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Engineering Performance Evaluation of Small Community Airport Microwave Landing System (TI Model) at Philadelphia International Airport Runway 17

August 1986

Final Report

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16. Abstract

The Microwave Landing System (MLS) program is designed to meet both civil and military operational needs. It will eventually replace the Instrument Landing System (ILS). After a system/equipment development phase, the Federal Aviation Administration, in 1979 began a Service Test and Evaluation Program (STEP) to obtain experience for developing criteria for siting, installation and preliminary operational procedures. "Feasibility demo" ground equipment from the development phase was used and user aircraft were equipped with MLS receivers.

This report contains engineering evaluation of the FAA Technical Center flight test data taken on the Texas Instruments' manufactured Small Community MLS, as installed for STEP at Philadelphia International Airport Runway 17.

The equipment performance was found to generally meet the FAA-STD-022b Path Following Error and Control Motion Noise requirement, but not the linearity requirement. Apparent aircraft propeller induced noise effects were identified.

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I. INTRODUCTION

A. PURPOSE

The purpose of this program was to test the Texas Instruments (TI) model of a time reference scanning beam (TRSB) known as the "Small Community Airport Microwave Landing System" (SCAMLS), in the operational environment of Runway 17, Philadelphia International Airport. The system was previously tested at the FAA facility in Atlantic City, N.J. (See reference 1).

B. BACKGROUND

Microwave Landing System Development Program. In accordance with the "National Plan for the Development of the Microwave Landing System," published in July 1971, the United States (U.S.) MLS program is a joint, interservice Department of Transportation (DOT)/Department of Defense (DOD)/National Aeronautics and Space Administration (NASA) development activity, with DOT Federal Aviation Administration (FAA) designated as the lead agency. The National Plan initiated a three-phase, multiyear development program to identify and demonstrate a new approach and landing system which is intended to eventually replace the Instrument Landing System (ILS), and is designed to meet both civil and military operational needs as stated by Special Committee (SC)-117 of the Radio Technical Commission for Aeronautics (RTCA) in December 1970.

Phase I of the program involved technique analysis and contract definition. During this phase it appeared that both the Time Reference Scanning Beam (TRSB) and Doppler techniques had the potential for meeting the full range of operational requirements.

Phase II, the feasibility demonstration phase, involved design, fabrication, and demonstration of both the Doppler and scanning beam techniques using systems installed at the FAA's National Aviation Facilities Experimental Center (NAFEC) and NASA's Wallops Station test facilities. The test results from Phase II were thoroughly analyzed in December 1974 by an interservice government committee, with full-time participation of international MLS experts from Australia, France, and the United Kingdom and part-time participation from other countries. This committee selected the TRSB technique over the Doppler technique for further development and, as a result, the TRSB was submitted to the International Civil Aviation Organization (ICAO) as a candidate for (and subsequently adopted as) the international standard.

Phase III of the program was concerned with the fabrication of prototype TRSB equipment in the different configurations necessary to show compliance with the requirements of all major user groups. One of these configurations was the TI SCAMLS intended for short runway operations typical of general aviation

requirements and is the subject of this report.

Service Test and Evaluation Program. In 1979, the FAA began a Service Test and Evaluation Program (STEP) to obtain the experience necessary for developing criteria for siting, installation and preliminary operational procedures. Ground MLS installations (of upgraded prototype equipment) were completed and operations conducted at: 1) Washington National (Runway 18 and Runway 33); 2) Philadelphia (Runway 17); and 3) Clarksburg, West Virginia (Runway 21). User participants in STEP include Ransom Airlines and Wright/Aeromech Airlines. Two helicopter operators (Sun Oil and Keystone) agreed to join the program at Philadelphia. Initially, operations are in VFR conditions only. The operational procedures and criteria are being developed under this program for use when the first production MLS installations are made in 1986.

C. GENERAL SYSTEM DESCRIPTION

All configurations of the Phase III TRSB MLS (which is an air-derived system) operate at C-band (5032.0 - 5090.7 megahertz (MHz)). The airborne receiver/processor measures a vertical angle from the elevation transmitting antenna, assumed relative to the horizontal plane tangent to the runway surface near the glidepath intercept point (GPIP), and measures a horizontal angle relative to the runway centerline from the azimuth transmitting antenna. In the TRSB technique, the airborne angle information is derived by precisely timing the passage of narrow fan beams which are scanned sequentially TO-FRO at high rates through azimuth and the elevation coverage volumes. The time interval between passage of the TO and FRO beams is directly proportional to the azimuth and elevation of the receiver and, therefore, the approach aircraft. Both the azimuth antenna and elevation antenna have a transmitter power output of 20 watts and respective gains of 14.5 and 16.5 decibels (dBi) relative to an isotropic source, thus providing usable guidance signals out to a range of 15 nautical miles (nmi), assuming a receiver sensitivity of -100 dBm.

Azimuth antenna beamwidth is the major factor in tailoring a system to a particular runway length in order to prevent inbeam multipath. [In beam multipath is the result of the scanning beam illuminating a reflecting object at the same time it is illuminating the aircraft. The signal arriving at the aircraft via the reflection path can cause noise and errors to be processed through the receiver.] A narrower beamwidth reduces the area where potential reflecting surfaces would be "in-beam". [Current obstruction criteria require hangers, etc, which might have large vertical reflecting surfaces oriented to reflect into the approach, to be at least 850 feet from an instrument runway.] The receiver processor can discriminate against most main beam reflections if the reflector is about 2 beamwidths or more removed from the beam pointing angle to the aircraft.

Azimuth antenna beamwidth is also a consideration for the

angular accuracy required. Accuracies are linearly specified (in feet) which translates to a smaller angle as the distance to threshold increases. The basic receiver accuracy performance is a function of the beamwidth. Thus the accuracy requirements dictate a narrower beam for a long runway. The TI SCAMLS azimuth antenna has a 3° beamwidth, which matches to about a 6000 foot threshold distance. The configuration at Philadelphia had 6567 feet between the azimuth and threshold.

One of the design considerations operative in the MLS is the concept of modularity, in which the system can be configured or upgraded to suit the changing needs of a particular user by adding other subsystems such as flare, missed approach, or range as needed at a later time. In addition, most of the electronics used in the TI SCAMLS azimuth and elevation units can be interchanged, with some system monitor parameters changed.

II. TEXAS INSTRUMENTS' SMALL COMMUNITY MLS

The TI SCAMLS is a prototype of the system intended to provide approach and landing guidance in a low cost package to relatively short runways, typical of low-density feeder and general aviation airports, while retaining compatibility with more expanded versions of TRSB and allowing for growth potential. The system error budget and monitor are designed to support at least Category I Instrument Flight Rules (IFR) operations (200-foot ceiling and 2,400-foot runway visual range) for runway lengths up to 5,000 feet.

The TI SCAMLS is comprised of two subsystems; an azimuth unit and an elevation unit. Each unit is completely self-contained within its climate-controlled antenna case and does not require additional equipment shelters. Figure 1 shows the azimuth guidance set which consists of the azimuth electronics cabinet and the azimuth antennas.

The azimuth unit uses a bifocal pillbox feeding a flat-plate array of 32 waveguides with 37 "C"-shaped slots in each waveguide spaced so as to form a vertical fan beam (3 degree beamwidth). Vertical coverage is provided from 1 degree to 15 degrees in elevation with a sharp underside cutoff (13 dB/degree). This prototype antenna scans a beam from left 12 degrees through centerline to right 12 degrees, providing proportional guidance from left 10 degrees to right 10 degrees. Built-in sector clearance antennas provide full fly-left and full fly-right coverage from left 40 degrees to left 10 degrees, and right 40 degrees to right 10 degrees. The same antennas provide right and left side lobe suppression (SLS) signals except that output power is reduced by 6 dB relative to the clearance signals. The back SLS antenna covers the region -90 degrees through 180 degrees to +90 degrees with 3 dB more power output than the left-right SLS signals.

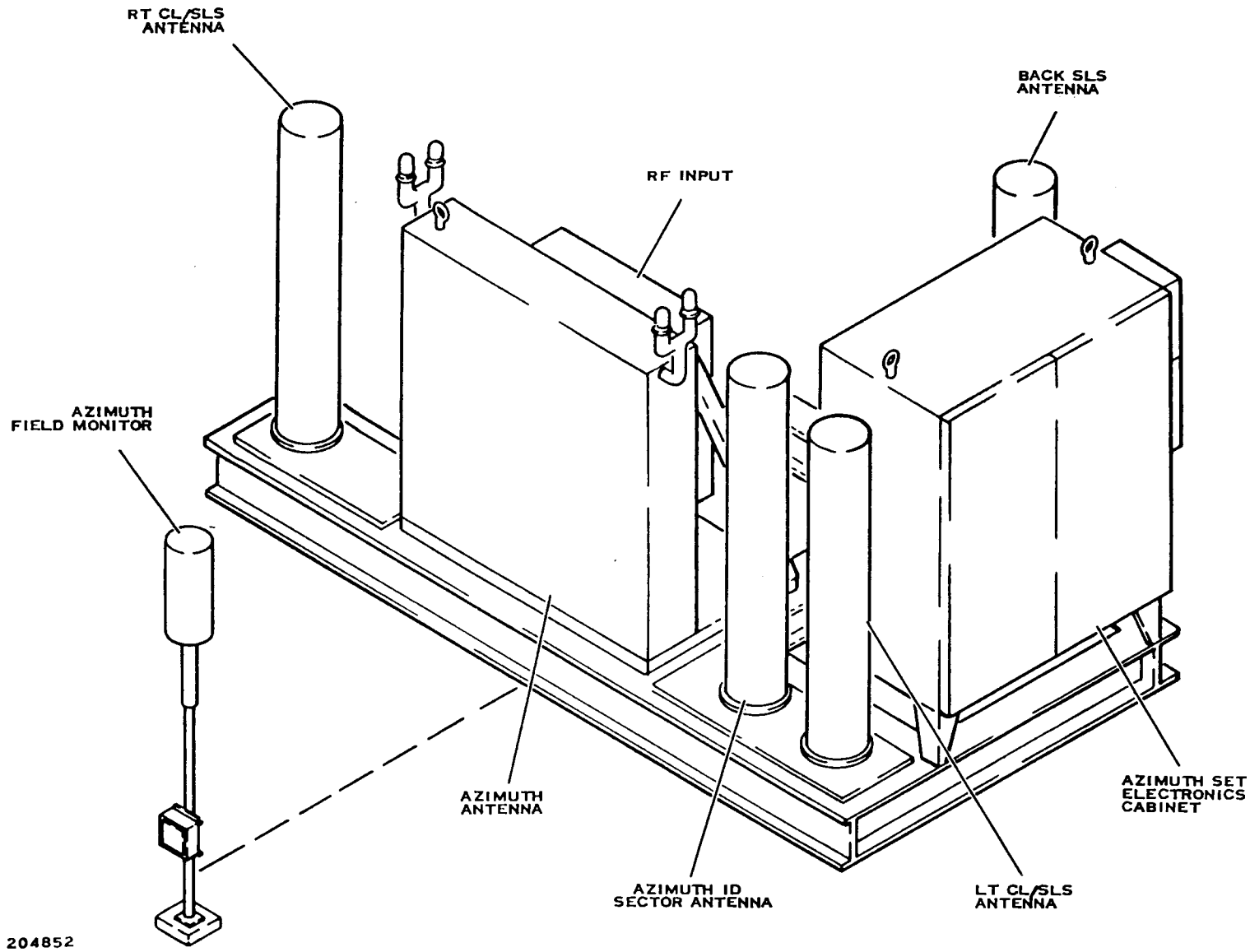

Figure 1 Azimuth Guidance Set

A typical elevation pattern of the azimuth antenna is shown in Figure 2, and the azimuth coverage of the various azimuth antennas is shown in Figure 3. The scanning rate of the azimuth beam is 13.5 hertz (Hz). The identification (ID) antenna has the same gain and input power as the clearance antennas. The coverage is ±40 degrees in azimuth and from 1 degree to 15 degrees in elevation.

The small community system transmits the following data from the azimuth unit:

Airport identification (Morse code),
Azimuth Status (Category I or unusable),
Elevation Status (Category I or unusable),
Azimuth offset (lateral distance from runway centerline),
Elevation offset,
Elevation to threshold distance,
Airport identification (digital),
Runway identification, and
Minimum glide slope.

Figure 4 shows the elevation guidance set consisting of the scanning antenna (40.5 Hz rate), the ID sector antenna, and the electronics cabinet. The scanning antenna is a bifocal pillbox array consisting of 12 monopoles feeding a sub-reflector which feeds a primary reflector. The antenna radiates a beam 2 degrees in width which can scan from 1 degree to 15 degrees in elevation. The ID antenna transmits a Differential Phase Shift Keying (DPSK) signal which conditions the airborne receiver to receive the scanning beam that follows. Figure 5 shows the azimuth pattern of the elevation antenna. The TI SCAMLS summary parameters are listed in Table 1.

A. SPECIFICATIONS

The TI SCAMLS was subjected to numerous flight and static engineering tests as required by the Phase III test plan for the U.S. MLS. The object of those tests was to provide data to determine if the systems were operating within the accuracy and coverage limits specified by the Phase III TRSB contracts. For the small community system, specification FAA-ER-700-04 applies; with accuracy degradation allowances given in specification FAA-ER-700-07.

As the program has matured, these specifications have been superceded by FAA-STD-022b, which is in agreement with the recently adopted ICAO Standards and Recommended Practices (SARPS). For the purpose of the STEP program it is appropriate to use the current standards, even though they may be more stringent than those against which the equipment was designed. Parameters which may not meet the standards will be highlighted for corrective measures such as improved design or re-evaluated standards.

