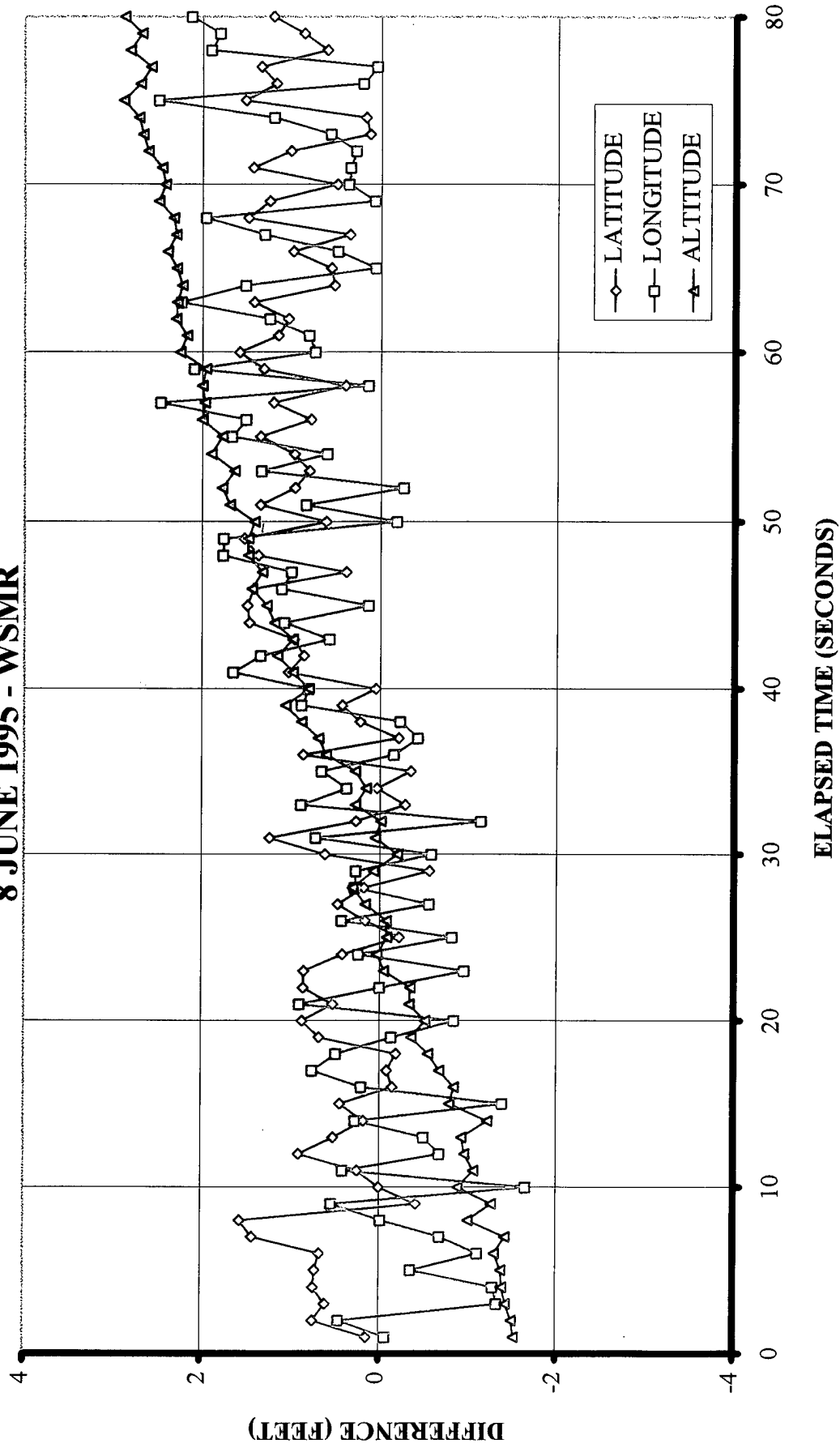
**REAL-TIME GPS vs OPTICS  
PASS # 18 - LEVEL FLIGHT  
8 JUNE 1995 - WSMR**



**REAL-TIME GPS vs OPTICS  
PASS # 19 - 15 DEGREE BANK  
8 JUNE 1995 - WSMR**



**REAL-TIME GPS vs OPTICS  
PASS # 20 - 30 DEGREE BANK  
8 JUNE 1995 - WSMR**





APPENDIX E. SUMMARY OF STATISTICS FOR POSTMISSION  
AND REAL-TIME PROCESSED DATA

POSTMISSION GPS vs OPTICS DIFFERENCE STATISTICS

AVERAGE TIME	ELAPSED TIME	RUN NO	NUMBER OF POINTS	AVERAGE		STD DEV		MAXIMUM		MINIMUM	
				LATITUDE DIFFERENCE (FEET)	LAT	LATITUDE DIFFERENCE (FEET)	LATITUDE DIFFERENCE (FEET)	LATITUDE DIFFERENCE (FEET)	LATITUDE DIFFERENCE (FEET)		
	FROM										
	START (SEC)										
65943.5	13.5	1	26	0.675	LAT	0.432	0.432	1.426	1.426	-0.364	-0.364
66046.5	116.5	2	50	0.528		0.471	0.471	1.749	1.749	-0.369	-0.369
66257.4	327.4	3	125	0.160		0.587	0.587	2.057	2.057	-1.163	-1.163
66442.0	512.0	4	95	-0.438		0.729	0.729	1.433	1.433	-2.114	-2.114
66601.0	671.0	5	77	-0.380		0.865	0.865	1.572	1.572	-2.763	-2.763
66740.5	810.5	6	64	0.043		0.828	0.828	2.241	2.241	-1.493	-1.493
66906.0	976.0	7	107	-0.430		1.004	1.004	4.454	4.454	-2.603	-2.603
67052.0	1122.0	8	31	0.716		0.695	0.695	2.404	2.404	-0.805	-0.805
67172.0	1242.0	9	37	-0.723		0.475	0.475	0.201	0.201	-1.510	-1.510
67289.5	1359.5	10	26	0.285		0.514	0.514	1.897	1.897	-0.480	-0.480
67443.5	1513.5	11	102	-0.330		0.763	0.763	1.353	1.353	-2.377	-2.377
67646.5	1716.5	12	76	0.286		0.630	0.630	1.705	1.705	-1.155	-1.155
67817.0	1887.0	13	59	0.146		0.999	0.999	2.667	2.667	-1.848	-1.848
67951.0	2021.0	14	57	0.023		1.095	1.095	2.529	2.529	-1.848	-1.848
68080.0	2150.0	15	57	-0.217		1.015	1.015	1.976	1.976	-2.179	-2.179
68235.5	2305.5	16	26	1.224		0.608	0.608	2.486	2.486	0.002	0.002
68376.5	2446.5	17	42	-1.388		0.441	0.441	-0.506	-0.506	-2.427	-2.427
68508.5	2578.5	18	28	0.904		0.686	0.686	2.165	2.165	-0.361	-0.361
68725.0	2795.0	19	107	-0.567		0.612	0.612	0.811	0.811	-2.183	-2.183
68940.5	3010.5	20	80	-0.281		0.654	0.654	1.121	1.121	-1.683	-1.683

POSTMISSION GPS vs OPTICS DIFFERENCE STATISTICS

AVERAGE TIME	ELAPSED TIME FROM START (SEC)	RUN NO	NUMBER OF POINTS	AVERAGE		STD DEV		MAXIMUM		MINIMUM	
				LONGITUDE DIFFERENCE (FEET)	LONGITUDE DIFFERENCE (FEET)	LONGITUDE DIFFERENCE (FEET)	LONGITUDE DIFFERENCE (FEET)	LONGITUDE DIFFERENCE (FEET)	LONGITUDE DIFFERENCE (FEET)		
				LONG							
65943.5	13.5	1	26	0.434	0.782	2.387	-0.859				
66046.5	116.5	2	50	-0.903	0.674	0.469	-1.949				
66257.4	327.4	3	125	-0.549	0.725	1.035	-2.097				
66442.0	512.0	4	95	-0.382	0.905	1.542	-2.291				
66601.0	671.0	5	77	-0.140	0.796	1.992	-1.537				
66740.5	810.5	6	64	-0.262	0.909	1.703	-1.616				
66906.0	976.0	7	107	-0.317	0.754	1.517	-1.831				
67052.0	1122.0	8	31	-0.522	0.521	0.733	-1.387				
67172.0	1242.0	9	37	-0.404	0.790	0.784	-1.834				
67289.5	1359.5	10	26	0.237	0.650	1.344	-1.027				
67443.5	1513.5	11	102	-0.550	0.718	1.144	-2.054				
67646.5	1716.5	12	76	-0.237	0.793	1.612	-1.850				
67817.0	1887.0	13	59	0.012	0.957	2.547	-1.523				
67951.0	2021.0	14	57	-0.296	0.817	1.265	-2.028				
68080.0	2150.0	15	57	-0.223	0.798	1.924	-2.203				
68235.5	2305.5	16	26	0.511	0.649	1.603	-0.959				
68376.5	2446.5	17	42	0.137	0.727	1.272	-1.107				
68508.5	2578.5	18	28	0.757	0.768	2.303	-0.545				
68725.0	2795.0	19	107	0.332	0.762	2.004	-1.344				
68940.5	3010.5	20	80	0.301	0.761	1.791	-1.031				