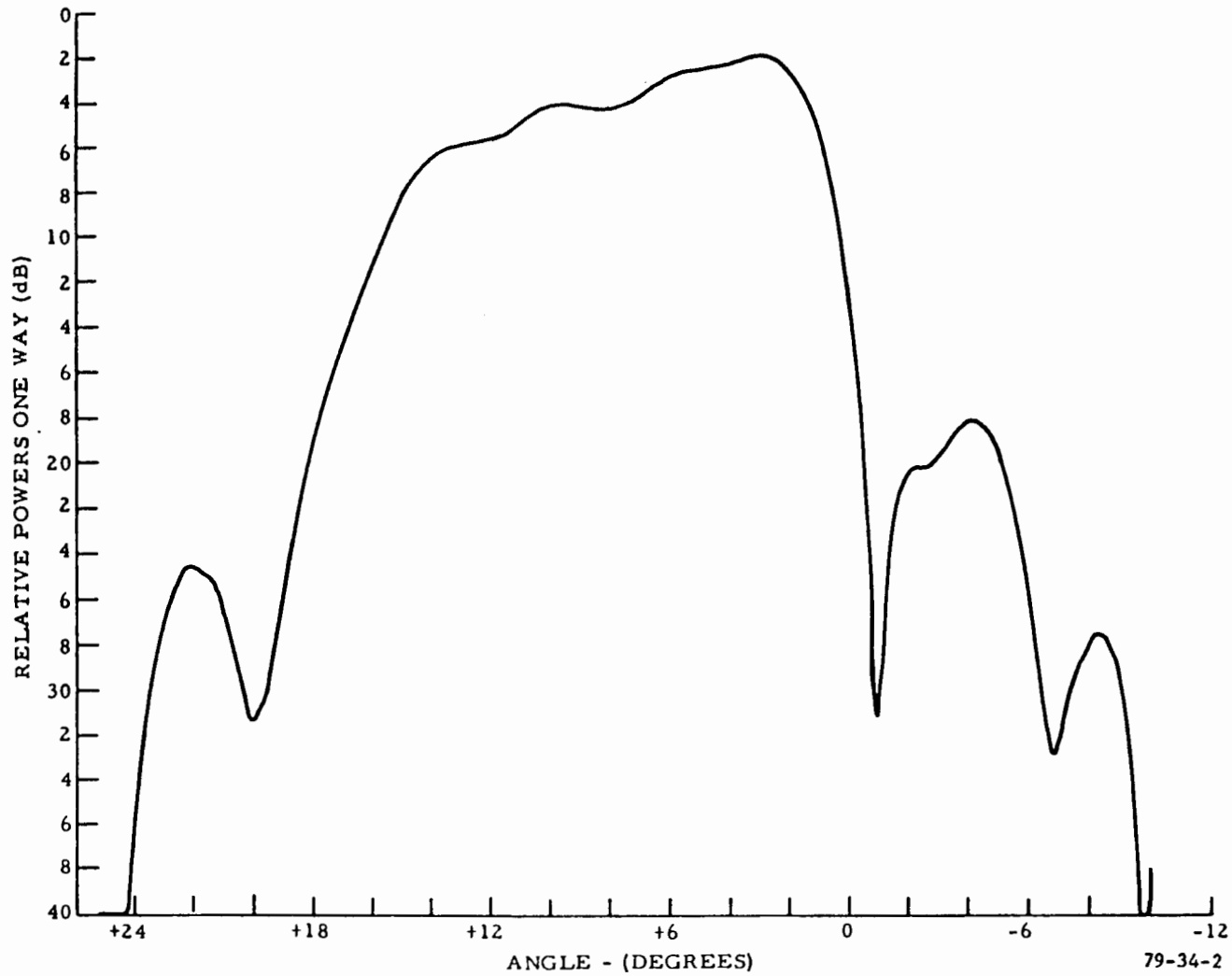

FIGURE 2. TYPICAL ELEVATION PATTERN OF AZIMUTH GUIDANCE SET

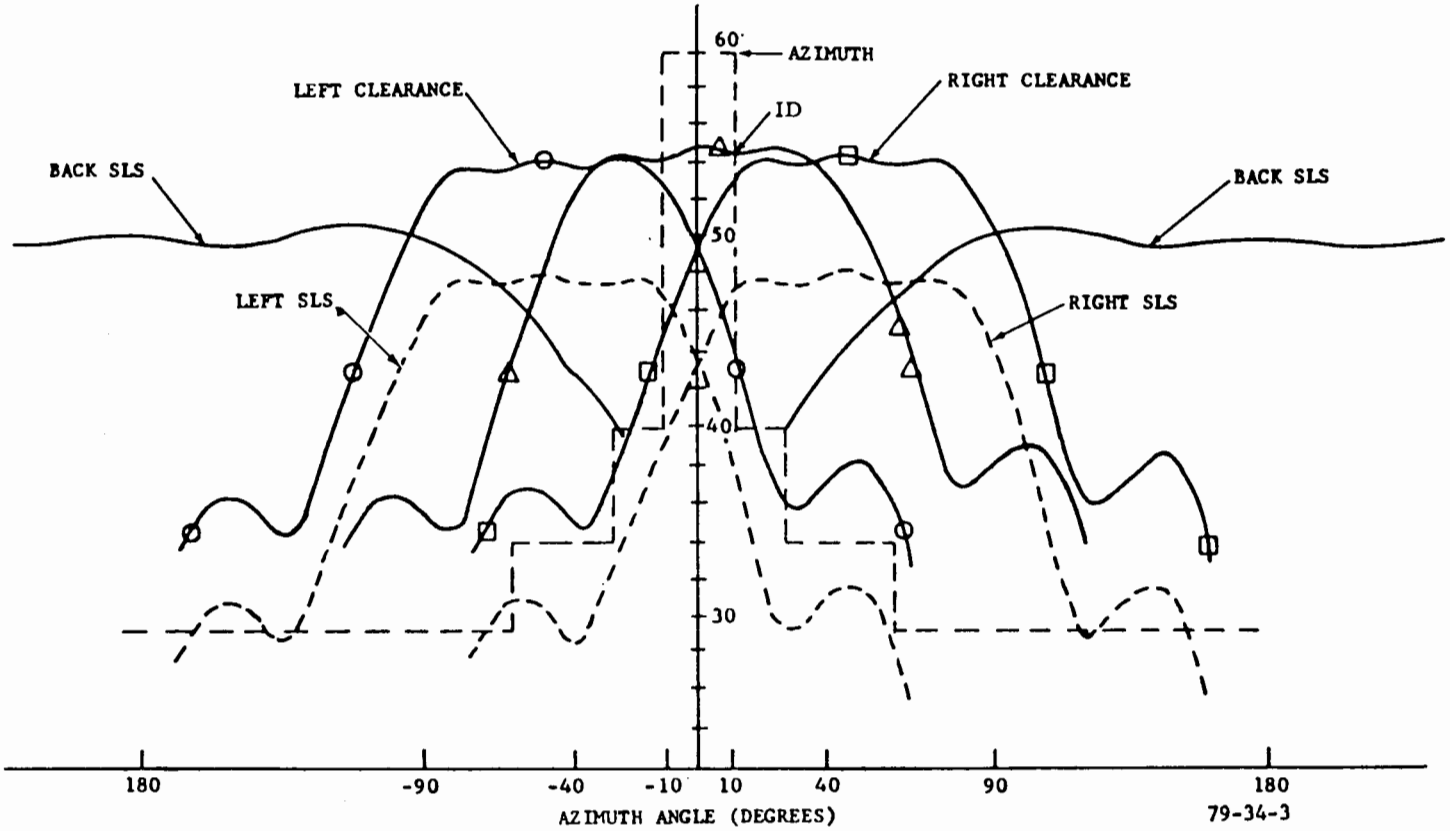

FIGURE 3. AZIMUTH ANTENNA PATTERNS OF AZIMUTH GUIDANCE SET

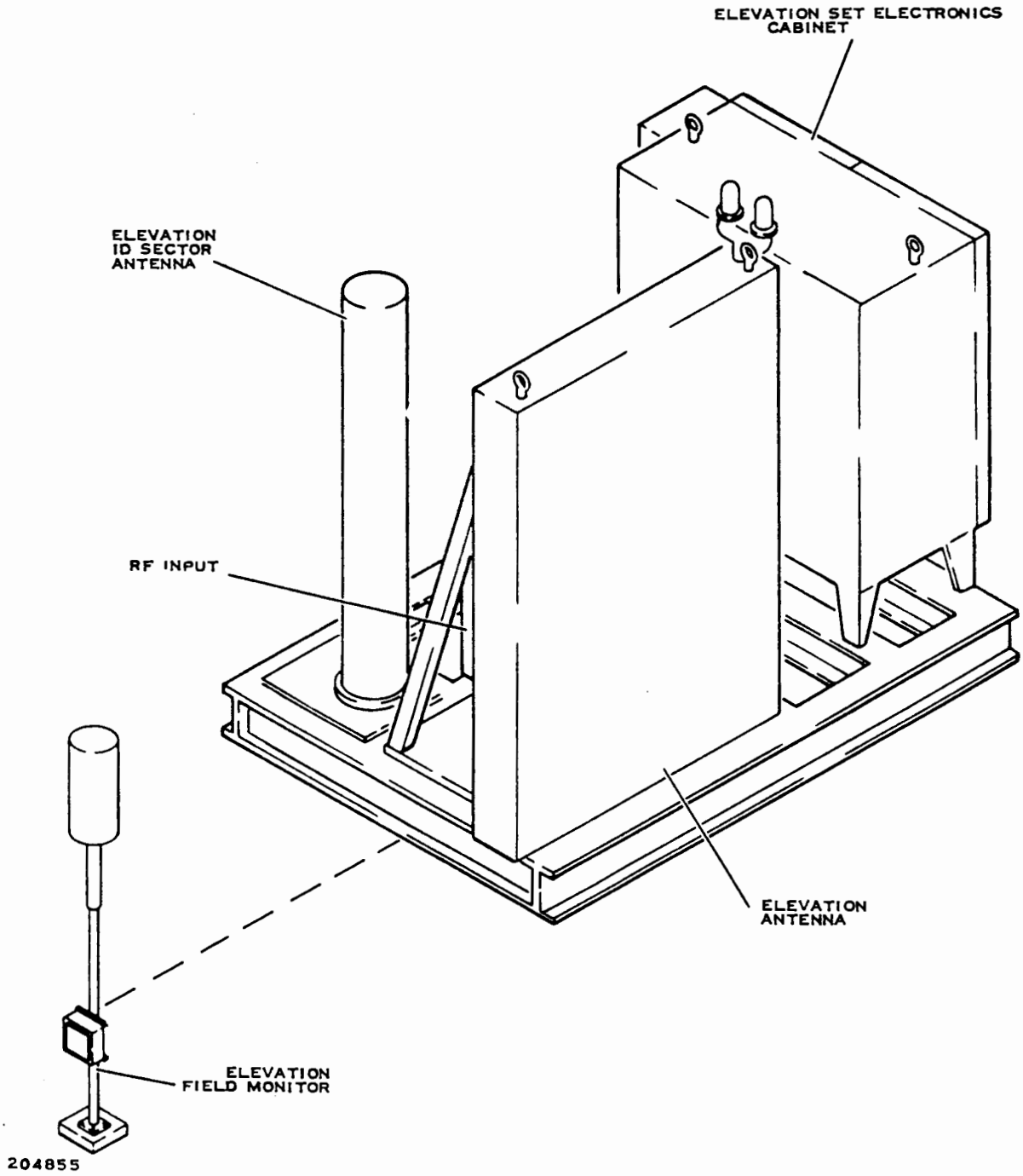

FIGURE 4 Elevation Guidance Set

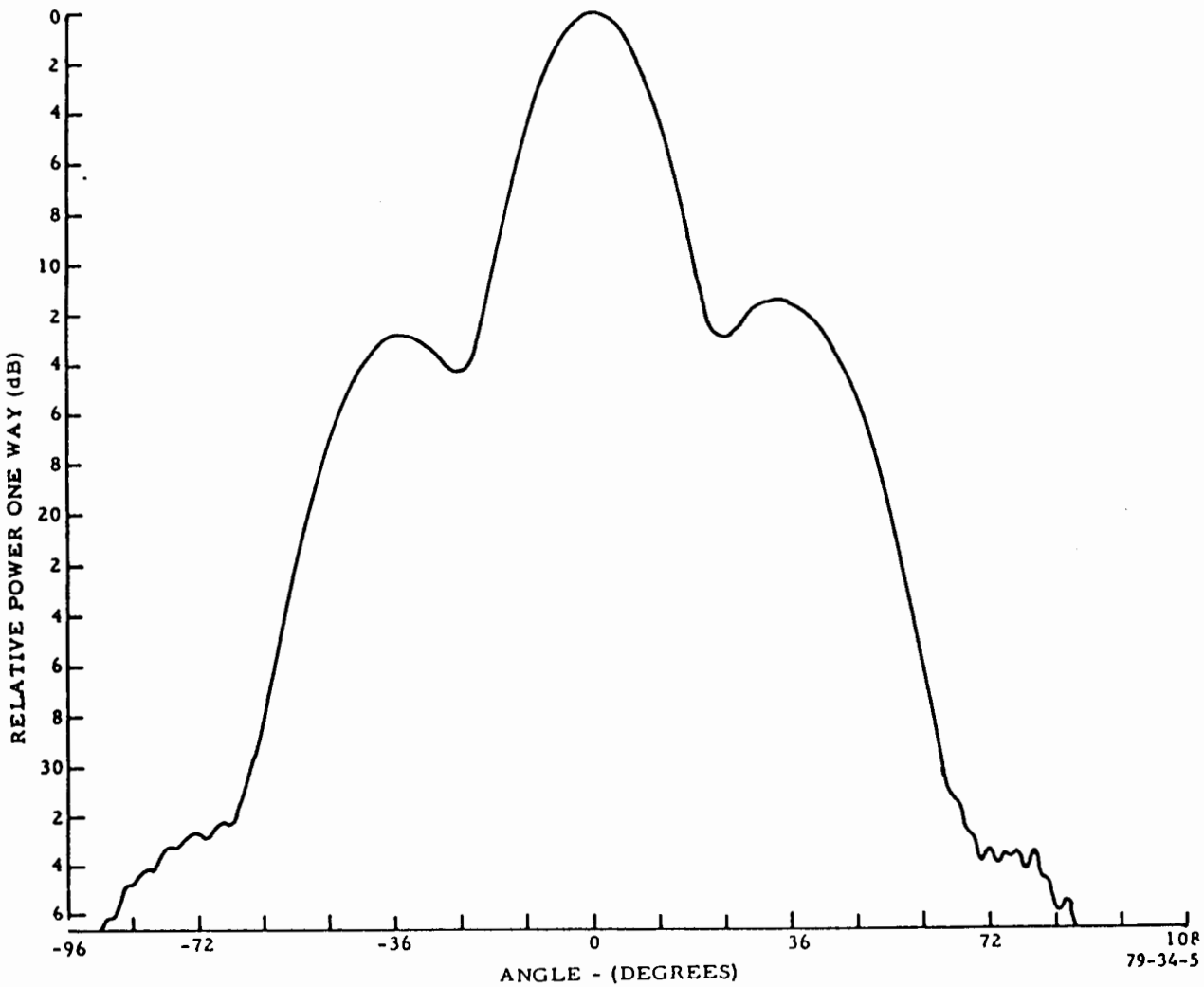

FIGURE 5. TYPICAL AZIMUTH PATTERN OF ELEVATION ANTENNA

TABLE 1. TI SCAMLS SUMMARY PARAMETERS

	Antenna Type	Beamwidth (Degrees)	Frequency (MHz)	Physical Aperture	Coverage	Gain (dBi)	Trans Power	No. of Output Elements	Scan Rate (Hz)
				(Wavelengths)			(Watts)		
Azimuth	Rotman Lens	3	5059.8	25 by 26	±10° Prop. 10-40° Clearance 1-15° Vertical	14.5	20	1,184 Slots	13.5
Elevation	Bifocal Pillbox	2	5059.8	5 by 34	1-15° Prop ±40° Horizontal	16.5	20	12	40.5

Flight measurements were made to determine the azimuth and elevation angular errors in the system (i.e., the difference between the angle received and processed by the airborne receiver and the true angle at the same instant in time). The guidance signals are subject to propagation distortion and processing inaccuracies introduced in both the ground and airborne equipment. These errors fall into two categories, constant bias errors and cyclical errors of all frequencies. These errors interact with the flight control system in a variety of ways, resulting in two general types of guidance errors: Path Following Error (PFE) and Control Motion Noise (CMN).

The PFE is that portion of the guidance signal error which could cause aircraft displacement from the desired course or glide path. These perturbations fall within the loop guidance bandwidth of an aircraft. The path following error is composed of the path following noise and the mean course error in the case of azimuth functions, or the mean glidepath error, in the case of elevation functions.

The CMN is that portion of the guidance signal error which could affect aircraft attitude and cause control surface, wheel and column motions during coupled flight, but which does not cause aircraft displacement from the desired course or glidepath. It may contribute to control surface and servo wear, and diminish flight crew confidence by presenting them with a "shaky stick".

The PFE is comprised of those frequency components of the guidance signal error at the output of the airborne receiver which lie below 0.5 radians per second for azimuth guidance and below 1.5 radians per second for elevation guidance information. The control motion noise is comprised of those frequency components of the guidance signal error at the output of the airborne receiver which lie above 0.3 radian per second for azimuth guidance or above 0.5 radian per second for elevation guidance information. The output filter corner frequency of the receiver used for this measurement is 10 radians per second.

NOTE: The PFE and CMN are evaluated by filtering the output of the receiver (see Figure 6). The filter characteristics are based on a wide range of existing aircraft response properties, and are considered adequate for foreseeable aircraft designs as well.

The FAA-STD-022b (Table 5) System Error Limits at the Approach Reference Datum are:

Approach Azimuth ±20 ft. (PFE) ±10.5 ft. (CMN)
Approach Elevation ±0.133° (PFE) ±0.050° (CMN)

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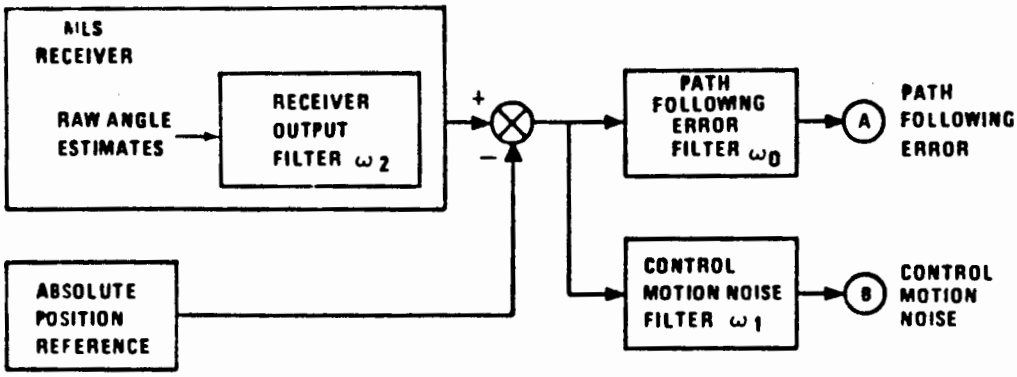

GUIDANCE FUNCTION	CORNER FREQUENCIES (RADIANS/SEC)		
	ω_0	ω_1	ω_2
APPROACH AZIMUTH	0.5	0.3	10
APPROACH ELEVATION	1.5	0.5	10
FLARE	2.0	0.5	10

RECEIVER OUTPUT FILTER $\frac{\omega_2}{S + \omega_2}$

PATH FOLLOWING FILTER $\frac{\omega_n^2}{S^2 + 2\zeta\,\omega_n\,S + \omega_n^2}$ $\zeta = 1;$

CONTROL MOTION NOISE FILTER: $\frac{S}{S + \omega_1}$ $\omega_n = 1.56\,\omega_0$

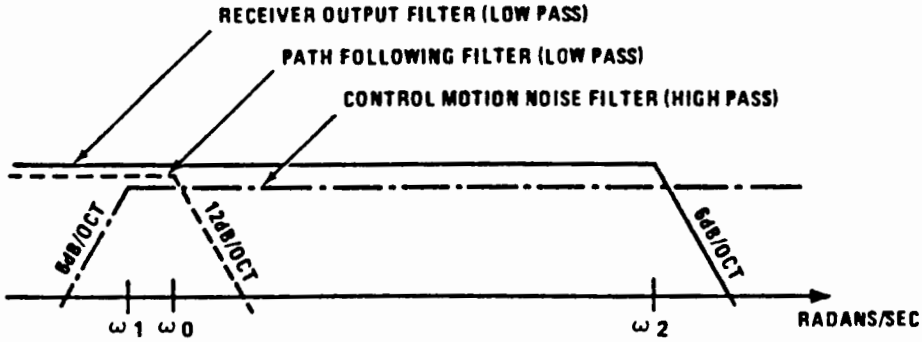

Figure 6. Filter Configurations and Corner Frequencies

The approach reference datum is 50 feet above threshold on the minimum glidepath. From the reference datum to the coverage limit, the PFE and CMN limits, expressed in angular terms, are allowed to linearly increase as follows:

(1) For azimuth functions:

(a) With the distance along the runway centerline extended, by a factor of 1.2 for the PFE limits and to ±0.10 degree for the CMN limits.

(b) With azimuth angle, by a factor of 1.5 at the ±40 degrees and a factor of 2.0 at the ±60 degrees azimuth angles for the PFE and CMN limits.

(c) With elevation angle from +9 degrees to +15 degrees, by a factor of 2.0 for the PFE limits.

(d) Maximum angular limits. The PFE limits shall not exceed ±0.25 degrees in any coverage region below an elevation angle of +9 degrees nor exceed ±0.50 degrees in any coverage region above that elevation angle. The CMN limits shall not exceed ±0.10 degrees in any coverage region within ±10 degrees of runway centerline extended nor exceed ±0.20 degrees in any other region within coverage.

NOTE: It is desirable that the CMN limits not exceed ±0.10 degrees throughout the coverage.

(2) For approach elevation functions:

(a) With distance along the runway centerline extended at the minimum glidepath angle, by a factor of 1.2 for the PFE limits and to ±0.10 degrees for the CMN limits.

(b) With azimuth angle, from runway centerline extended to the coverage extreme, by a factor of 1.2 for the PFE limits and by a factor of 2.0 for the CMN limits.

(c) With increasing elevation angle from +3 degrees to +15 degrees, by a factor of 2.0 for the PFE limits.

(d) With decreasing elevation angle from +3 degrees (or 60% of the minimum glidepath angle, whichever is less) to the coverage extreme, by a factor of 3 for the PFE and CMN limits.

(e) Maximum angular limits. The CMN limits shall not exceed ±0.10 degrees in any coverage region, within ±10 degrees laterally of runway centerline extended, which is above the elevation angle specified in (d) above.

NOTE: It is desirable that the CMN limits not exceed ±0.10 degrees throughout the coverage region above the elevation angle specified in (d) above.

For this equipment, the design coverage of the azimuth unit is 15 nm in range, ±10 degrees in azimuth angle, and 1 degree to 15 degrees in elevation. The design coverage of the elevation unit is 15 nm in range, ±10 degrees in azimuth (relative to the azimuth site), and 1.9 degrees to 10.67 degrees in elevation.

The calculated accuracy specification limits for the three types of flight patterns flown against the TI SCAMLS are shown on the data plots. Both the contract hardware specification limits and the FAA-STD-022b specification limits are shown. The three types of flight profiles are centerline approach, radials, and orbits. The curves are plotted only out to 8 nmi because laser tracking beyond this point was not considered highly accurate, usually due to weather conditions during flights.

NOTE: For FAA-STD-022b purposes, the PFE and CMN for approach azimuth or for back azimuth shall be evaluated over any 40-second interval of the flight error record taken within the coverage limits. The PFE and CMN for approach elevation shall be evaluated over any 10-second interval of the flight error record taken within the coverage limits. The requirement is interpreted to be met if the PFE or CMN does not exceed the specified error limits for more than 5 percent of the evaluation interval.

B. TEXAS INSTRUMENTS MLS PHILADELPHIA INTERNATIONAL AIRPORT TESTS

1. LOCATION. The Texas Instrument Small Community Airport MLS (SCAMLS) was located to serve Runway 17 at Philadelphia International Airport. The Morse code identifier was XZY. The assigned MLS channel was 596 (5059.8MHz). An ILS has also been installed to serve Runway 17. Although Runway 17 has a 743' displaced threshold due to obstacles outside of threshold, the elevation site is located to give a 55' crossing height over the normal threshold (beginning of the pavement). This may place the obstacles closer to the elevation beam lower limit than would be normal. Figure 7 shows the MLS elevation location 250 feet from centerline and also the ILS glide slope antenna location 538 feet from centerline.

The azimuth site is located on the centerline extended (Runway 17/35) 1100' beyond the stop end of Runway 17. This puts it well below the clearance surface for Runway 35. The nearest building to the runway is at an azimuth angle of about 7 degrees from runway centerline and at a maximum elevation of about 0.7 degree. In this position it should not cause noticeable interference on the approach path for either the elevation or azimuth signals. Figure 8 shows the MLS azimuth location on centerline with the DME antenna located 400 feet off centerline, and the ILS localizer located 245 feet behind the azimuth antenna.

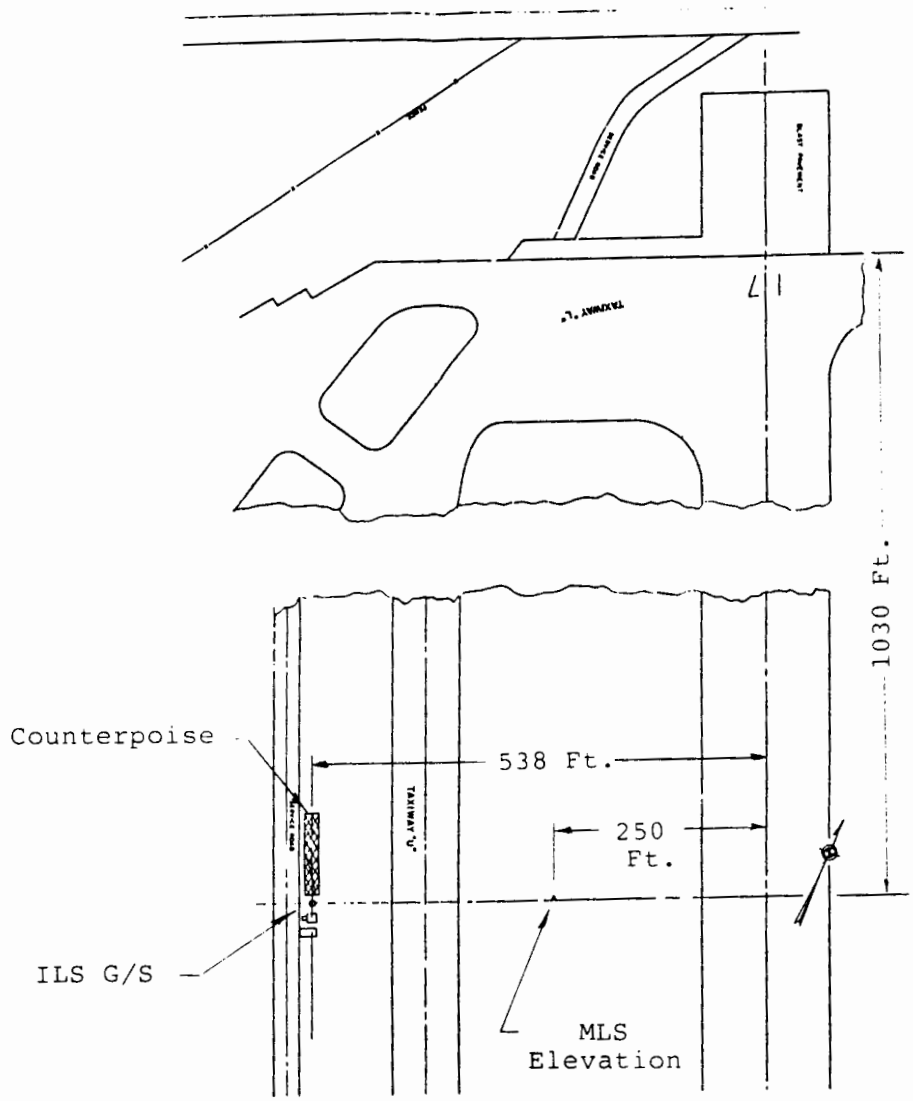

FIGURE 7 ILS and MLS Elevation Location

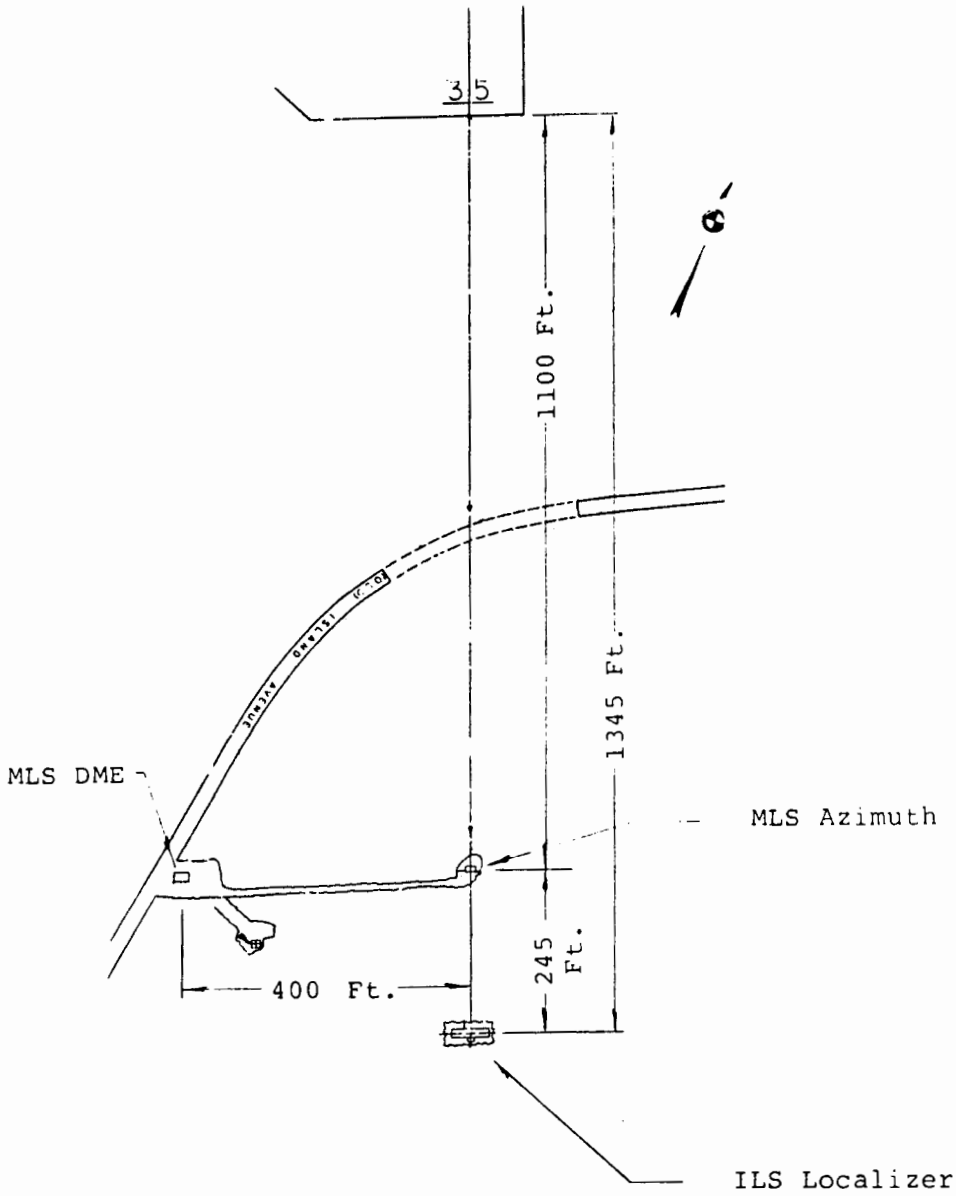

FIGURE 8 ILS Localizer MLS Azimuth and DME Location

As part of the normal ILS installation procedures, an FAA flight inspection crew and aircraft measured the performance of the ILS against the ILS flight inspection commissioning criteria. The MLS elevation and the ILS glide slope antennas are abeam one another but separated by 288 feet so no interferring effects should be anticipated. The azimuth antenna is 246 feet directly in front of the ILS localizer. The flight inspection of 9/20/83 reported the ILS facility operation was satisfactory and gave it an unrestricted rating. [Note: At some other facilities, the ILS has been inspected before and again after the MLS was located in front of the ILS. It has been found that objects placed in front of the localizer symmetrically about the runway centerline do not have a serious affect on the localizer performance. In this case at Philadelphia the MLS was installed first, so no "before" data are available on the ILS.] The ILS was located so it would have no affect on the MLS performance.