POSTMISSION GPS vs OPTICS DIFFERENCE STATISTICS

AVERAGE TIME	ELAPSED TIME FROM START (SEC)	RUN NO	NUMBER OF POINTS	AVERAGE		STD DEV		MAXIMUM		MINIMUM	
				ALTITUDE DIFFERENCE (FEET)	ALTITUDE DIFFERENCE (FEET)	ALTITUDE DIFFERENCE (FEET)	ALTITUDE DIFFERENCE (FEET)	ALTITUDE DIFFERENCE (FEET)	ALTITUDE DIFFERENCE (FEET)		
				ALT							
65943.5	13.5	1	26	-0.160	0.116	0.123	0.123	0.123	0.123	-0.333	
66046.5	116.5	2	50	2.345	0.485	3.122	3.122	3.122	3.122	1.353	
66257.4	327.4	3	125	1.996	0.482	3.460	3.460	3.460	3.460	1.424	
66442.0	512.0	4	95	1.793	0.351	2.439	2.439	2.439	2.439	1.033	
66601.0	671.0	5	77	0.361	0.459	1.665	1.665	1.665	1.665	-0.287	
66740.5	810.5	6	64	0.800	0.411	1.669	1.669	1.669	1.669	0.031	
66906.0	976.0	7	107	0.336	0.337	1.150	1.150	1.150	1.150	-0.427	
67052.0	1122.0	8	31	0.971	0.299	1.500	1.500	1.500	1.500	0.357	
67172.0	1242.0	9	37	0.708	0.356	1.370	1.370	1.370	1.370	-0.110	
67289.5	1359.5	10	26	1.014	0.315	1.630	1.630	1.630	1.630	0.373	
67443.5	1513.5	11	102	-0.137	0.326	0.721	0.721	0.721	0.721	-0.711	
67646.5	1716.5	12	76	0.758	0.206	1.283	1.283	1.283	1.283	0.247	
67817.0	1887.0	13	59	0.036	0.362	0.670	0.670	0.670	0.670	-0.830	
67951.0	2021.0	14	57	0.606	0.413	1.380	1.380	1.380	1.380	-0.240	
68080.0	2150.0	15	57	0.885	0.393	1.607	1.607	1.607	1.607	0.107	
68235.5	2305.5	16	26	0.295	0.100	0.493	0.493	0.493	0.493	0.137	
68376.5	2446.5	17	42	-1.395	0.209	-0.973	-0.973	-0.973	-0.973	-1.747	
68508.5	2578.5	18	28	0.393	0.225	0.793	0.793	0.793	0.793	0.057	
68725.0	2795.0	19	107	-1.274	0.379	-0.439	-0.439	-0.439	-0.439	-1.940	
68940.5	3010.5	20	80	-0.827	0.320	-0.059	-0.059	-0.059	-0.059	-1.425	