2. FLIGHT TEST. The tests were divided into three flight pattern types: centerline approaches; constant altitude radial flights; and constant altitude orbital runs. The centerline approaches were made on 3-degree, 4.5-degree and 6-degree glidepaths to test the elevation and azimuth guidance along centerline.

The radial runs were designed to keep a constant 3,000 foot altitude and a constant radial direction from the azimuth site. Flights were flown inbound on centerline and ±15 degree radials from the coverage limits.

The orbital runs, made at altitudes of 2,000, 4,500 and 8,000 feet and at a constant 6 nm range from azimuth, also test the limits of coverage. The azimuth error plots normally can be used as a good indication of azimuth pointing errors at various elevation angles. The flight test runs are listed in Table 2.

3. MEASUREMENT STANDARD. The true spatial position of the test aircraft was considered to be the position measured by the FAA's laser radar tracking system. The system, built by Sylvania, uses a pulsed laser beam to track a retro-reflector mounted on the aircraft. The horizontal angular, vertical angular and distance coordinates measured from the tracking system are translated by the system computer in to a coordinate system relative to the MLS antenna phase centers. A correction is made for the displacement of the retro-reflector from the MLS receiver antenna on the aircraft.

4. TEST AIRCRAFT. The flight test aircraft was an FAA twin engine, turbo prop Convair 580 based at the FAA Technical Center, Atlantic City, N.J. The MLS receiving antenna was an omni-directional stub mounted on the aircraft nose in front of the windscreen. The laser retro-reflector was mounted

Flight Test Data Runs For Record

TABLE 2

CENTERLINE APPROACHES

Date	Run	Glidescope
31 March 1981	1	3°
"	2	3°*
"	3	3°
"	4	4.5°
"	5	4.5°
04 April 1981	1	3°
"	2	3°
"	3	4.5°
"	4	4.5°
"	5	6°
"	6	6°
20 April 1981	1	3°
"	3	4.5°
13 May 1981	3	6°

RADIAL APPROACHES

Date	Run	Radial	Altitude
31 March 1981	6	10L	3Kft
"	7	10L	"
"	8	5L	"
"	9	0	"
"	10	5R	"
"	11	10R	"
15 April 1981	1	10L	3Kft*
"	2	5L	"
"	3	0	"
"	4	5R	"
"	5	10R	"
20 April 1981	7	10L	"

PARTIAL ORBITS

Date	Run	Direction	Range	Altitude
31 March 1981	12	CW	6nm	2Kft
"	13	CCW	"	"
15 April 1981	6	CW	"	"
"	7	CCW	"	"
"	8	CW	"	4.5Kft
"	9	CCW	"	"
"	10	CW	"	8Kft
"	11	CCW	"	"

*Indicates bad run

on the aircraft top over the cockpit area. The MLS installation consisted of two receivers mounted in racks in the cabin. About 30 ft. of one-half inch diameter semi-rigid coax and RG-214 brought the signal from the receiving antenna to the receivers. A signal splitter was used to feed both receivers. This installation results in about 6 dB loss between the antenna and the receiver. The digital output of the MLS receiver was digitally recorded on tape along with time of day and other parameters of interest for later correlation with data from the laser tracking system.

C. RESULTS

1. CENTERLINE APPROACHES. Twelve runs were evaluated with glidepaths of 3°, 4 1/2° and 6°. All exhibited laser tracker loss for 1 to 1.5 nm between 6 and 8 nm from the azimuth site; however, no obstacles were apparent on the Obstacle Clearance Chart to account for this loss, especially at higher glidepath angles. In most cases the data were valid from there to threshold, although on some runs there was another laser tracker loss at about 4 nm.

a. Azimuth Path Following (C-L). There appears to be a correlation between the low frequency component of the azimuth error and the approach course deviations. Where course deviations are great, the low frequency component is great. Runs 3 and 4 of 31 March 1981, are examples of this characteristic Run 3 is a fairly straight flight with deviations from about +0.45 degree to +0.1 degree during the major portion of the approach as indicated in Figure 9. The azimuth error plot shows a very low amplitude low frequency component (Figure 10). Run 4 deviates (over the same range) from +0.7 to -0.5 degree (Figure 11) causing a very large low frequency component in the azimuth error plot (Figure 12).

The initial assessment was that the correlation was related to the tracker or the filtering applied to the tracker data. However, it appears that the major factor is the antenna beam pointing error. See Figure 31 for a composite plot of an orbital flight at 6 nm, 3000 foot altitude with the factory antenna test range data at a 3° elevation angle superimposed. There is good agreement. Orbital error data have been extracted from the Figure 31 orbital flight data and superimposed on the approach error data of Run 4 of 31 March 1981. See Figure 12. [The deviation angle from centerline was obtained from Figure 11 which shows the aircraft position about centerline. The angle was used to enter Figure 31 to read the orbital error data.] Figure 12 shows the orbital and approach error data in close agreement.

The azimuth path following error was within both original hardware and FAA-STD-022b tolerances for all centerline approaches even with the antenna beam pointing errors.

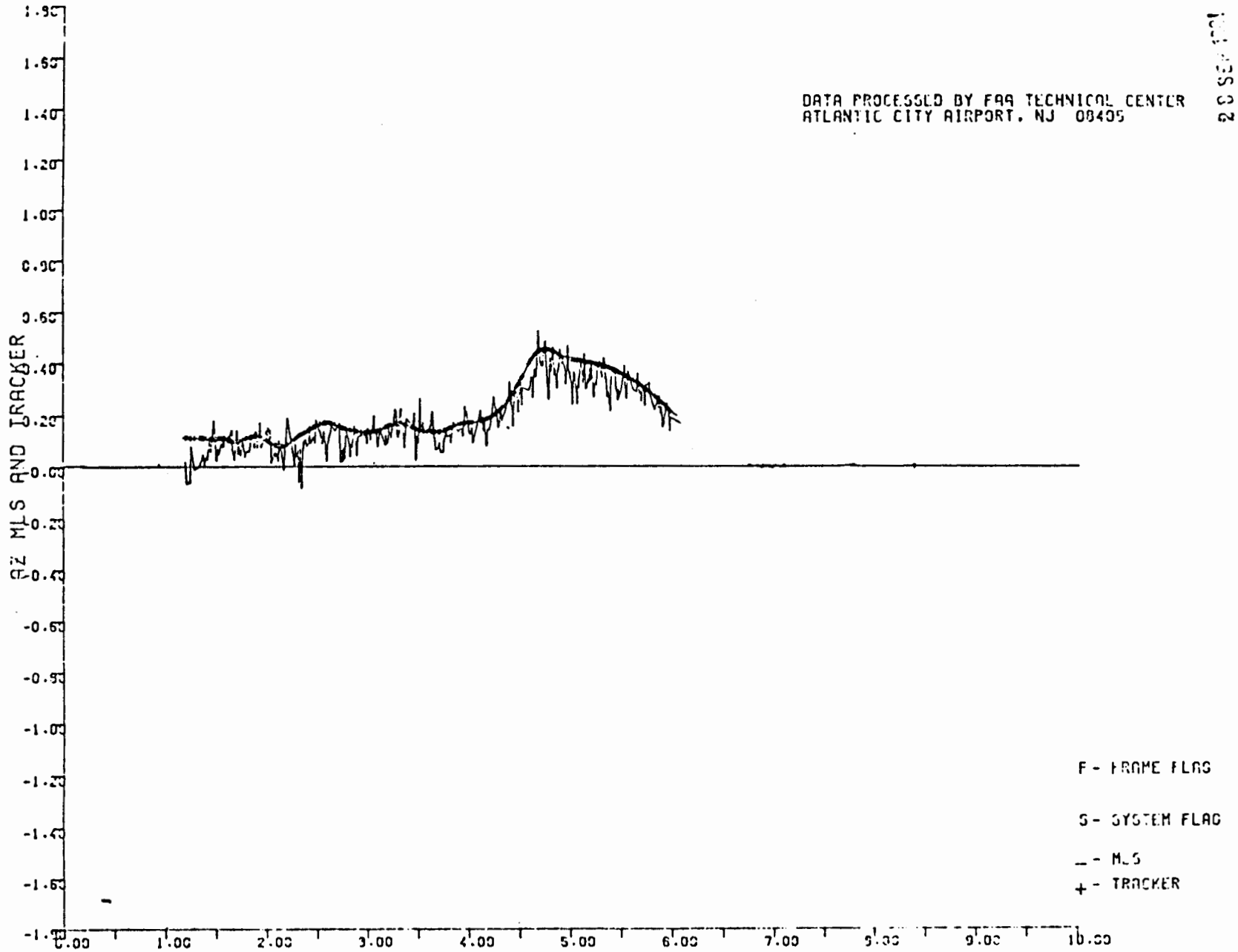

FIGURE 9 AZ; MLS AND TRACKER; RUN 3, MAR 31, 1981, CL 3 DEG APP

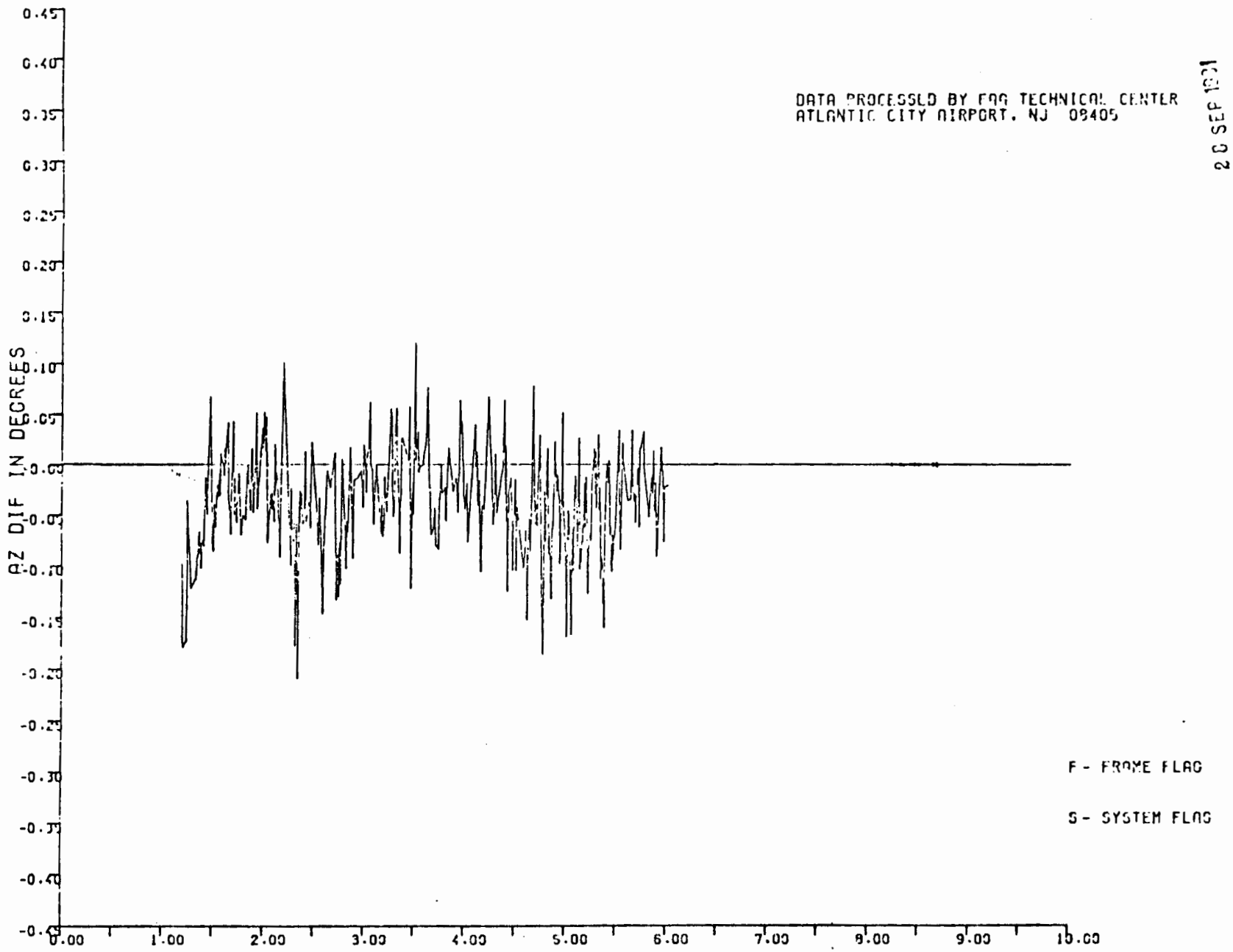

FIGURE 10 AZ DIFF; RUN 3, MAR 31, 1981, CL 3 DEG APP

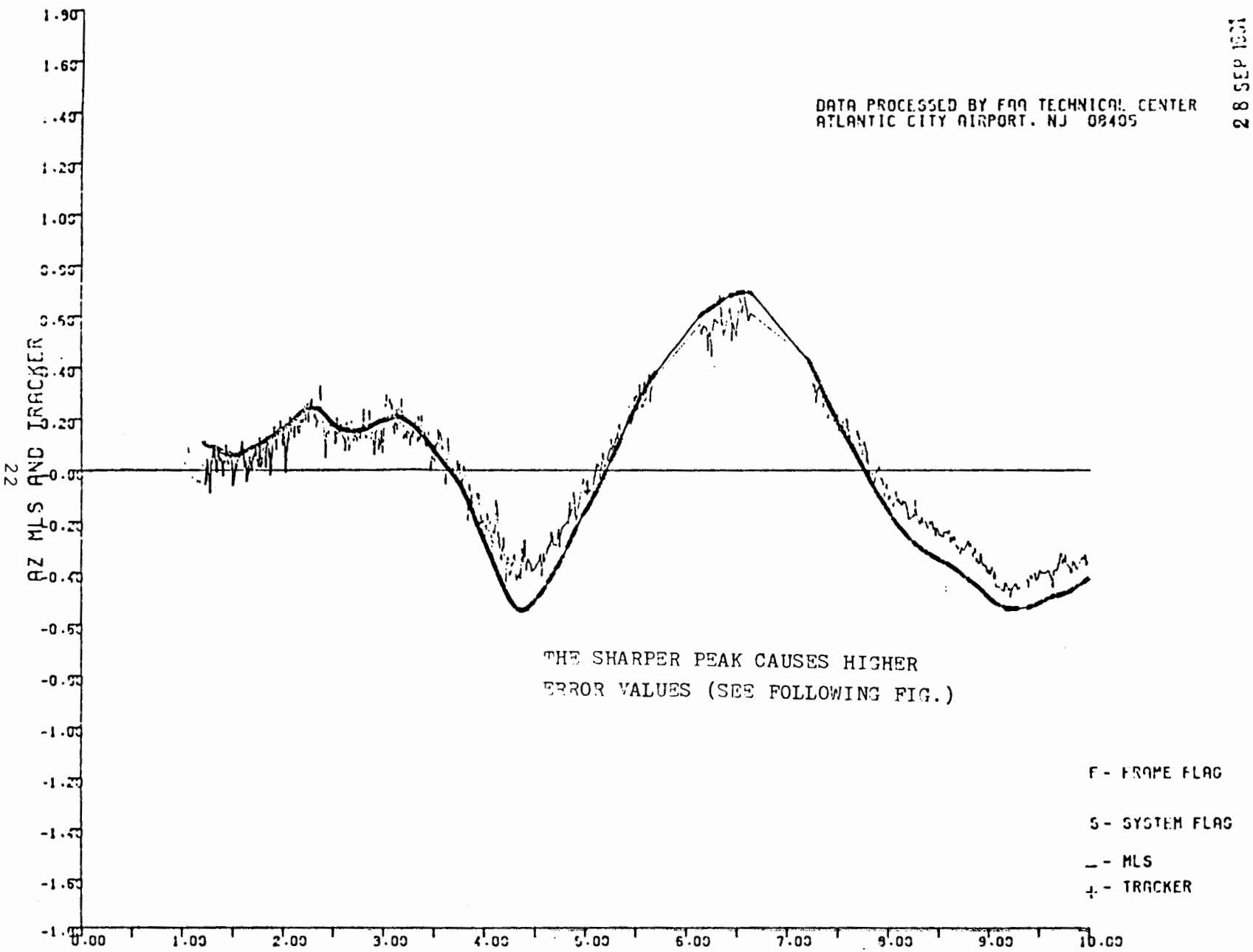

FIGURE 11 AZ; MLS AND TRACKER; RUN 4, MAR 31, 1981, CL 4.5 DEG APP

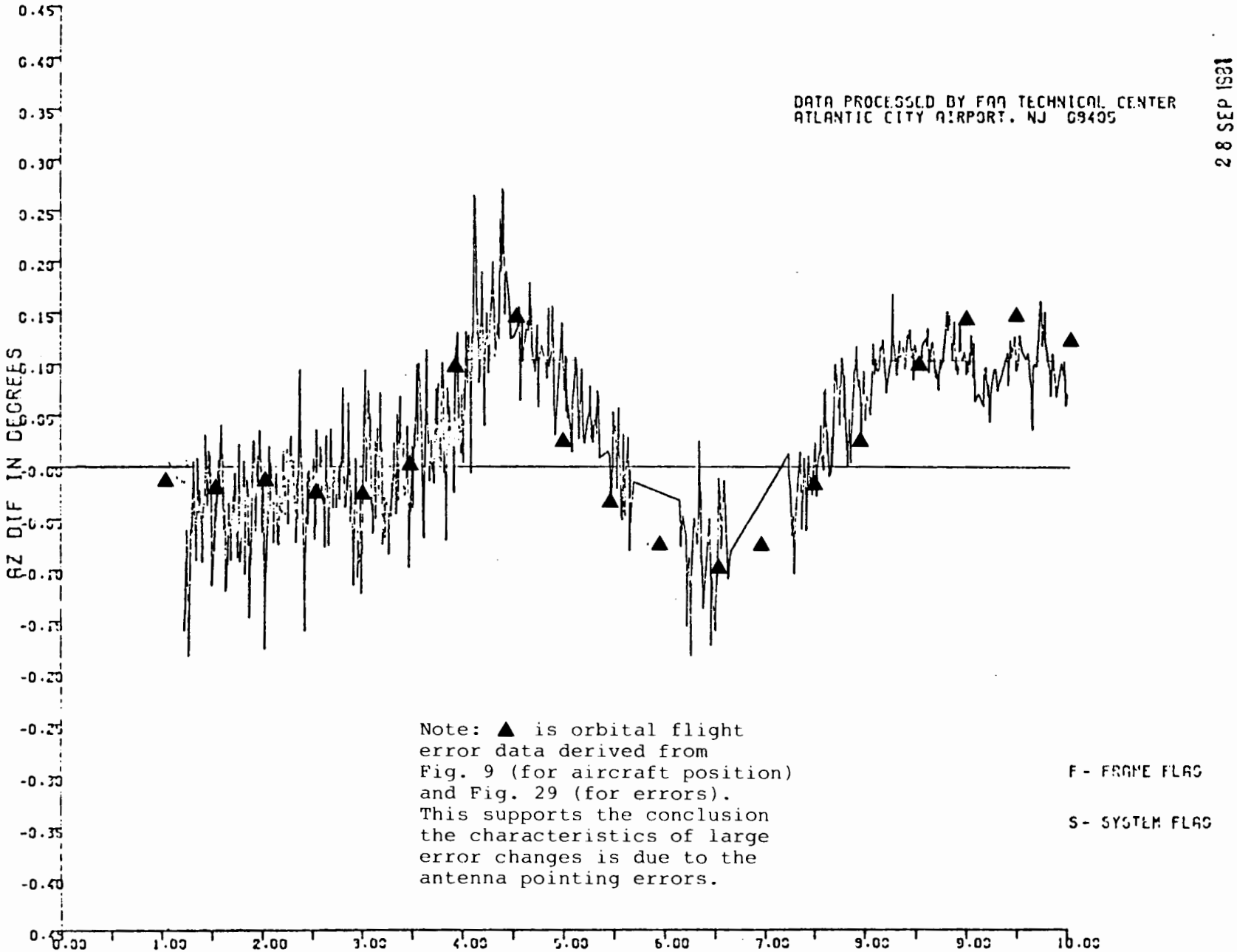

FIGURE 12 AZ DIFF; RUN 4, MAR 31, 1981, CL 4.5 DEG APP (WITH ORBITAL DATA SUPERINPOSED)

These low frequency components affect the path following error and control motion noise plots. The PFE filter will respond only to the lower frequency components of the raw error. However, some of the lower frequency effects are also reflected in the control motion noise plots.

Figure 13 is a plot of the azimuth PFE for Run 3 of 20 April 1981, showing the lower frequency effects. Figure 14 is the azimuth CMN for the same run. It can be seen that the lower frequency components cause the CMN to exceed the tolerance limits, and although actual peak-to-peak levels of the higher frequency "noise" are large but they would be within tolerance if the varying bias component is removed. The large excursion at about 5.5 nm must be considered a tracker fault and ignored since the tracker was not locked for the previous 1.4 nm and was locking on the reflector again at this time.

b. Azimuth Control Motion Noise. The azimuth noise was high on the lower glideslopes, moderating only slightly on the higher (6 degrees) glidepath approaches. If the major cause of the noise was vertical obstacles, the noise would have moderated more, and as noted previously, the nearest vertical obstacle, at 7 degrees from centerline, would be considered out of beam. The noise was significantly less at greater ranges as can be seen in Figure 15 which is a 4.5 degree glideslope starting at 10 nm from the azimuth site (Run 4 on 31 March 1981).

Early in the MLS development program, the errors due to signal blockage by, or reflection from, propellers were investigated. It was concluded the reflected interference under these conditions would only cause small amplitude variations in the received scanning beam envelope. More recently, noise effects have been noticed in certain MLS flight data collected on wider beamwidth systems installed to support the MLS STEP. The peak errors recorded are not consistent with signal-to-noise ratios in the receiver and become particularly noticeable after a change of MLS antennas on the CV-580 test aircraft. The MLS receiving antenna for these flights was an omni-directional stub mounted on the aircraft nose in front of the windshield. This turbo-prop aircraft has unusually large propeller blades, and the typical propeller rotation rates are high enough to cause a significant relative phase change (and thus a distortion of the direct signal) during the dwell time of the wider scanning beam envelopes. The effects appear to be function of the propeller pitch, becoming noticeable when the pitch is set for approach power settings. This may be the effect shown in Figure 15 with the lower noise levels at greater ranges corresponding to cruise configuration. This is further supported by noting the lower noise levels on the level flyovers, (Figure 26, 30) which would be in cruise configuration.

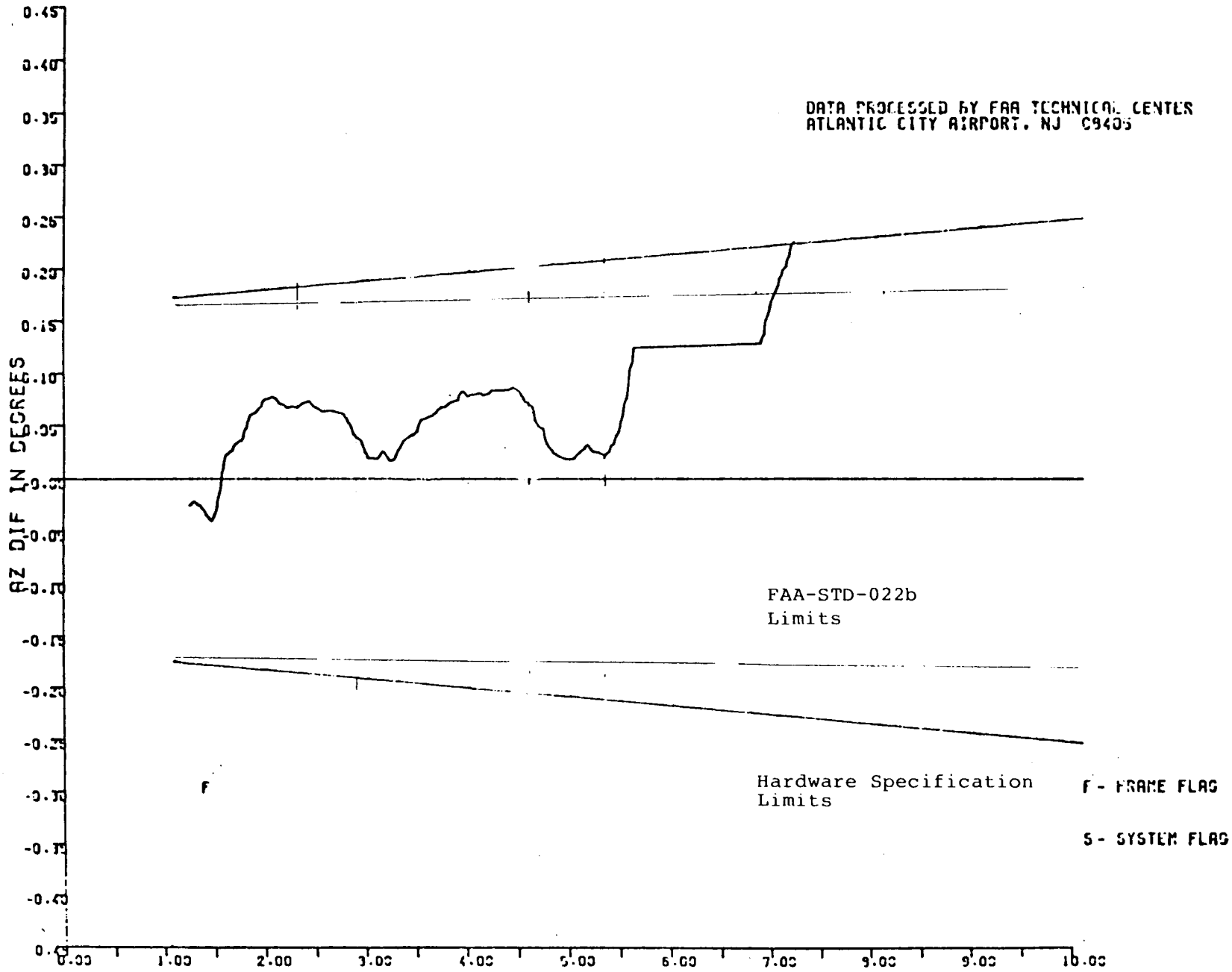

FIGURE 13 AZ DIFF; RUN 3, APR 20, 1981, CL 4.5 DEG APP; PFE

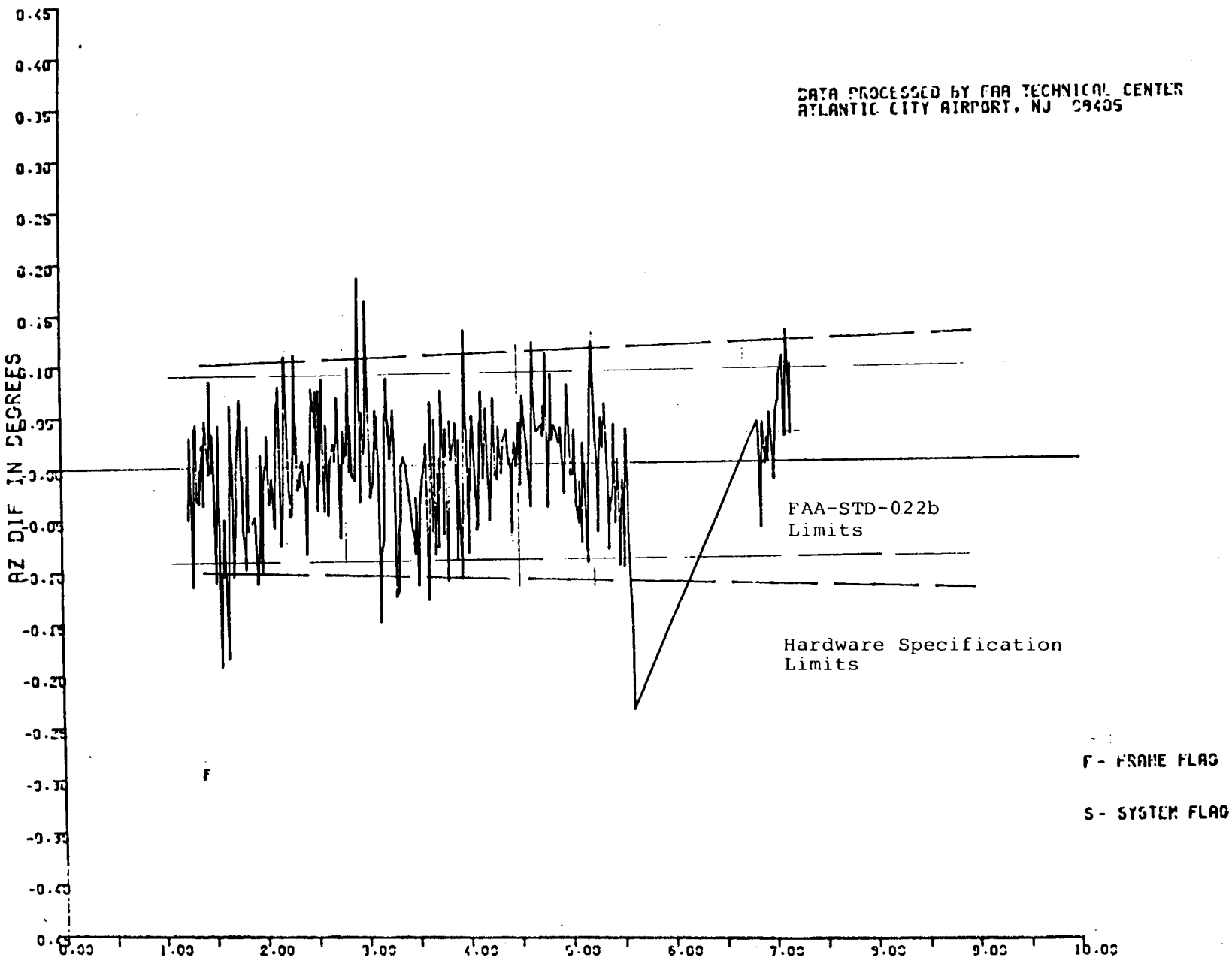

FIGURE 14 AZ DIFF; RUN 3, APR 20, 1981, CL 4.5 DEG APP; CMN

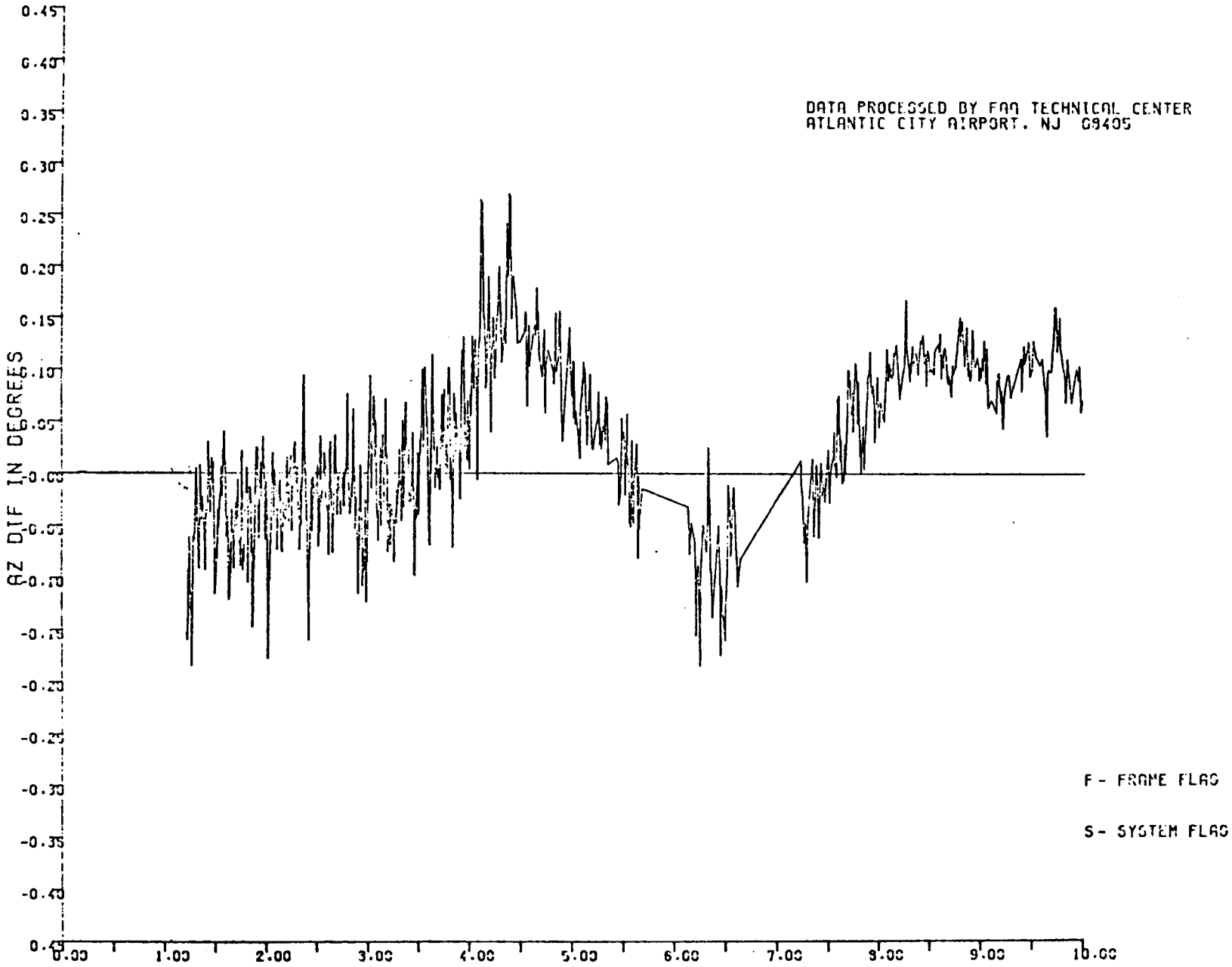

FIGURE 15 AZ DIFF; RUN 4, MAR 31, 1981

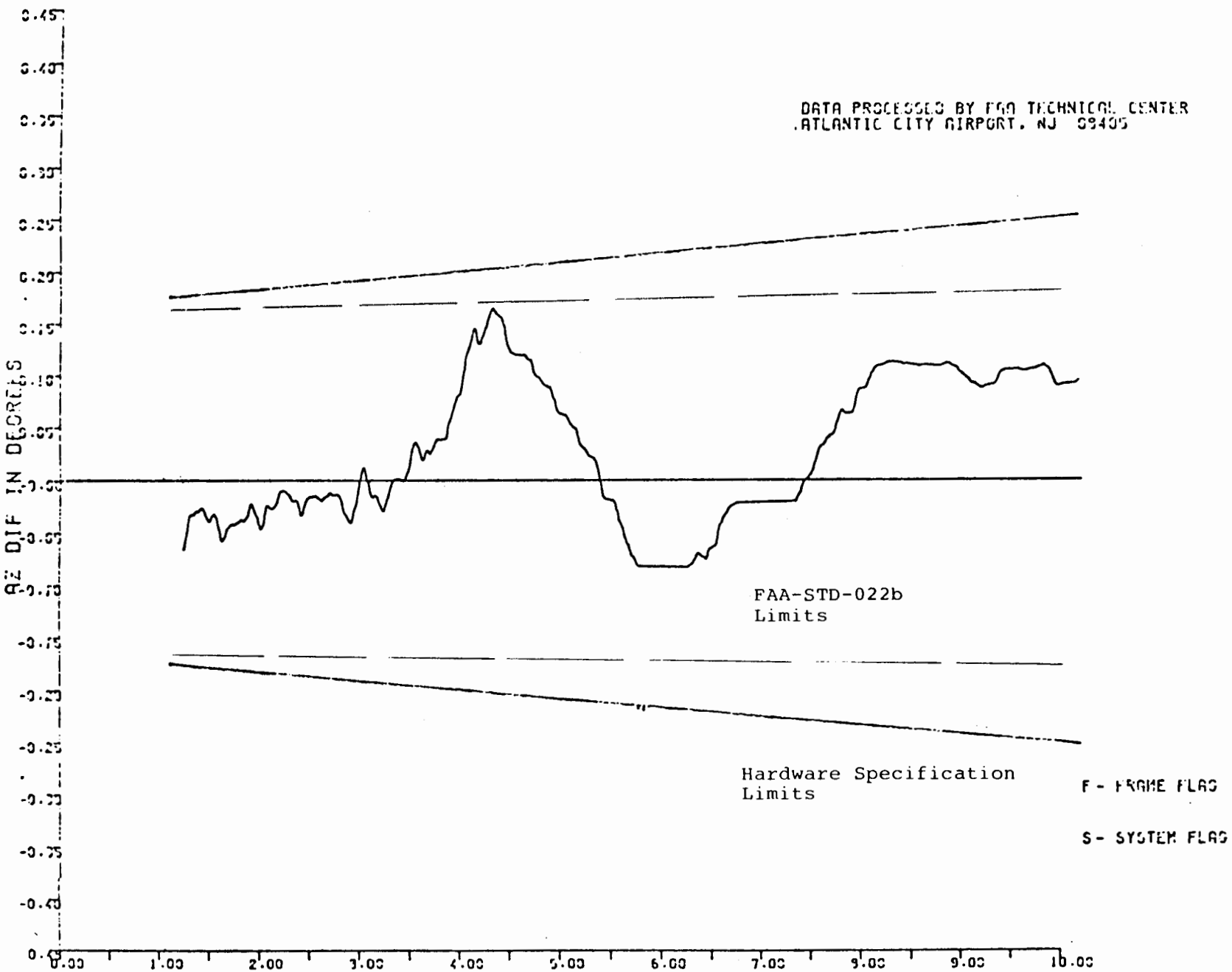

FIGURE 16 AZ DIFF; RUN 4, MAR 31, 1981, CL 4.5 DEG APP; PFE

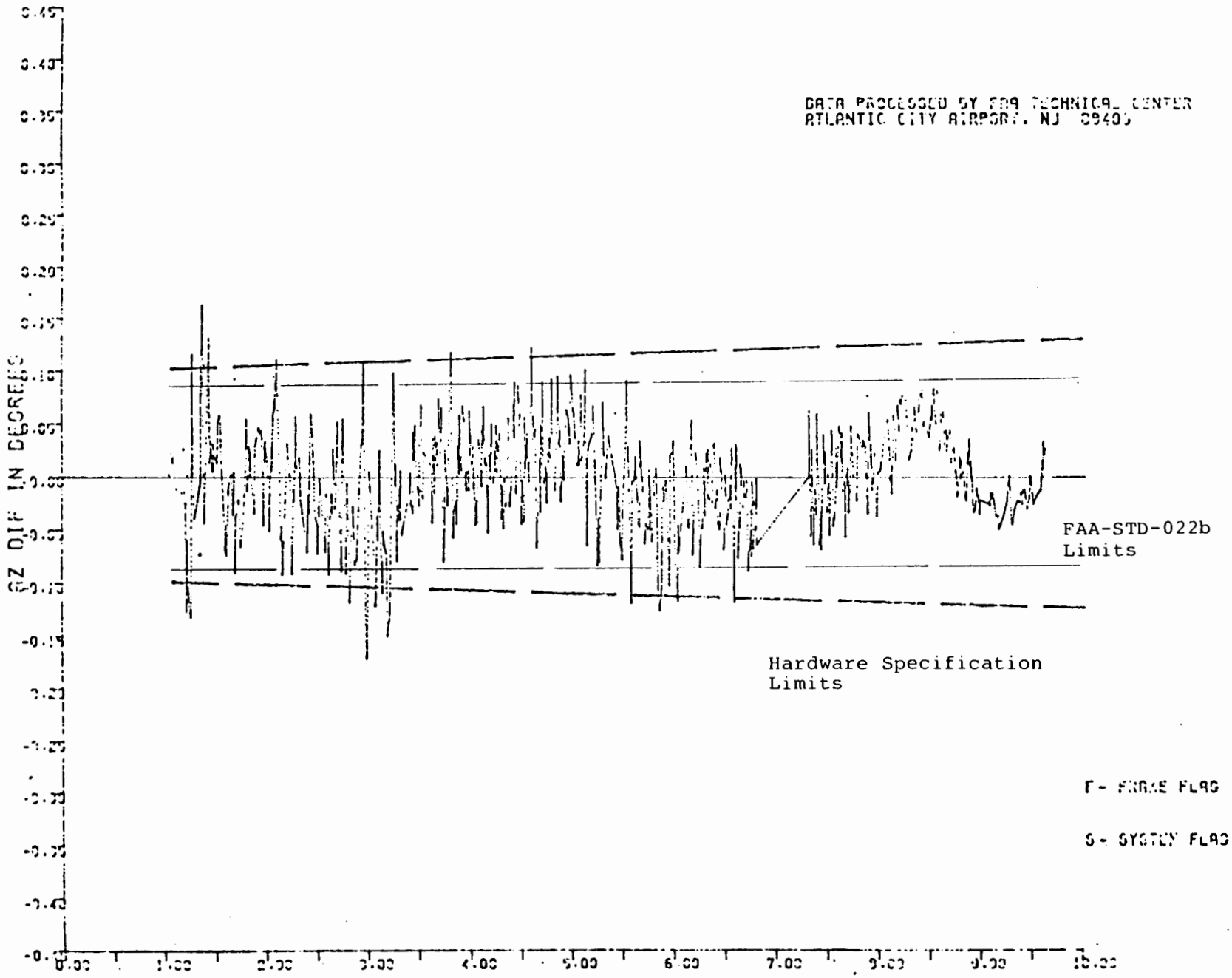

FIGURE 17 AZ DIFF; RUN 5, MAR 31, 1981, CL 4.5 DEG APP; CMN

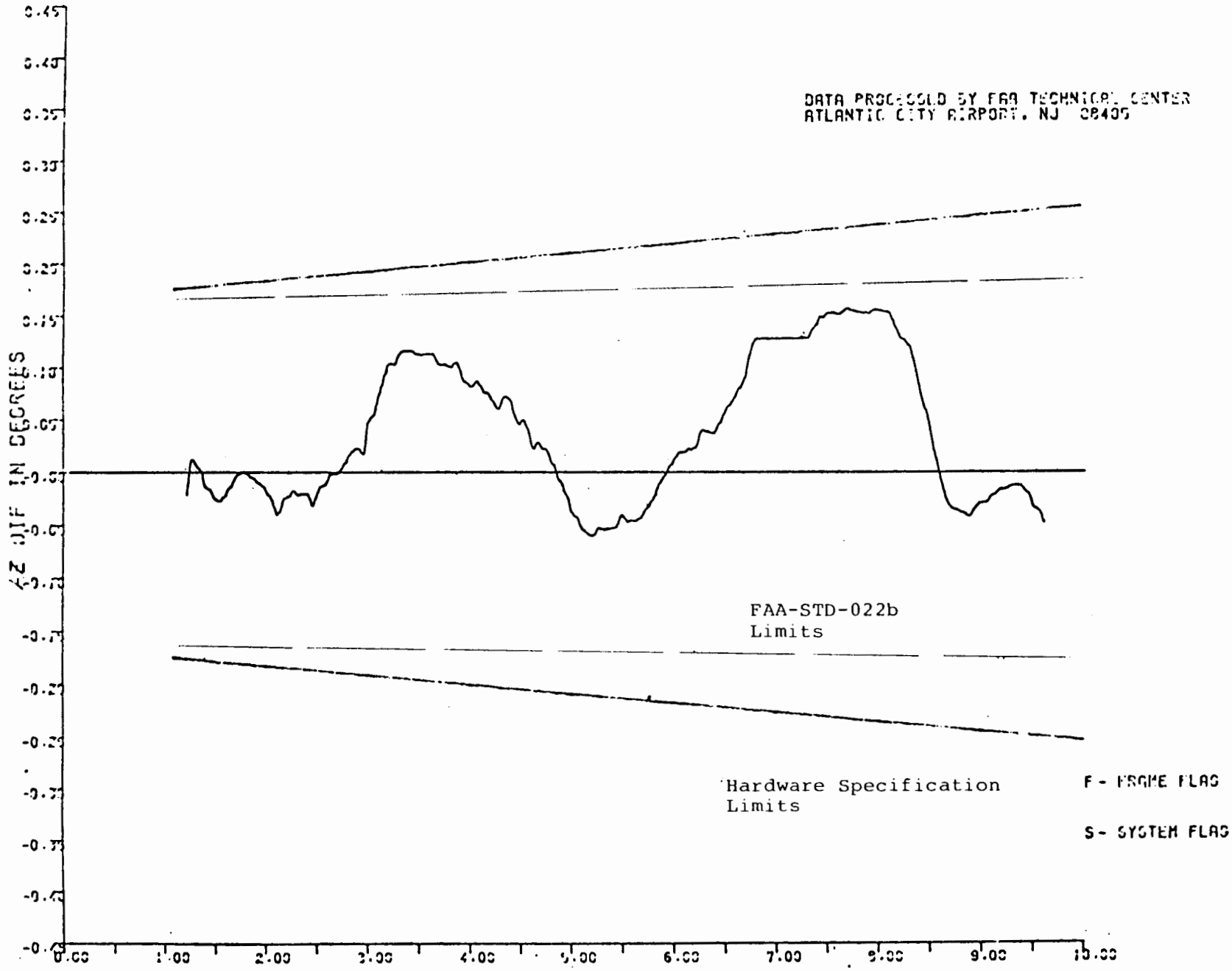

FIGURE 18 AZ DIFF; RUN 5, MAR 31, 1981, CL 4.5 DEG APP; PFE

The azimuth Control Motion Noise (CMN) data are considered not to meet the hardware or the FAA-STD-022b specification limits, having too many points outside the limits. However, the data are also considered to have a high likelihood of being contaminated by propeller multipath effects. The 6° approach data shown in Figure 19 come close to meeting requirements.

c. Elevation Path Following (C-L). The path following error was well within limits on all runs (and glide path angles) with higher relative amplitude at the lower elevation angles and low relative amplitude at the higher elevation angles. Some noise appeared in the path following plots as indicated in Figure 20, Run 4 of 31 March 1981.

d. Control Motion Noise (C-L). The elevation CMN has low frequency components that tend to drive peaks (probably exceeding the 5% allowed) out of the established tolerances at the lower elevation angles. This can be seen on Figure 21, Run 1 of 20 April 1981, where the low frequency (bias) takes the form of a ramp function during the middle section of the run. However, the ramp may due to the CMN filter response to the one mile break in the data and the amplitude change from negative errors to positive errors (Figure 22) during the break.