POSTMISSION GPS vs OPTICS DIFFERENCE STATISTICS

AVERAGE TIME	ELAPSED TIME	RUN NO	NUMBER OF POINTS	LINEAR ERROR		CIRCULAR ERROR		SPHERICAL ERROR		
				PROBABLE (VERTICAL)	PROBABLE (HORIZONTAL)	PROBABLE	PROBABLE	PROBABLE	PROBABLE	
	FROM START (SEC)									
65943.5	13.5	1	26	0.078039732		0.714985639		0.681347702		
66046.5	116.5	2	50	0.327187579		0.67410201		0.835131309		
66257.4	327.4	3	125	0.325029377		0.772653027		0.91923046		
66442.0	512.0	4	95	0.236835291		0.961630183		1.01661308		
66601.0	671.0	5	77	0.309699137		0.97762084		1.085901475		
66740.5	810.5	6	64	0.277274789		1.022500308		1.100304108		
66906.0	976.0	7	107	0.227095599		1.034909478		1.072963901		
67052.0	1122.0	8	31	0.201801787		0.715785187		0.77610247		
67172.0	1242.0	9	37	0.240425908		0.744766339		0.830670404		
67289.5	1359.5	10	26	0.212432111		0.685129904		0.757511421		
67443.5	1513.5	11	102	0.220204808		0.87194796		0.925950379		
67646.5	1716.5	12	76	0.139142448		0.837573963		0.834437608		
67817.0	1887.0	13	59	0.244114083		1.151812645		1.187603704		
67951.0	2021.0	14	57	0.278667275		1.12560681		1.191065053		
68080.0	2150.0	15	57	0.264780526		1.067357646		1.129834352		
68235.5	2305.5	16	26	0.067207662		0.73991608		0.694804813		
68376.5	2446.5	17	42	0.141082541		0.687586259		0.705422777		
68508.5	2578.5	18	28	0.151887466		0.855983394		0.860140027		
68725.0	2795.0	19	107	0.255918343		0.8087349		0.898097304		
68940.5	3010.5	20	80	0.215897159		0.83303505		0.888822335		
				MEANS:						
				0.220736181		0.864181881		0.919597734		

REAL-TIME GPS vs OPTICS DIFFERENCE STATISTICS

AVERAGE TIME	ELAPSED TIME FROM START (SEC)	RUN NO	NUMBER OF POINTS	AVERAGE		STD DEV		MAXIMUM		MINIMUM	
				LATITUDE DIFFERENCE (FEET)	LAT	LATITUDE DIFFERENCE (FEET)	LATITUDE DIFFERENCE (FEET)	LATITUDE DIFFERENCE (FEET)	LATITUDE DIFFERENCE (FEET)		
65943.5	13.5	1	26	-0.079		0.531		1.008		-1.091	
66046.5	116.5	2	50	-0.351		0.531		0.839		-1.315	
66257.4	327.4	3	125	-0.528		0.625		1.414		-1.915	
66442.0	512.0	4	95	-0.682		1.072		1.846		-2.828	
66601.0	671.0	5	77	-1.089		0.607		0.087		-2.763	
66740.5	810.5	6	64	-1.157		1.136		1.586		-3.288	
66906.0	976.0	7	107	-0.397		1.012		4.515		-2.372	
67052.0	1122.0	8	31	0.800		0.684		2.452		-0.660	
67172.0	1242.0	9	37	-0.267		0.518		0.699		-1.255	
67289.5	1359.5	10	26	0.280		0.505		1.775		-0.456	
67443.5	1513.5	11	102	1.418		0.623		2.409		-0.521	
67646.5	1716.5	12	76	-1.272		0.988		1.062		-3.187	
67817.0	1887.0	13	59	1.362		0.814		3.479		-0.291	
67951.0	2021.0	14	57	-0.733		1.119		1.874		-2.549	
68080.0	2150.0	15	57	0.653		1.209		2.849		-1.779	
68235.5	2305.5	16	26	-0.626		0.645		0.825		-1.950	
68376.5	2446.5	17	42	1.983		0.479		2.841		0.896	
68508.5	2578.5	18	28	-0.447		0.596		0.568		-1.518	
68725.0	2795.0	19	107	0.319		0.523		1.188		-1.128	
68940.5	3010.5	20	80	0.702		0.557		1.590		-0.555	