As the elevation angle increases the control motion noise moderates from peak-to-peak of 0.1° at 3° elevation to about 0.05° at 6° elevation (Figures 22 & 23). However, a significant portion of the CMN is believed due to the propeller pitch during the aircraft's approach configuration causing a multipath reflection forward into the omni receiving antenna.

2. RADIAL TESTS. Thirteen radial runs were evaluated on centerline, on five degrees, and on ten degrees off centerline (left and right). These runs were all made at 3000' altitude from about 10 to 4 nm or about 7 degrees elevation angle from the azimuth site at the minimum range.

The results were similar in nature to the centerline approaches. With the wider tolerances, all test data are well within requirements.

a. Path Following Error (Radial). The path following error was within tolerances for all radial runs. Some of the plotted PFE can be attributed to antenna pointing errors and to the aircraft flight path corrections. This can be seen in Figures 24 and 25 which represent the tracker vs MLS and azimuth error plots for Run 11 of 31 March 1981. The effects were reflected in the CMN as indicated in Figure 26. A positive bias error of about 0.06° was evident on the 5° right radial while a negative error of about the same magnitude was present on the 5° left radial. Figures 27 and 28 illustrate this bias. At centerline and 10° on either side of centerline there was no significant bias.

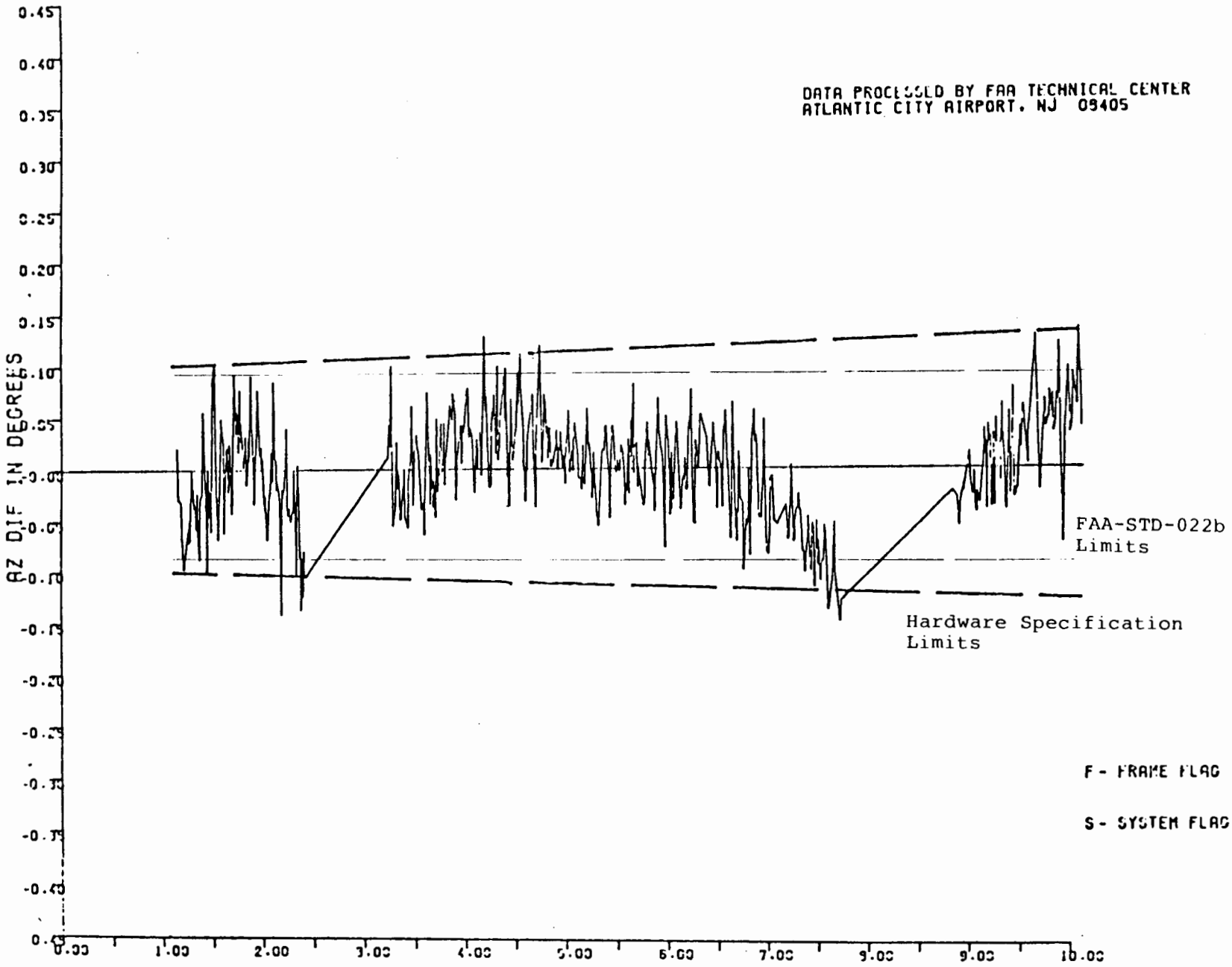

FIGURE 19 AZ DIFF; RUN 3, MAY 13, 1981, CL 6 DEG APP; CMN

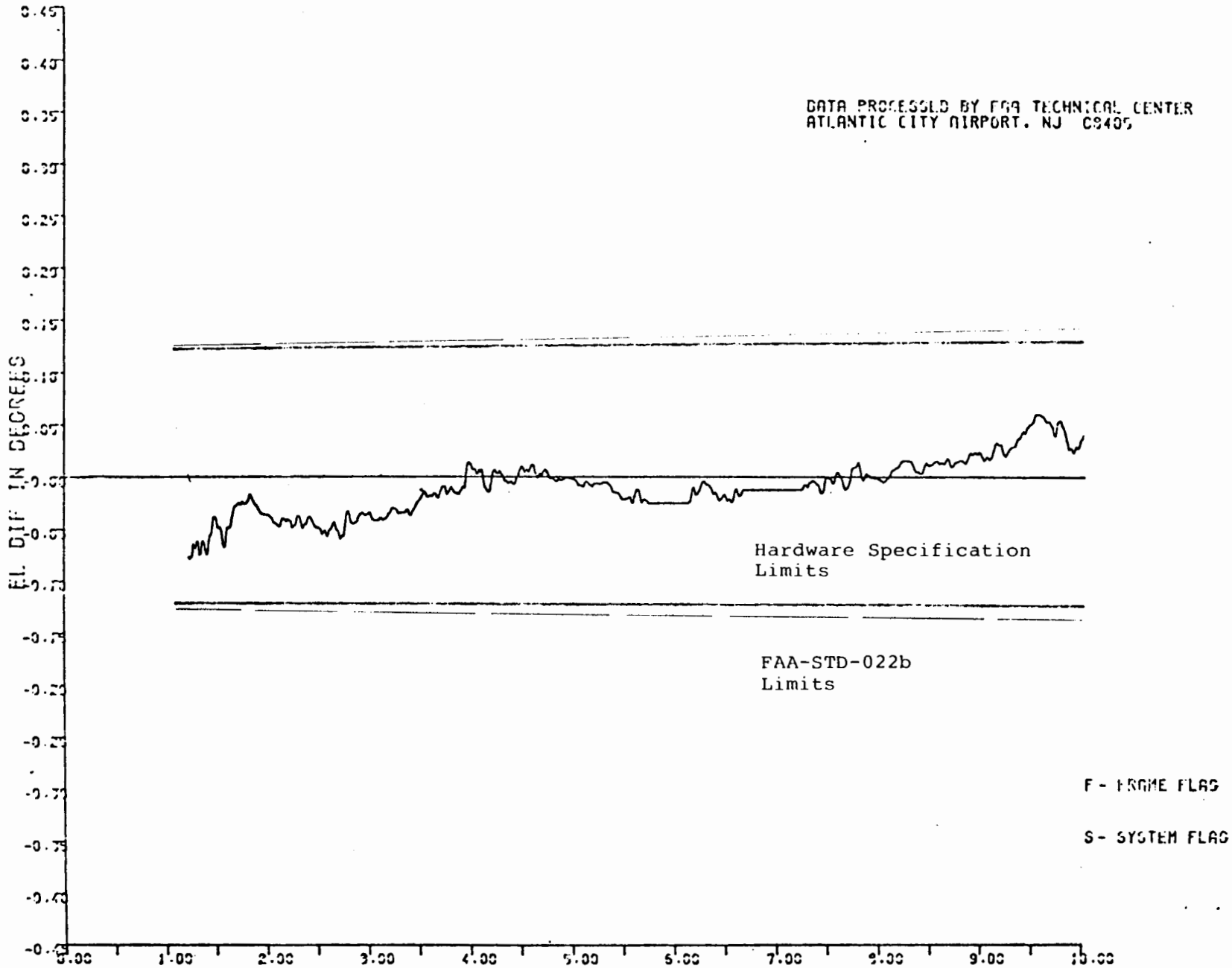

FIGURE 20 EL DIFF; RUN 4, MAR 31, 1981, CL 4.5 DEG APP; PFE

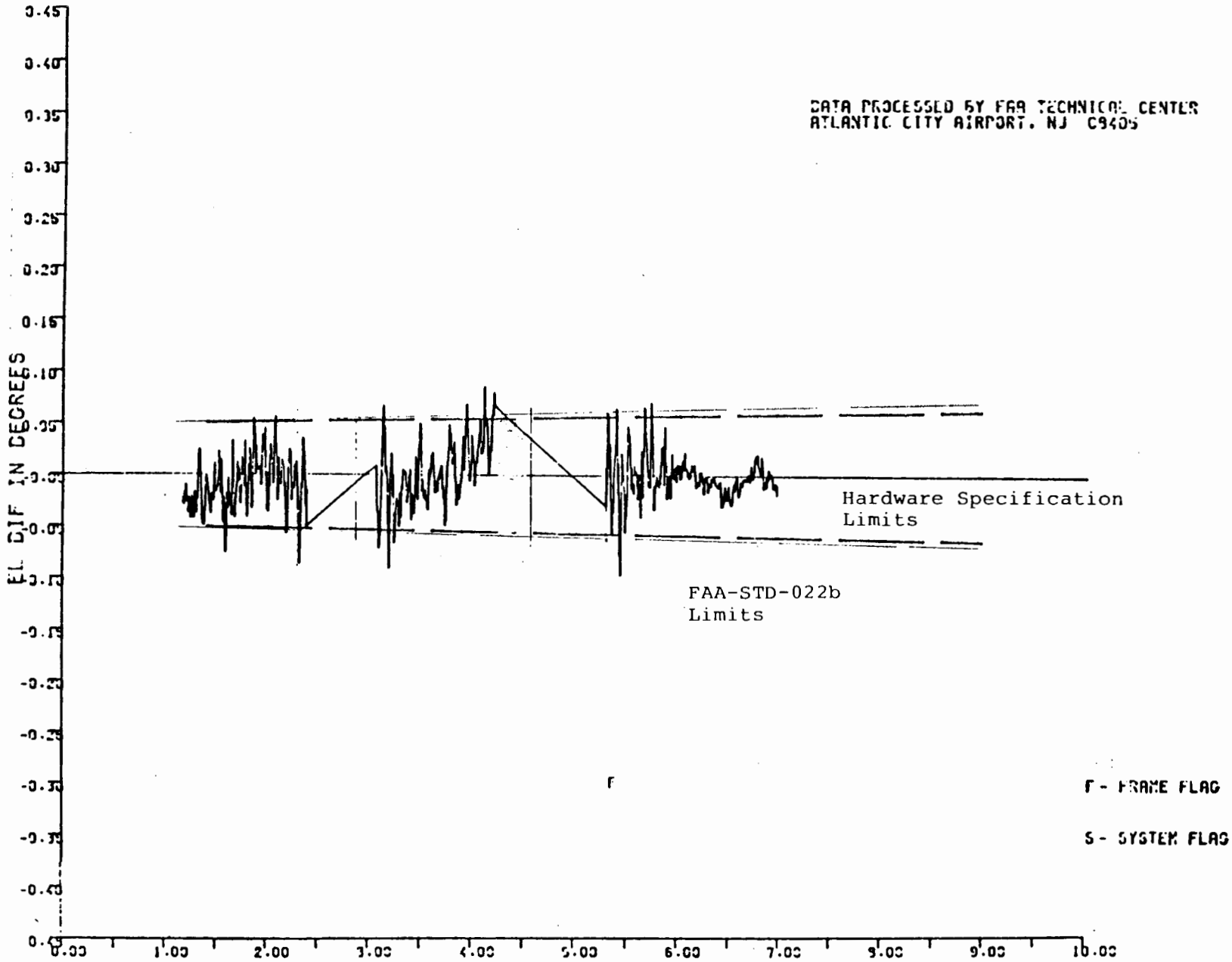

FIGURE 21 EL DIFF; RUN 1, APR 20, 1981, CL 3 DEG APP; CMN

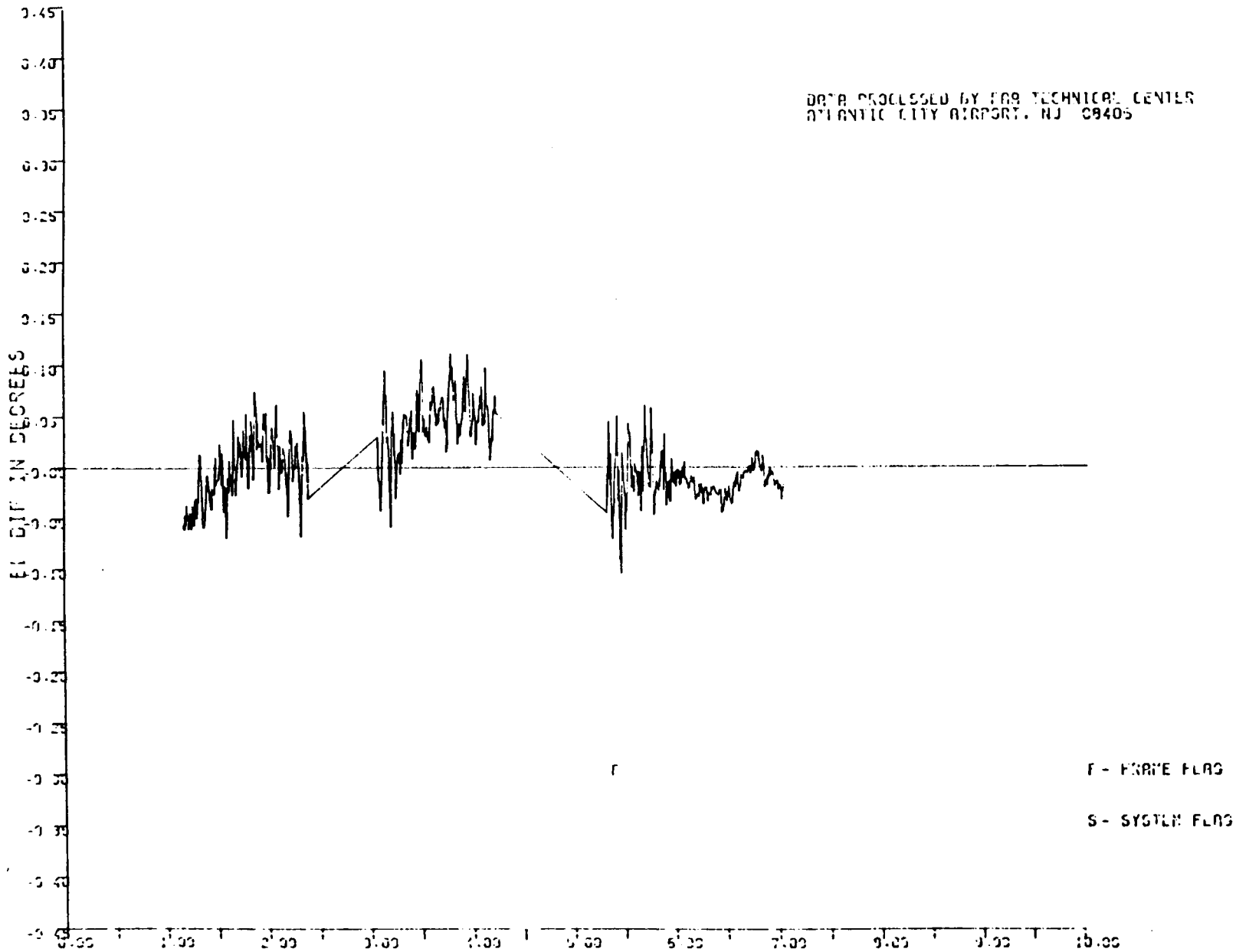

FIGURE 22 EL DIFF; RUN 1, APR 20, 1981, CL 3 DEG APP

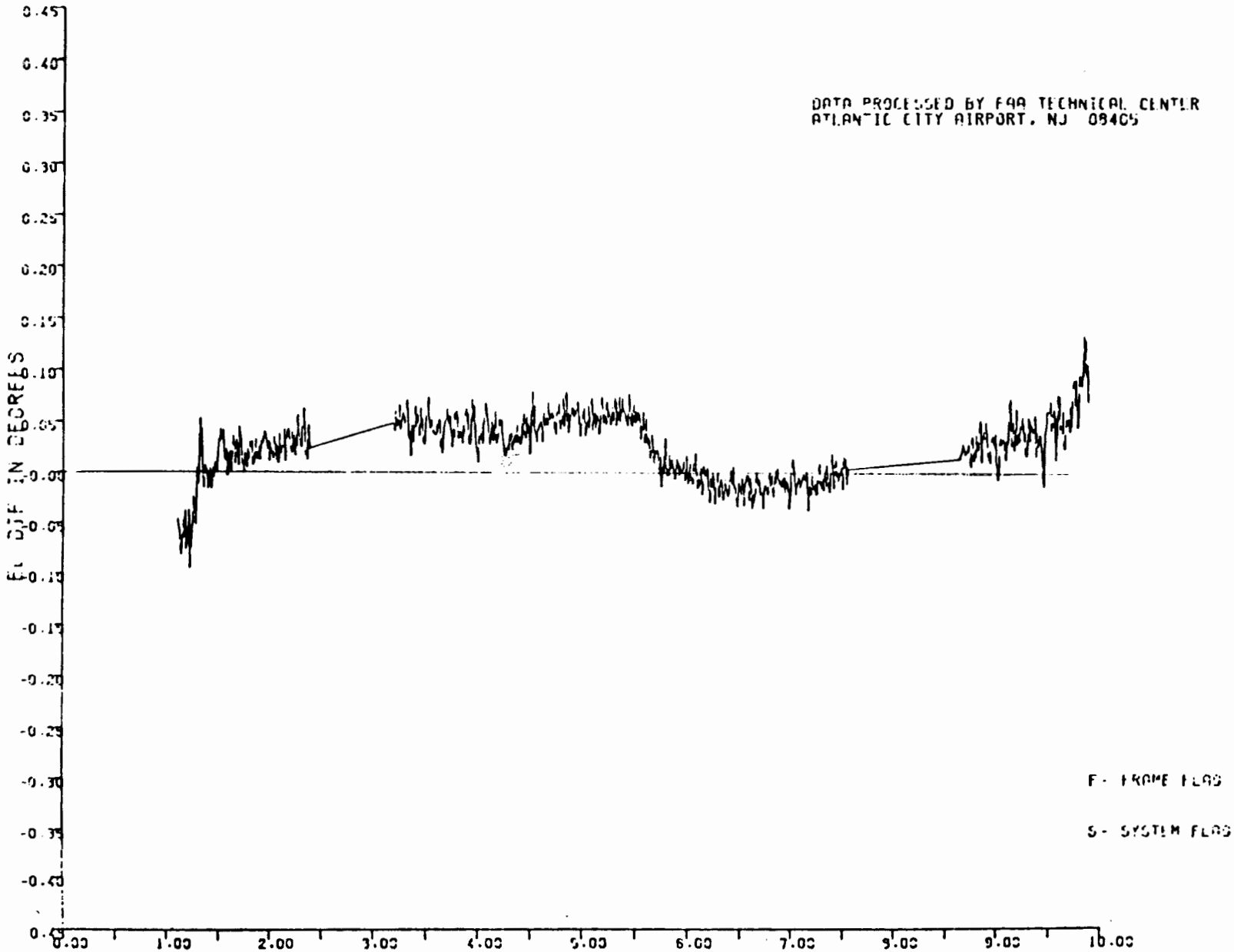

FIGURE 23 EL DIFF, RUN 3, MAY 13, 1981, CL 6 DEG APP

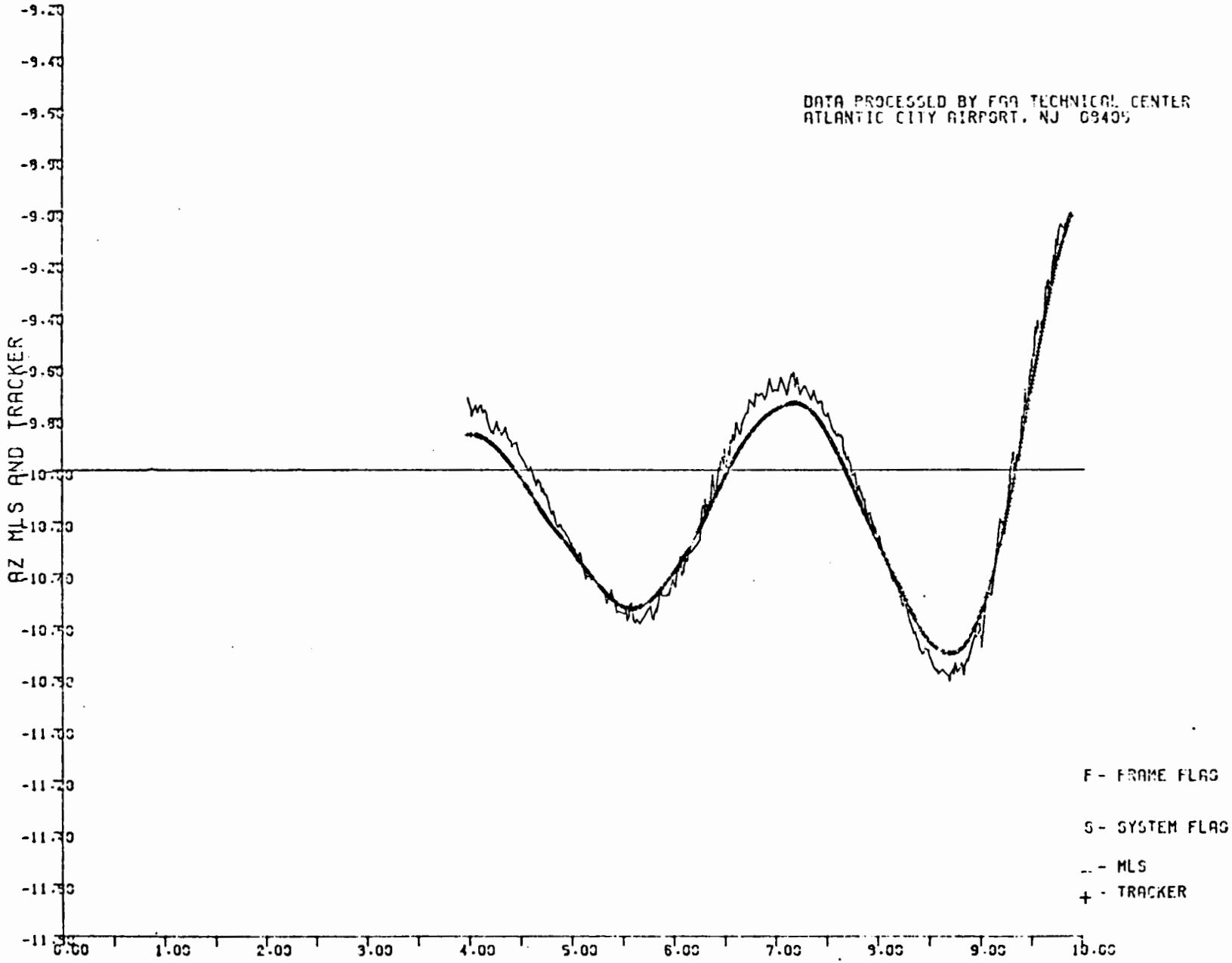

FIGURE 24 AZ; MLS AND TRACKER; RUN 11, MAR 31, 1981, 10R RADIAL 3000 FT

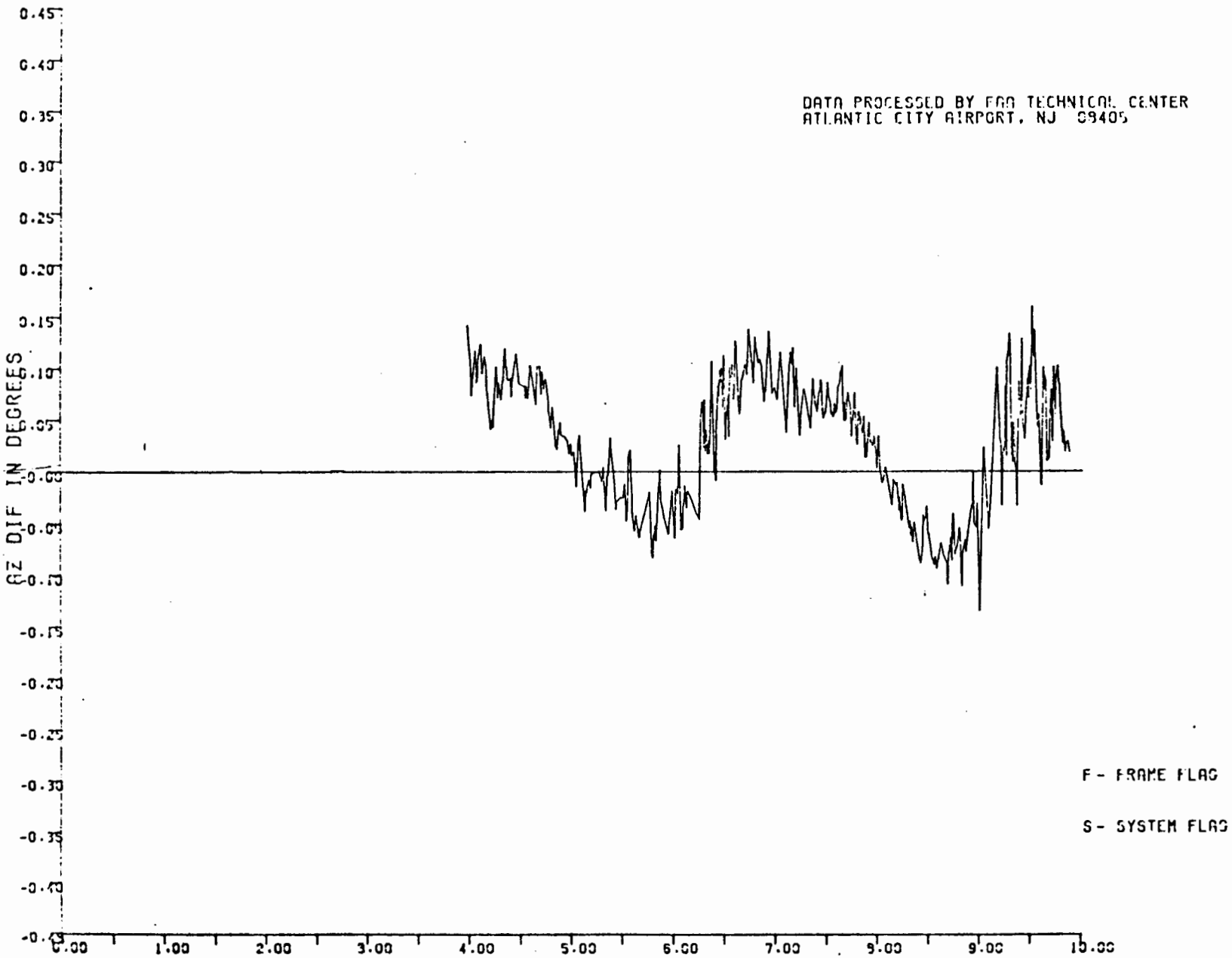

FIGURE 25 AZ DIFF; RUN 11, MAR 31, 1981, 10R RADIAL 3000 FT

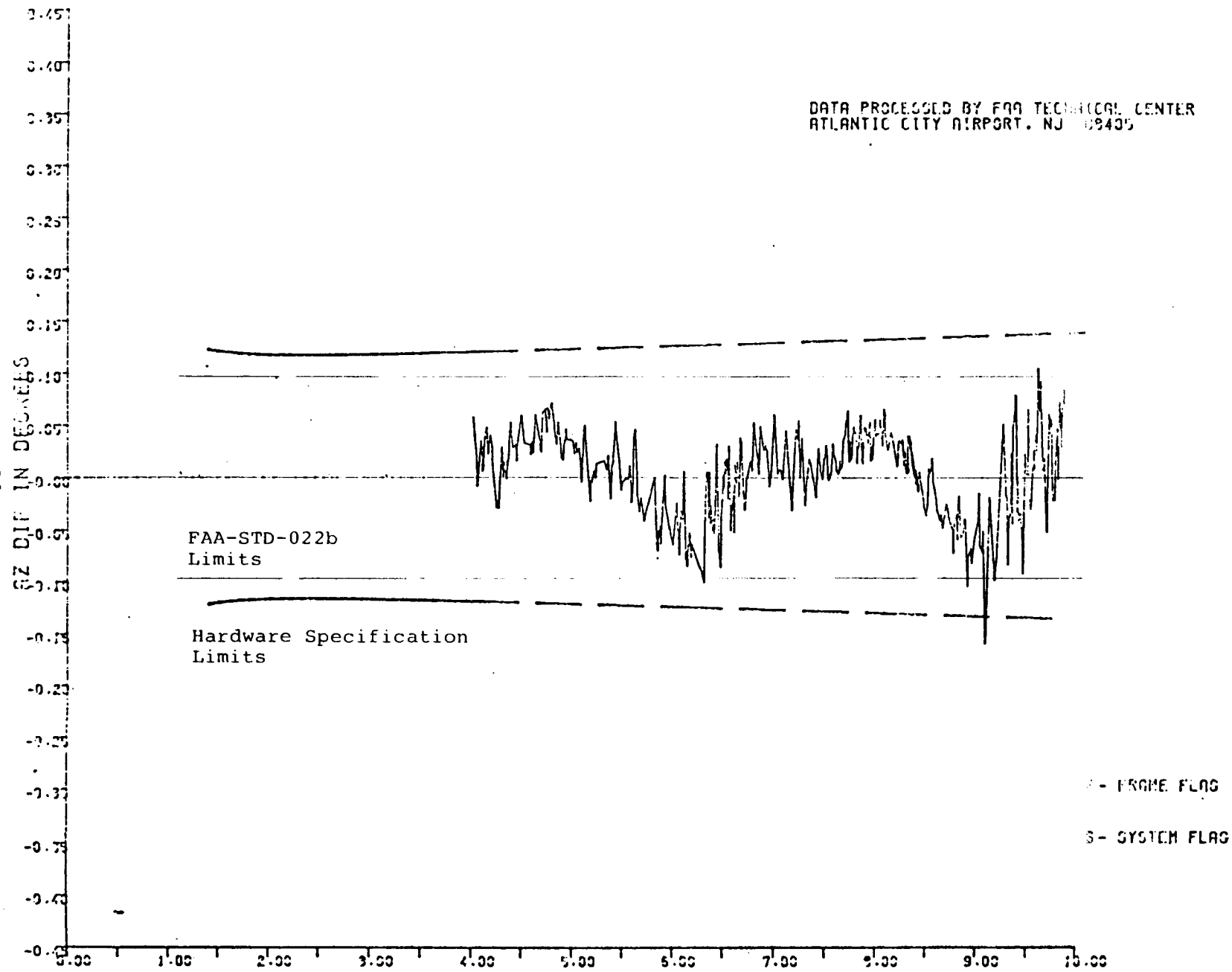

FIGURE 26 AZ DIFF; RUN 11, MAR 31, 1981, 10R RADIAL 3000 FT

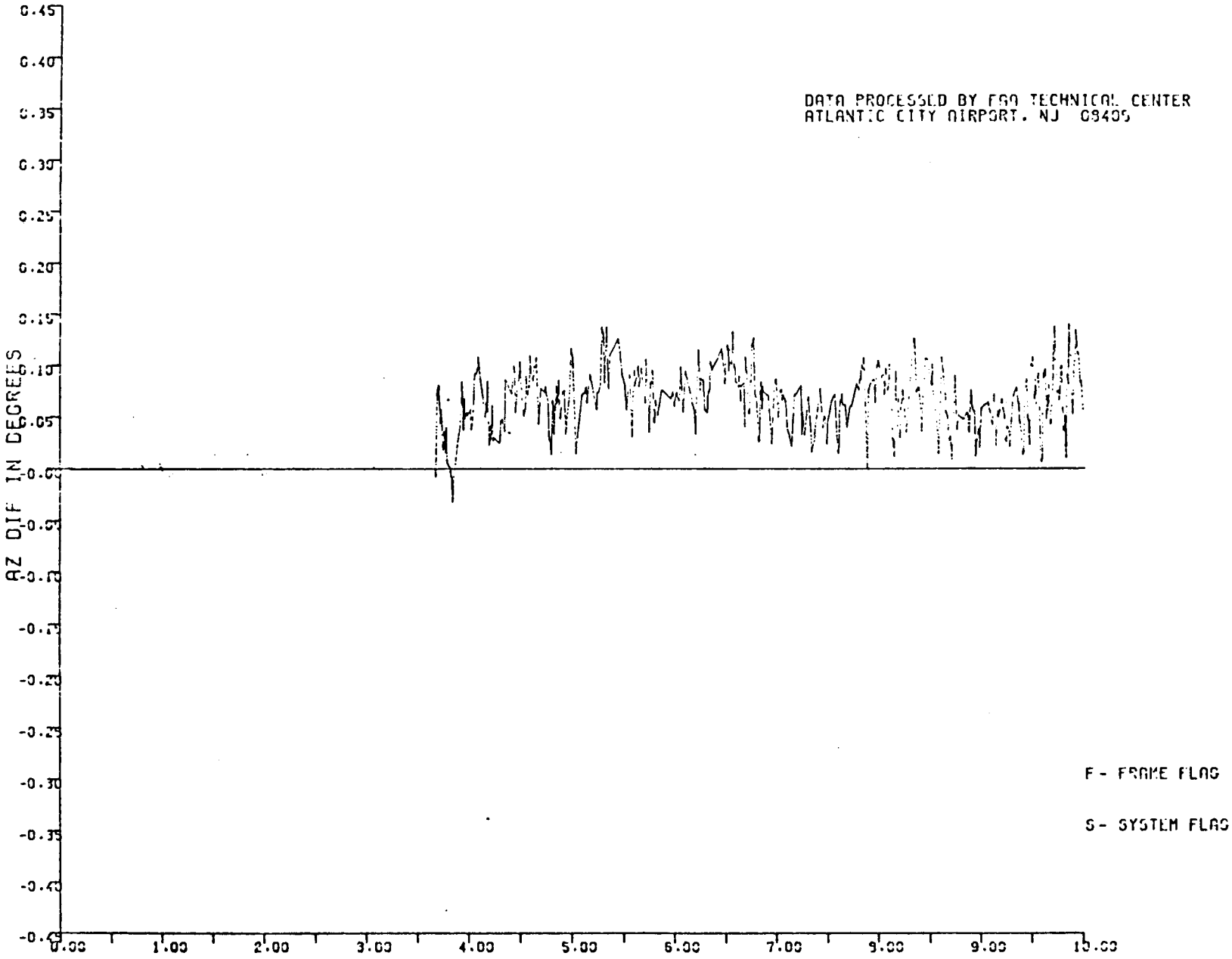

FIGURE 27 AZ DIFF; RUN 10, MAR 31, 1981, 5R RADIAL 3000 FT

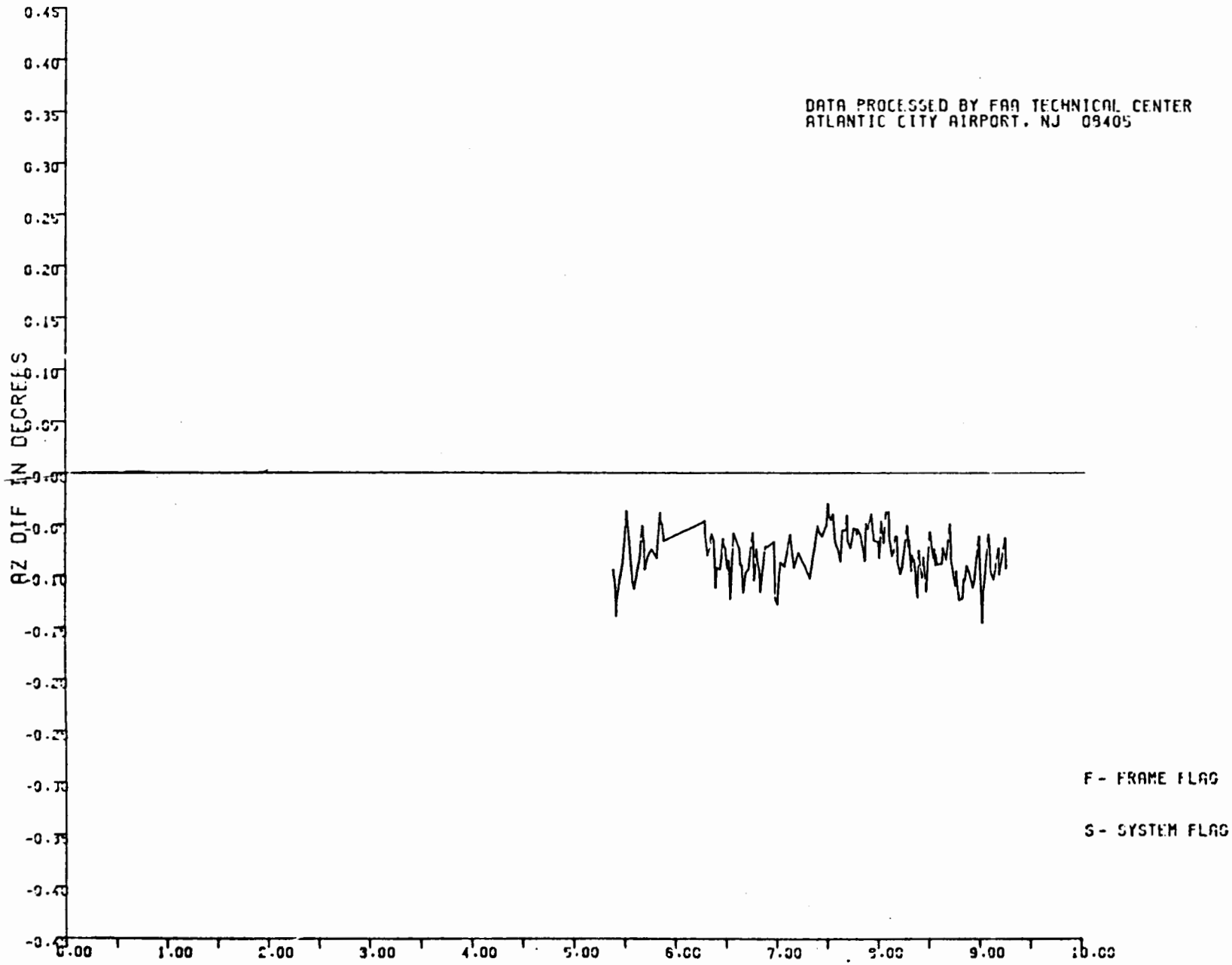

FIGURE 28 AZ DIFF; RUN 2, APR 15, 1981, 5L RADIAL 3000 FT

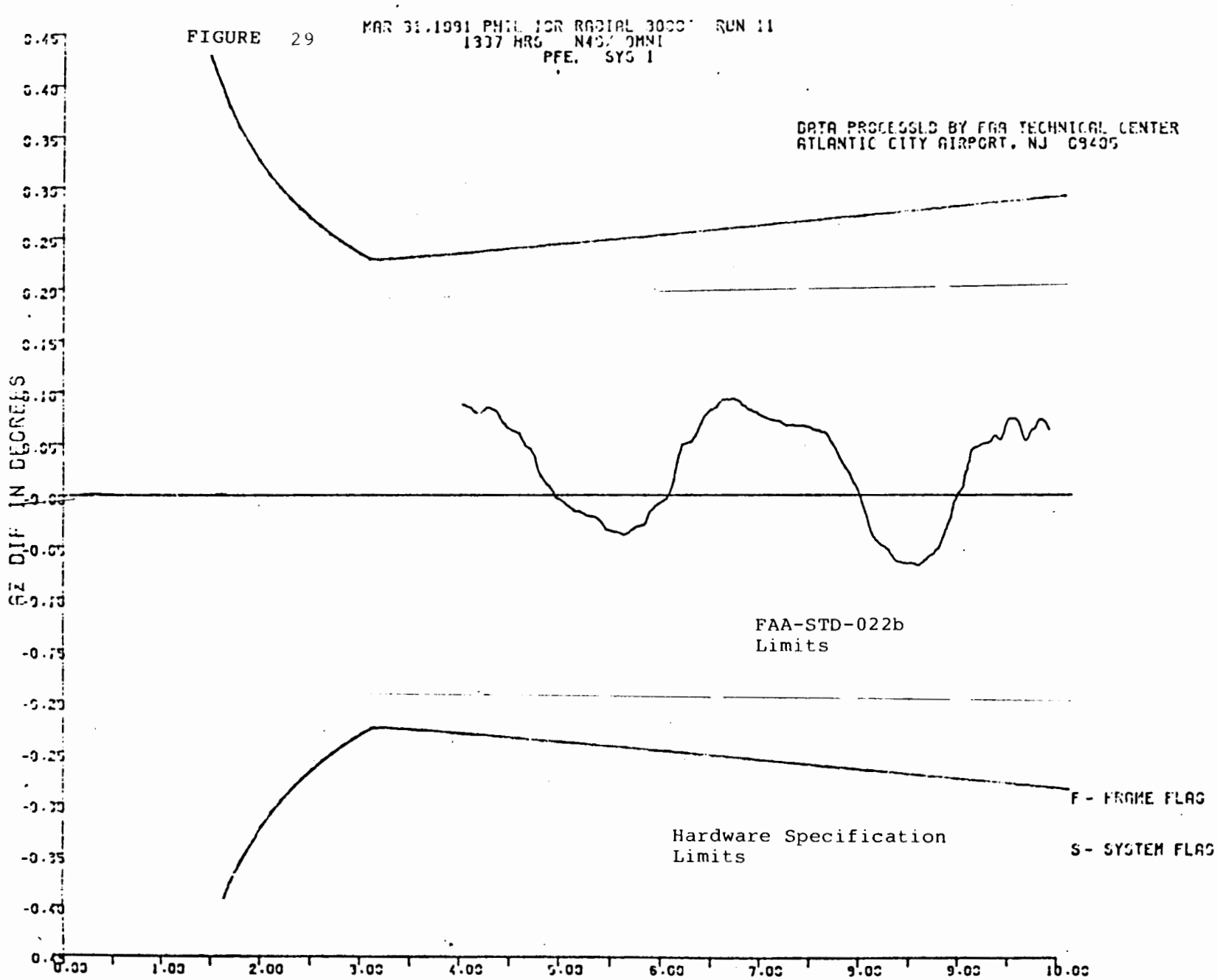

FIGURE 29 AZ DIFF; RUN 11, MAR 31, 1981, 10R RADIAL 3000 FT; PFE

b. Control Motion Noise (Radial). Control motion noise was within specs for all radial runs, although higher in amplitude than when previously tested at the FAA Technical Center. Some low frequency error effects are evident which cannot be considered "noise", similar to that evident on the centerline approaches. Figure 30 for a 10 degree R radial is a typical plot of CMN with a low frequency effect. The noise level on radials is about 1/2 the level experienced during approaches and is considered due to the different multipath environment (propeller path) between level radial and approach descents.

3. ORBITAL RUNS. There were 12 orbital runs made, all at a range of 6 nm, at altitudes of 2k, 3k, 4.5k and 8k feet yielding a range in elevation angles of from 3 to 15 degrees from the azimuth site. The runs were both clockwise (R-L) and counter clockwise (L-R). These runs test the coverage requirements and indicate beam pointing errors. Two counter clockwise runs out of four runs at 2000' lost track (tracker) at about 6° before centerline until well after centerline.

At the higher altitudes, the aircraft was out of elevation coverage and thus indicated a very large elevation angular error. One azimuth plot at the 8000' level (above 15 degrees) indicated a weak signal by a number of frame flags, apparently due to the beam pattern rolloff.

The scale, measured in time, is greatly different on these plots than on either radial or centerline approach runs. Assuming the same speed (e.g., 250'/sec) the aircraft moves almost 4 degrees on the orbital plots while only about 0.4 nm in 10 seconds, as scaled on the radial and centerline approach plots. This is a factor of about 4 to 1 and makes the orbital noise frequency appear much lower.

a. Azimuth Path Following (ORB). The orbital flight patterns measure the azimuth beam pointing errors. It can be seen from the azimuth error plot, Run 6 of 13 May 1980 (Figure 31) that guidance down the -1 degree radial would yield a 0.175 degree PFE. For reference, the pointing errors measured at the factory at 3° elevation have been superimposed on a flight data plot, showing good agreement. Radial flights were run on centerline and 5 and 10 degrees on either side of center-line, where the errors are indicated to be within tolerances.