REAL-TIME GPS vs OPTICS DIFFERENCE STATISTICS

AVERAGE TIME	ELAPSED TIME	RUN NO	NUMBER OF POINTS	AVERAGE		STD DEV		MAXIMUM		MINIMUM	
				LONGITUDE DIFFERENCE (FEET)	LONG	LONGITUDE DIFFERENCE (FEET)	LONG	LONGITUDE DIFFERENCE (FEET)	LONG	LONGITUDE DIFFERENCE (FEET)	LONG
	START (SEC)										
65943.5	13.5	1	26	-2.943	LONG	0.950	0.950	-0.542	0.950	-4.713	-4.713
66046.5	116.5	2	50	-2.352		1.060	1.060	-0.080	1.060	-4.252	-4.252
66257.4	327.4	3	125	-1.935		0.990	0.990	0.773	0.990	-3.541	-3.541
66442.0	512.0	4	95	-0.871		0.790	0.790	0.853	0.790	-2.460	-2.460
66601.0	671.0	5	77	-0.721		0.958	0.958	1.825	0.958	-2.398	-2.398
66740.5	810.5	6	64	1.125		0.988	0.988	2.946	0.988	-0.536	-0.536
66906.0	976.0	7	107	-1.603		0.724	0.724	0.248	0.724	-2.981	-2.981
67052.0	1122.0	8	31	0.168		0.535	0.535	1.267	0.535	-0.752	-0.752
67172.0	1242.0	9	37	-0.652		0.822	0.822	0.851	0.822	-2.050	-2.050
67289.5	1359.5	10	26	-0.876		0.588	0.588	0.142	0.588	-1.982	-1.982
67443.5	1513.5	11	102	0.494		0.908	0.908	2.500	0.908	-1.818	-1.818
67646.5	1716.5	12	76	-0.264		0.868	0.868	1.428	0.868	-2.240	-2.240
67817.0	1887.0	13	59	0.068		0.937	0.937	2.578	0.937	-1.582	-1.582
67951.0	2021.0	14	57	-0.966		0.942	0.942	0.745	0.942	-2.932	-2.932
68080.0	2150.0	15	57	0.804		0.681	0.681	2.723	0.681	-0.698	-0.698
68235.5	2305.5	16	26	0.132		0.637	0.637	1.204	0.637	-1.247	-1.247
68376.5	2446.5	17	42	-1.459		0.783	0.783	-0.085	0.783	-2.756	-2.756
68508.5	2578.5	18	28	-0.456		0.751	0.751	1.039	0.751	-1.778	-1.778
68725.0	2795.0	19	107	0.237		0.849	0.849	2.066	0.849	-1.455	-1.455
68940.5	3010.5	20	80	0.460		0.961	0.961	2.491	0.961	-1.659	-1.659

REAL-TIME GPS vs OPTICS DIFFERENCE STATISTICS

AVERAGE TIME	ELAPSED TIME	RUN NO	NUMBER OF POINTS	AVERAGE		STD DEV		MAXIMUM		MINIMUM	
				ALTITUDE (FEET)	DIFFERENCE (FEET)	ALTITUDE (FEET)	DIFFERENCE (FEET)	ALTITUDE (FEET)	DIFFERENCE (FEET)	ALTITUDE (FEET)	DIFFERENCE (FEET)
	FROM START (SEC)			ALT							
65943.5	13.5	1	26	2.678	1.003	4.413	0.858				
66046.5	116.5	2	50	8.525	0.941	9.533	6.396				
66257.4	327.4	3	125	4.738	2.311	7.392	-1.105				
66442.0	512.0	4	95	0.025	1.043	2.348	-1.472				
66601.0	671.0	5	77	4.252	1.747	8.257	1.588				
66740.5	810.5	6	64	1.602	1.348	3.777	-0.910				
66906.0	976.0	7	107	2.264	1.215	4.194	-0.497				
67052.0	1122.0	8	31	3.192	0.208	3.630	2.718				
67172.0	1242.0	9	37	4.585	0.371	5.332	3.716				
67289.5	1359.5	10	26	0.600	0.170	0.965	0.307				
67443.5	1513.5	11	102	2.852	0.737	4.172	0.318				
67646.5	1716.5	12	76	-0.945	0.605	0.301	-2.206				
67817.0	1887.0	13	59	2.485	0.973	3.752	0.643				
67951.0	2021.0	14	57	1.967	0.351	2.978	1.382				
68080.0	2150.0	15	57	-2.800	1.419	-0.006	-4.548				
68235.5	2305.5	16	26	0.031	1.067	2.067	-1.619				
68376.5	2446.5	17	42	7.835	0.861	9.568	6.450				
68508.5	2578.5	18	28	2.618	0.208	3.103	2.259				
68725.0	2795.0	19	107	5.034	1.068	7.214	2.767				
68940.5	3010.5	20	80	0.813	1.403	2.890	-1.527				