The PFE were within tolerance for all runs, deviating at times due to the data processing filter initialization. This can be seen on Figure 30 which is the PFE plot from Run 6 of 13 May 1980. Referring to Figure 31, it can be seen that the error plot (at 10 degrees) does not indicate such a deviation within the coverage volume. Where these deviations occur, the test aircraft is always first entering the coverage area.

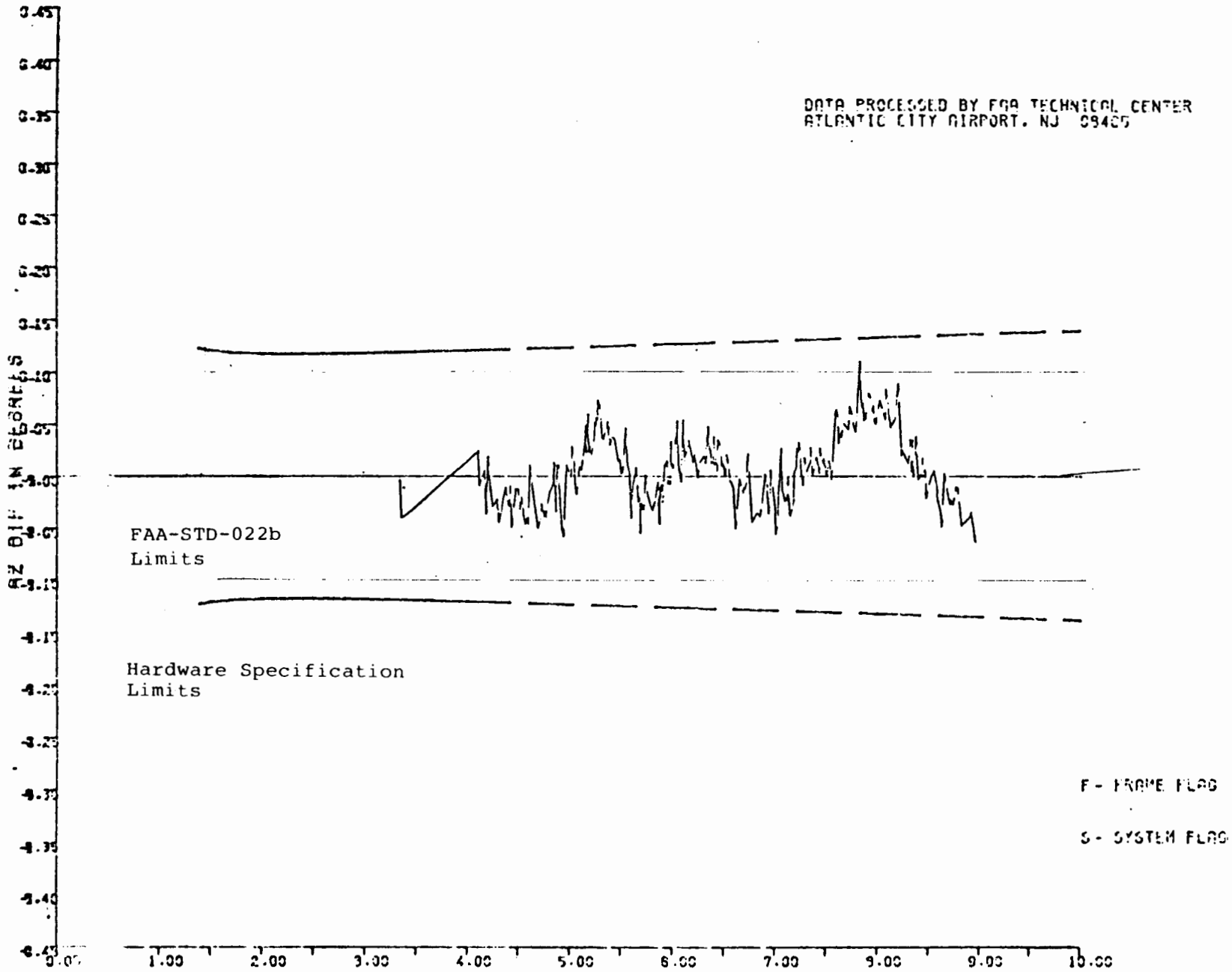

FIGURE 30 AZ DIFF; RUN 5, APR 15, 1981, 10R RADIAL 3000 FT; CMN

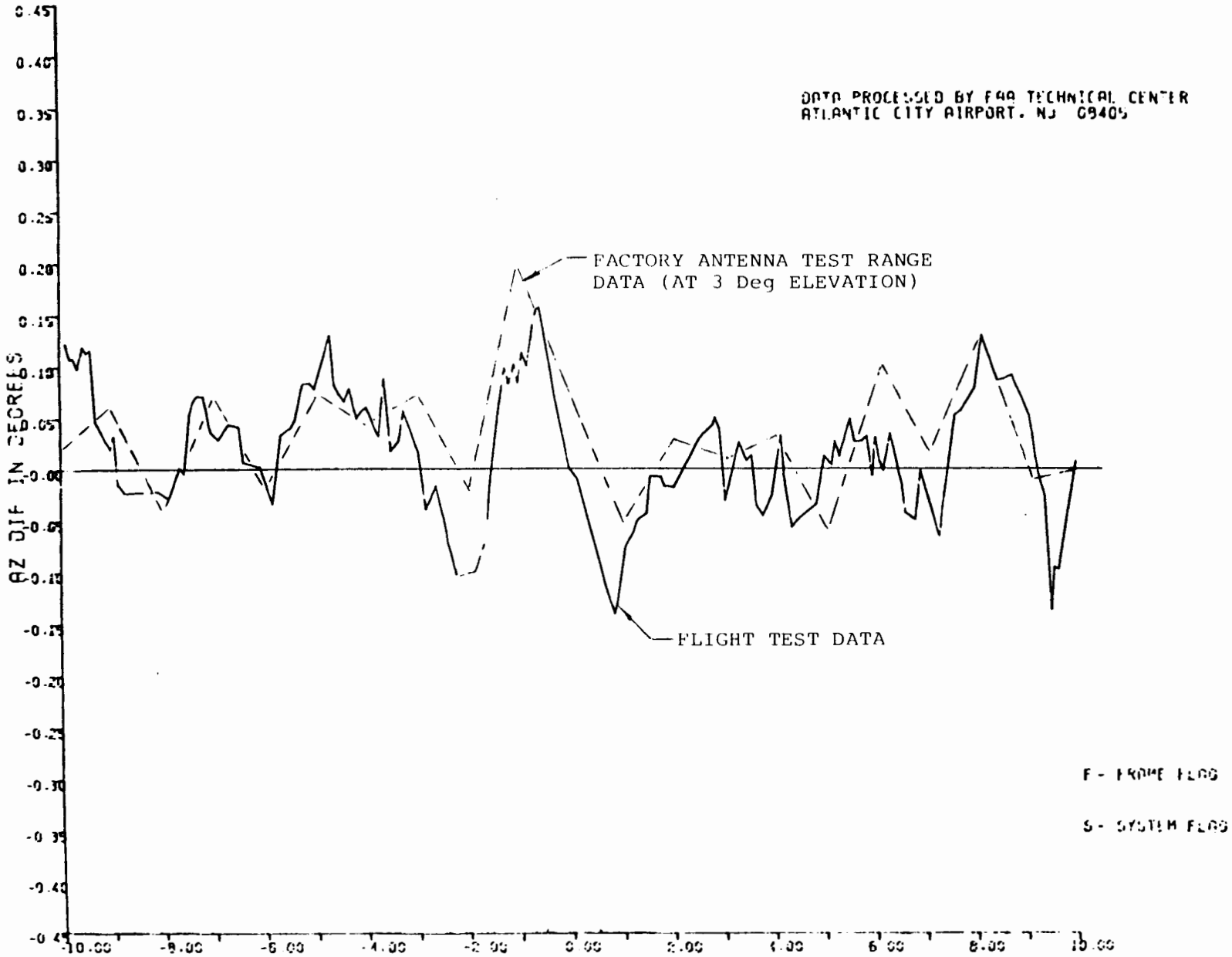

FIGURE 31 AZ DIFF; RUN 6, MAY 13, 1981, 6NM CCW ORB 3000 FT
(WITH FACTORY ANTENNA TEST DATA SUPERIMPOSED)

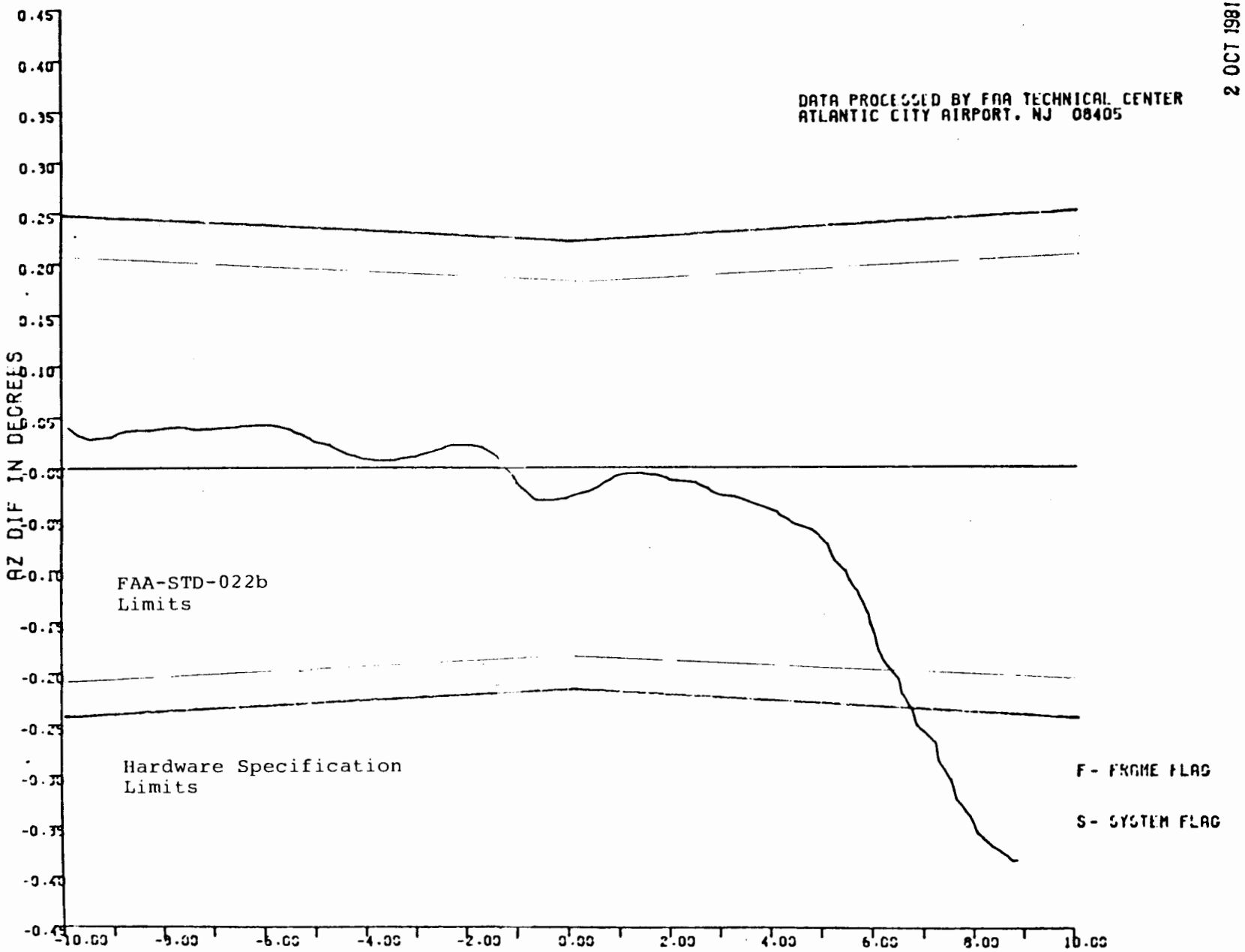

FIGURE 32 AZ DIFF; RUN 6, MAY 13, 1981, 6NM CCW ORB 3000 FT; PFE

Around centerline, where the 0.1° error per degree of angle linearity requirement (FAA-STD-022b) applies, large error changes are noted in Figure 31. These are calculated as 0.18° error per degree of angle or larger.

b. Azimuth Control Motion (ORB). Figure 33 from Run 5 of 13 May 1980 indicates two out-of-tolerance conditions on a single cycle of about eight seconds duration. This would be representative of a noise frequency of 0.13Hz, about 0.8 radians/s. This is well within the CMN band which includes frequencies from 0.3 to 10 radians/s. These excursions are due to azimuth beam pointing errors.

c. Elevation Path Following Error (ORB). The PFE were all within tolerance except for the 8000' runs where the aircraft was out of coverage. At the 4500' level, the elevation had a positive bias but was still well within tolerances as indicated by Figure 36 for Run 9 or 15 April 1981. The "clean" appearance of the error is typical of the orbital runs.

d. Elevation Control Motion Noise (ORB). The control motion noise was within tolerance for all runs. Almost all the raw error frequency spectrum was included as CMN as can be seen from Figures 37 and 38 of the raw error and the CMN for Run 8 of 15 April 1981. The CMN indicated a positive bias in Figure 38, probably caused by early initialization but should not be considered a part of the "noise".

Elevation noise appeared to be at a lower frequency than the radial or centerline approaches. However, taking into account the time scale differences, it was computed to be about the same. The noise moderated somewhat near centerline and the bias error was low at the important lower angles (3-6 degrees). Some of the higher angle orbits had no error plots, caused by the aircraft being above the highest scan angle. However, apparently the aircraft was receiving and recording the highest scan angle. Figure 35, Run 10 of 15 April 1981, indicates the types of errors encountered under these conditons.

4. Comparison with Previous Data. Figure 31 (page 45) shows orbital flight data for the azimuth. Also plotted on that figure is the factory antenna range data taken at an elevation angle of 3°. This is a degree or two below the elevation angle on the orbit, but the two sets of data show a good correlation. The lapsed time was about 4 years and the system was installed at the FAA Technical Center before being moved to Philadelphia.