REAL-TIME GPS vs OPTICS DIFFERENCE STATISTICS

AVERAGE TIME	ELAPSED TIME FROM START (SEC)	RUN NO	NUMBER OF POINTS	LINEAR			CIRCULAR			SPHERICAL						
				ERROR	PROBABLE	REALTIME	ERROR	PROBABLE	REALTIME	ERROR	PROBABLE	REALTIME				
65943.5	13.5	1	26	0.676407751	0.872006199	1.272715284	0.634858911	0.936682341	1.297406409	0.950649799	2.011942	0.703671286	1.096481857	1.488729393		
66046.5	116.5	2	50													
66257.4	327.4	3	125	1.559048257	0.950649799	2.011942	0.703671286	1.096481857	1.488729393	1.697178595	1.17805855	0.921671376	1.697178595	1.778588694		
66442.0	512.0	4	95													
66601.0	671.0	5	77	0.909120351	1.250180721	1.778588694	0.909120351	1.250180721	1.778588694	1.512251522	0.819521977	1.022315884	1.512251522	0.730977784		
66740.5	810.5	6	64	0.819521977	1.022315884	1.512251522	0.819521977	1.022315884	1.512251522	0.730977784	0.140545361	0.717429092	0.730977784	0.876372421		
66906.0	976.0	7	107													
67052.0	1122.0	8	31	0.140545361	0.717429092	0.730977784	0.140545361	0.717429092	0.730977784	0.646778424	0.249903405	0.789018198	0.646778424	1.161823976		
67172.0	1242.0	9	37	0.249903405	0.789018198	0.876372421	0.249903405	0.789018198	0.876372421	0.901096564	0.114619303	0.643296269	0.646778424	1.260502546		
67289.5	1359.5	10	26	0.114619303	0.643296269	0.646778424	0.114619303	0.643296269	0.646778424	1.031035737	0.407782068	1.092630086	1.031035737	1.396017335		
67443.5	1513.5	11	102	0.497197323	0.901096564	1.161823976	0.497197323	0.901096564	1.161823976	1.235430384	0.656600321	1.031035737	1.235430384	1.695534418		
67646.5	1716.5	12	76	0.407782068	1.092630086	1.260502546	0.407782068	1.092630086	1.260502546	1.235430384	0.23668427	1.213276251	1.235430384	1.695534418		
67817.0	1887.0	13	59	0.656600321	1.031035737	1.396017335	0.656600321	1.031035737	1.396017335	1.695534418	0.957151737	1.112757584	1.695534418	1.20397977		
67951.0	2021.0	14	57	0.23668427	1.213276251	1.695534418	0.23668427	1.213276251	1.695534418	1.20397977	0.719701123	0.755180363	1.20397977	1.087720959		
68080.0	2150.0	15	57	0.957151737	1.112757584	1.695534418	0.957151737	1.112757584	1.695534418	1.087720959	0.581033548	0.742684439	1.087720959	0.796557926		
68235.5	2305.5	16	26	0.719701123	0.755180363	1.20397977	0.719701123	0.755180363	1.20397977	1.087720959	0.140504123	0.792844588	0.796557926	1.250692842		
68376.5	2446.5	17	42	0.581033548	0.742684439	1.250692842	0.581033548	0.742684439	1.250692842	1.496585023	0.720590173	0.808096909	1.250692842			
68508.5	2578.5	18	28	0.140504123	0.792844588	1.496585023	0.140504123	0.792844588	1.496585023		0.946389172	0.893481899	1.496585023			
68725.0	2795.0	19	107	0.720590173	0.808096909		0.720590173	0.808096909								
68940.5	3010.5	20	80	0.946389172	0.893481899		0.946389172	0.893481899								
				MEANS:	0.64246945	0.927140808	1.294889285	0.64246945	0.927140808	1.294889285						

APPENDIX F. ABBREVIATIONS

app - appendix  
ATTTC - U.S. Army Aviation Technical Test Center

fig. - figure

GPS - global positioning system  
GMT - Greenwich mean time

IAW - in accordance with

No. - number

RMS - root mean square

SEP - spherical error probable

TDARDS - Truth Data Acquisition Recording And Display System

TSPI - time-space positioning information  
TECOM - U.S. Army Test and Evaluation Command

WSMR - White Sands Missile Range

APPENDIX G. DISTRIBUTION LIST

ADDRESSEES

REPORT

Commander U.S. Army Test and Evaluation Command ATTN: AMSTE-CT-T AMSTE-TA-L Aberdeen Proving Ground, MD 21005-5055	3 1
Commander White Sands Missile Range ATTN: STEWS-TD-P NRO-DR-S (Mr. Tony Palomino) White Sands Missile Range, NM 88002	1 1
Defense Technical Information Center 8725 John J. Kingman Road, Suite 0944 Fort Belvoir, VA 22060-6218	1