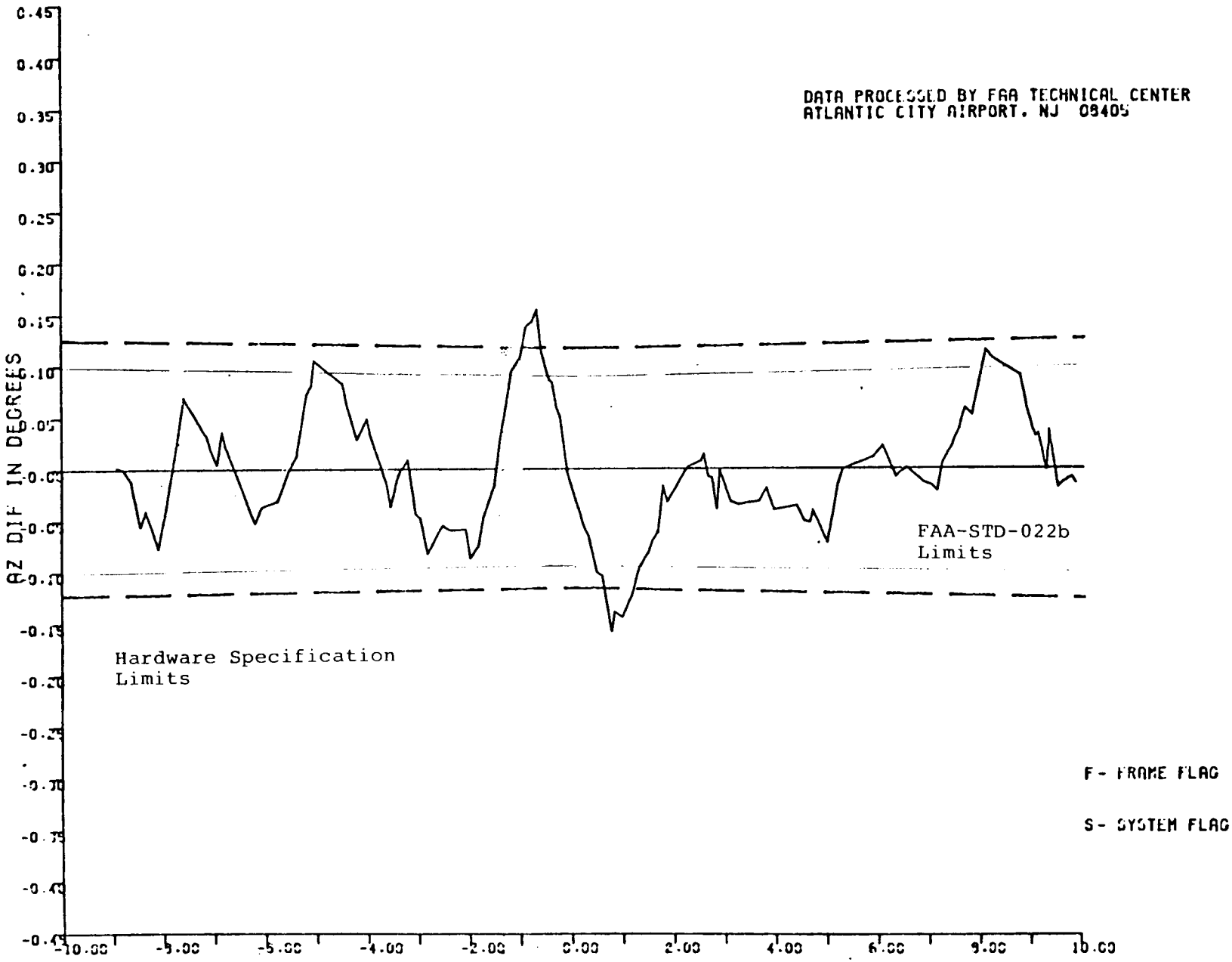

FIGURE 33 AZ DIFF; RUN 5, MAY 13, 1981, 6NM CCW ORB 3000 FT; CMN

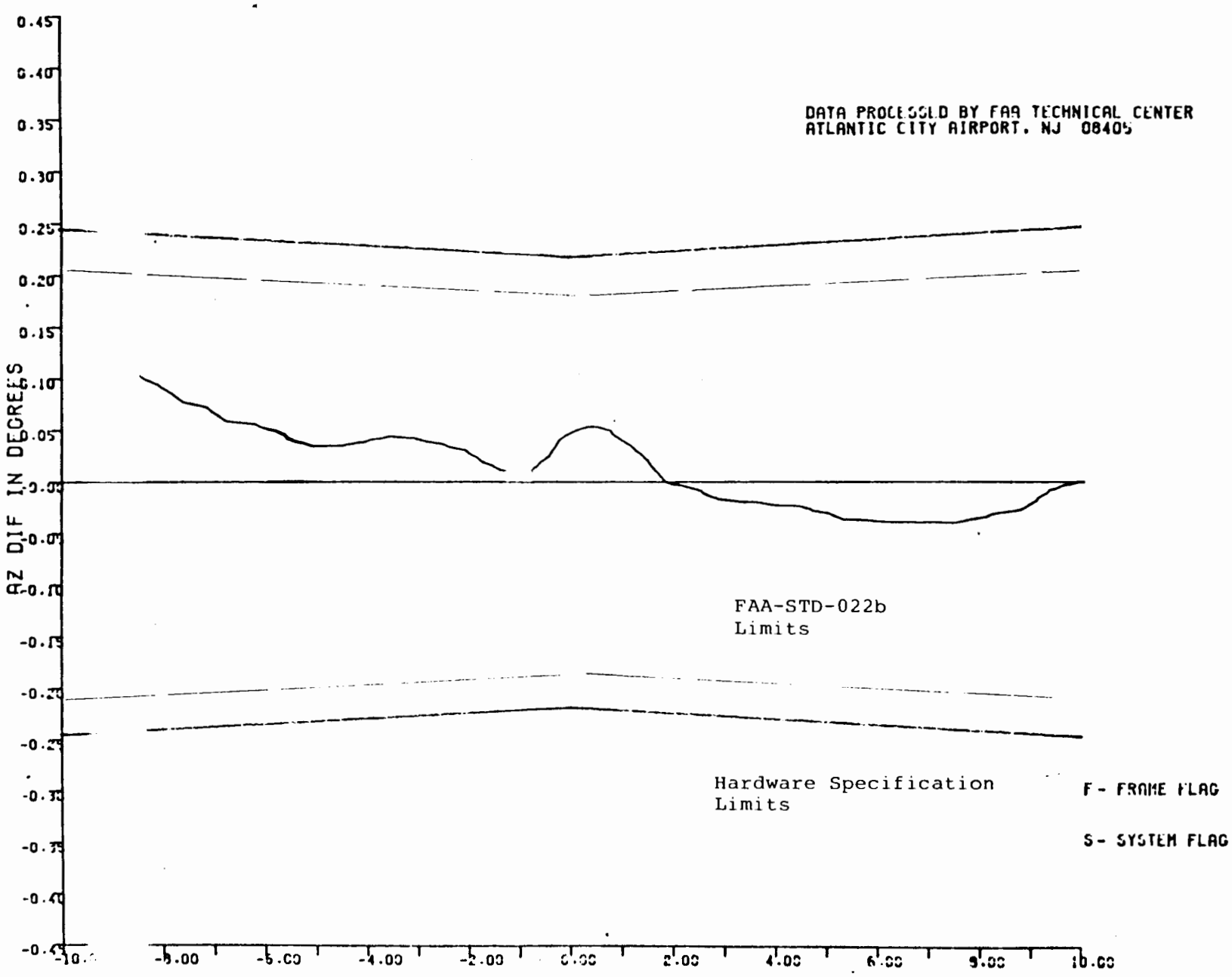

FIGURE 34 AZ DIFF; RUN 5, MAY 13, 1981, 6NM CW ORB 3000 FT; PFE

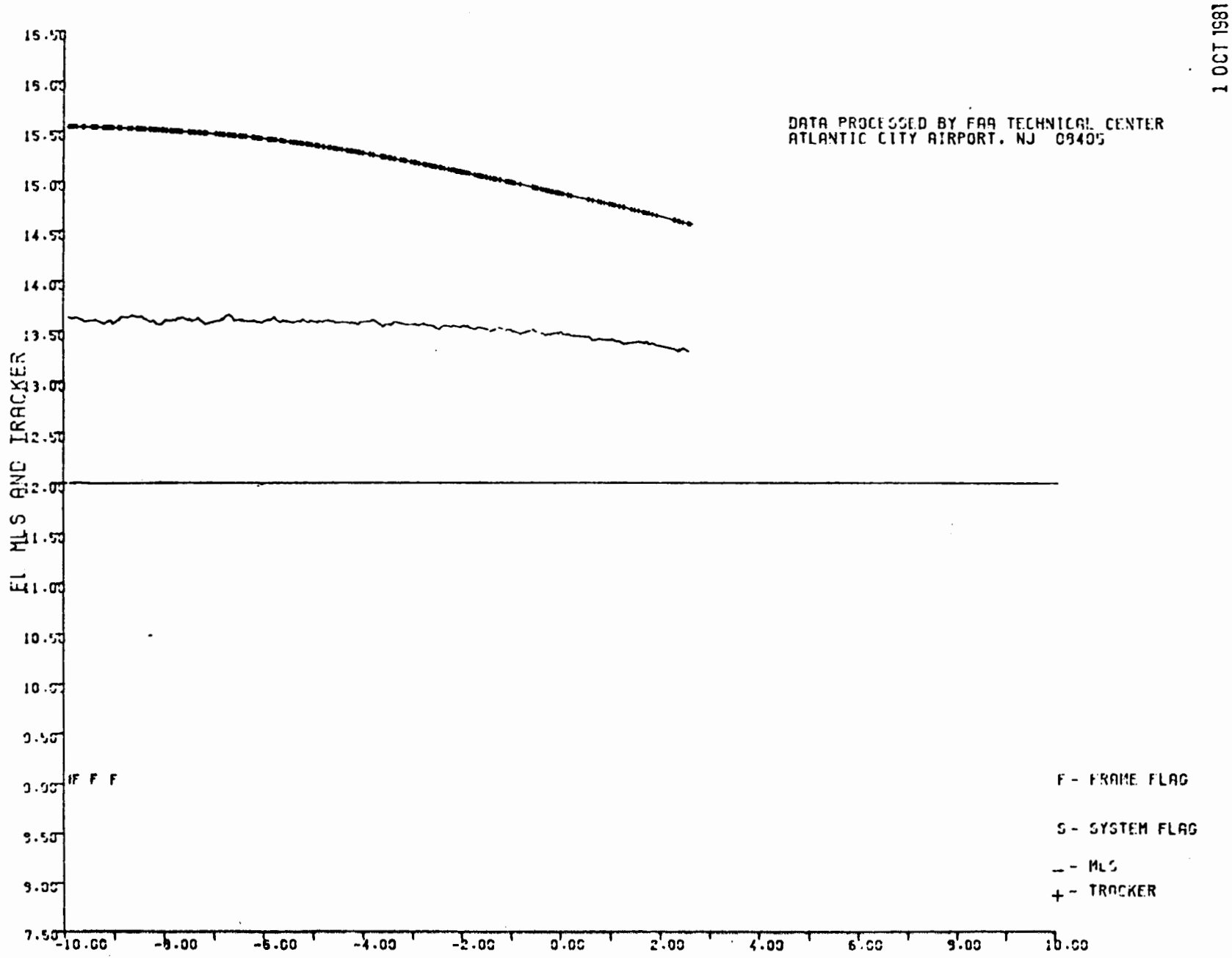

FIGURE 35 EL DIFF; RUN 10, APR 15, 1981, 6NM CW ORB 8000 FT

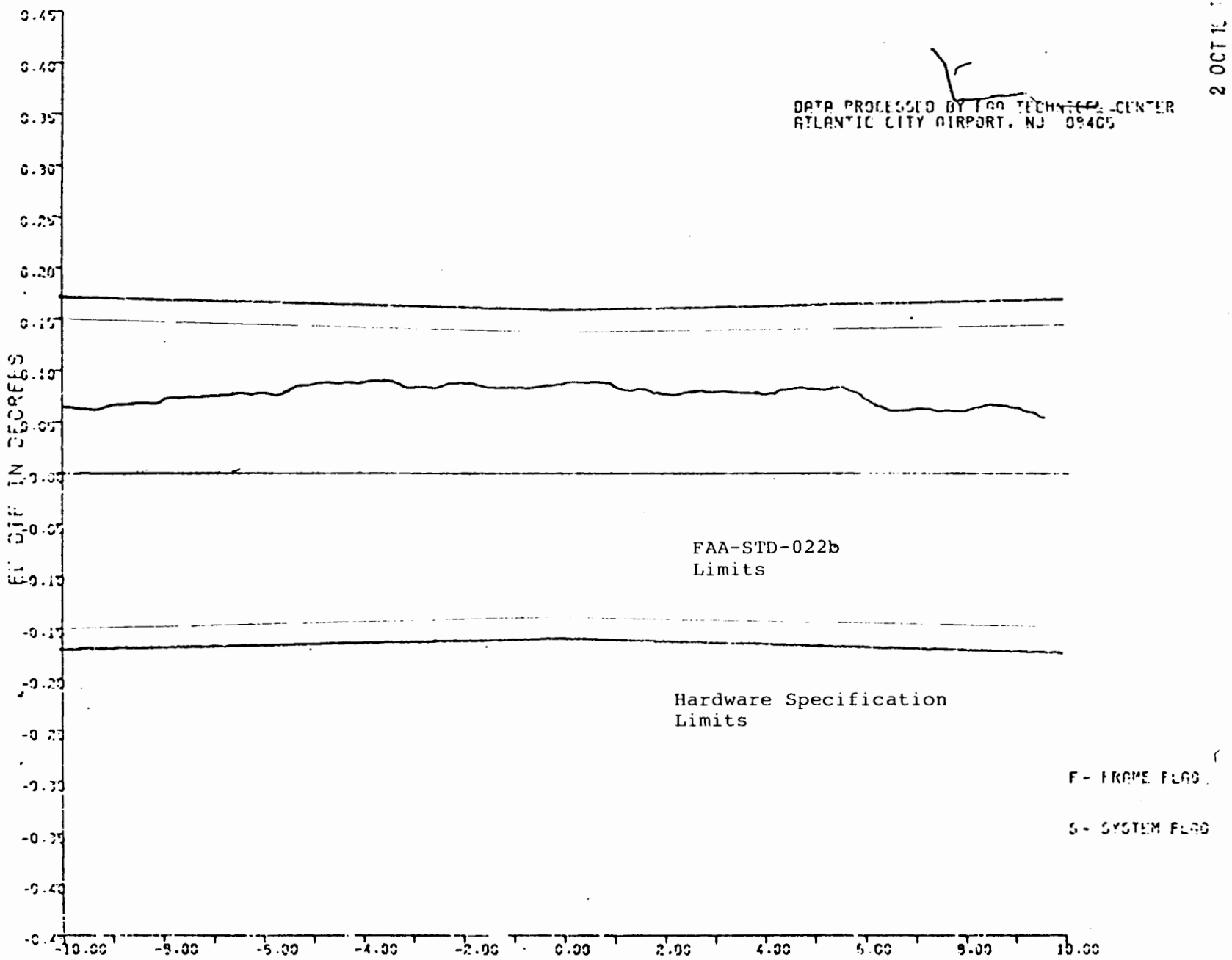

FIGURE 36 EL DIFF; RUN 9, APR 15, 1981, 6NM CCW ORB 4500 FT; PFE

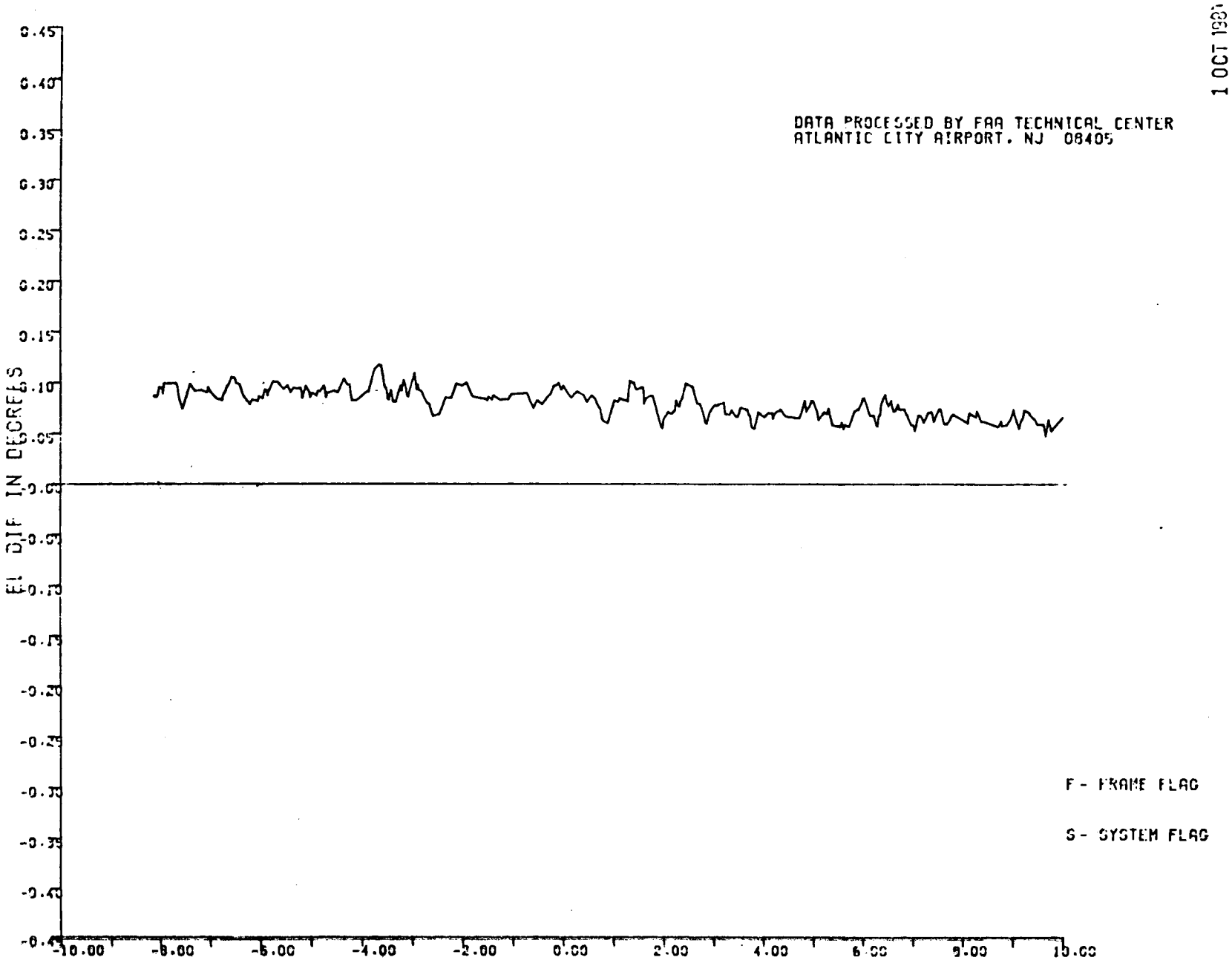

FIGURE 37 EL DIFF; RUN 8, APR 15, 1981, 6NM CW ORB 4500 FT

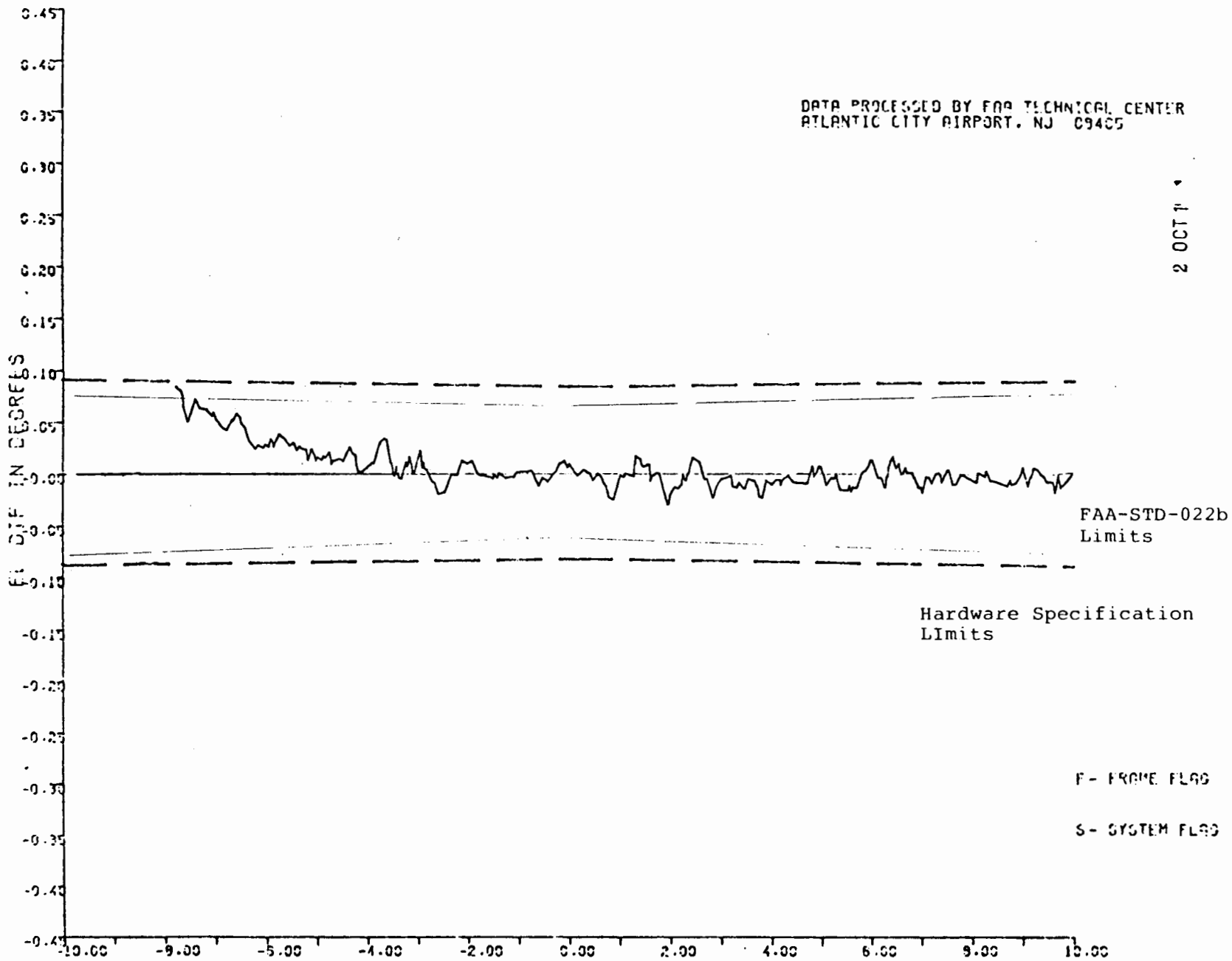

FIGURE 38 EL DIFF; RUN 8, APR 15, 1981, 6NM CW ORB 4500 FT; CMN

The Philadelphia flight data are noisier than the flight data taken at the Technical Center. The radial data are taken as an example because of the apparent propeller induced noise on the approaches. See Figures 24, 25, and 26 (10° R radial) at Philadelphia and Figures 39, 40, and 41 (9° R radial) at the Technical Center, N.J. The source of the extra noise is not identified here. Some factors may be:

- the system reliability seems to be low and problems difficult to find and fix;
- different installation/environment;
- different ground based tracker (theodolites at Tech Center, laser at Philadelphia; and
- some change in the airborne MLS receiving antenna/installation.

D. CONCLUSION

The Texas Instruments MLS installed at Philadelphia probably met the FAA-STD-022b performance requirements for PFE and CMN, if the apparent propeller induced noise effects are discounted. However, one requirement not met is for linearity, which (within ±0.5 degree laterally of centerline) requires the slope of the mean angle errors shall not exceed ±0.1 degree error per degree of angle.

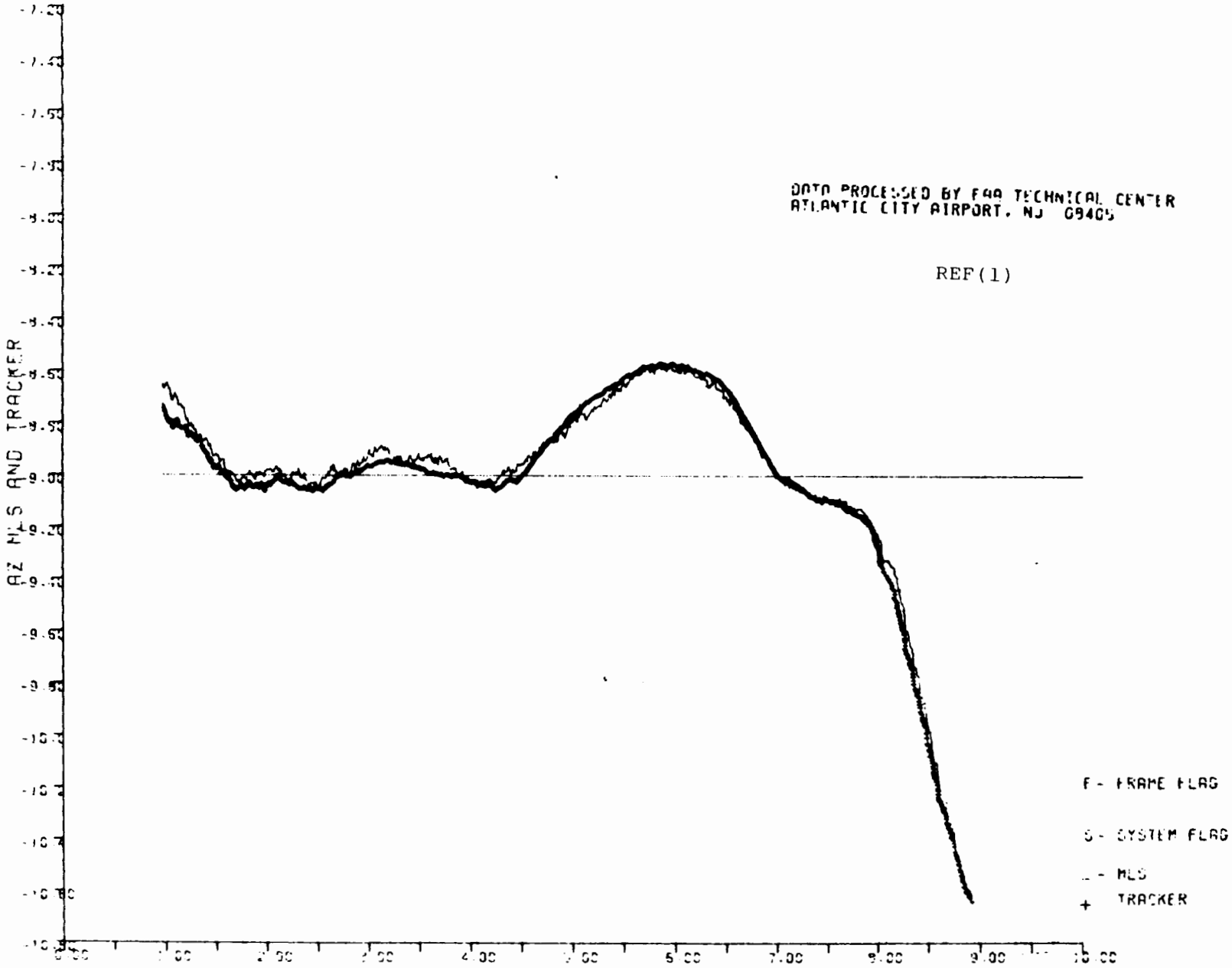

FIGURE 39 AZ; MLS AND TRACKER; RUN 7, AUG 21, 1978, 9R RADIAL (AT ATLANTIC CITY, NJ)

79-34-A-61

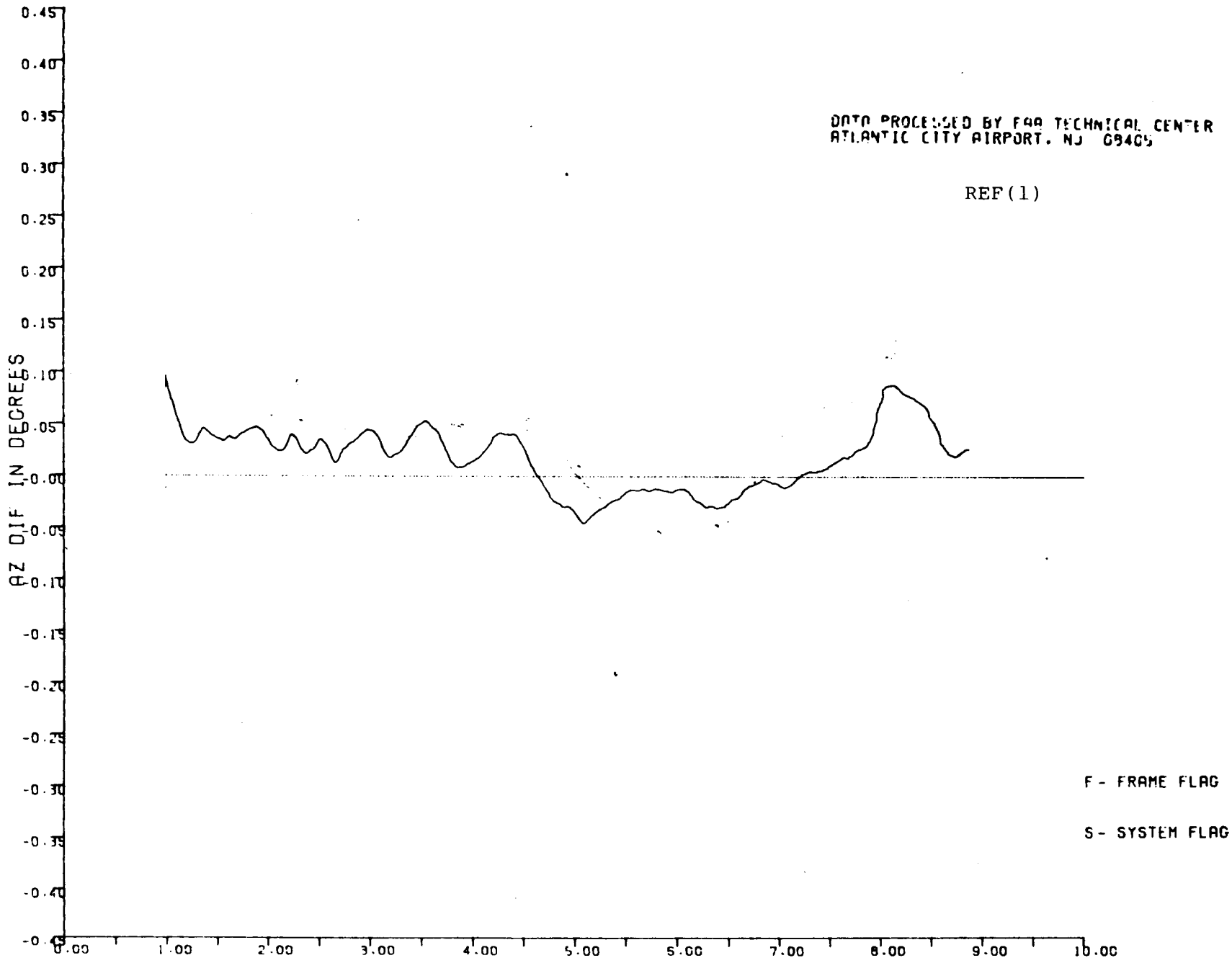

FIGURE 40 AZ DIFF; RUN 7, AUG 21, 1978, 9R RADIAL (AT ATLANTIC CITY, NJ) PFE

79-34-A-62

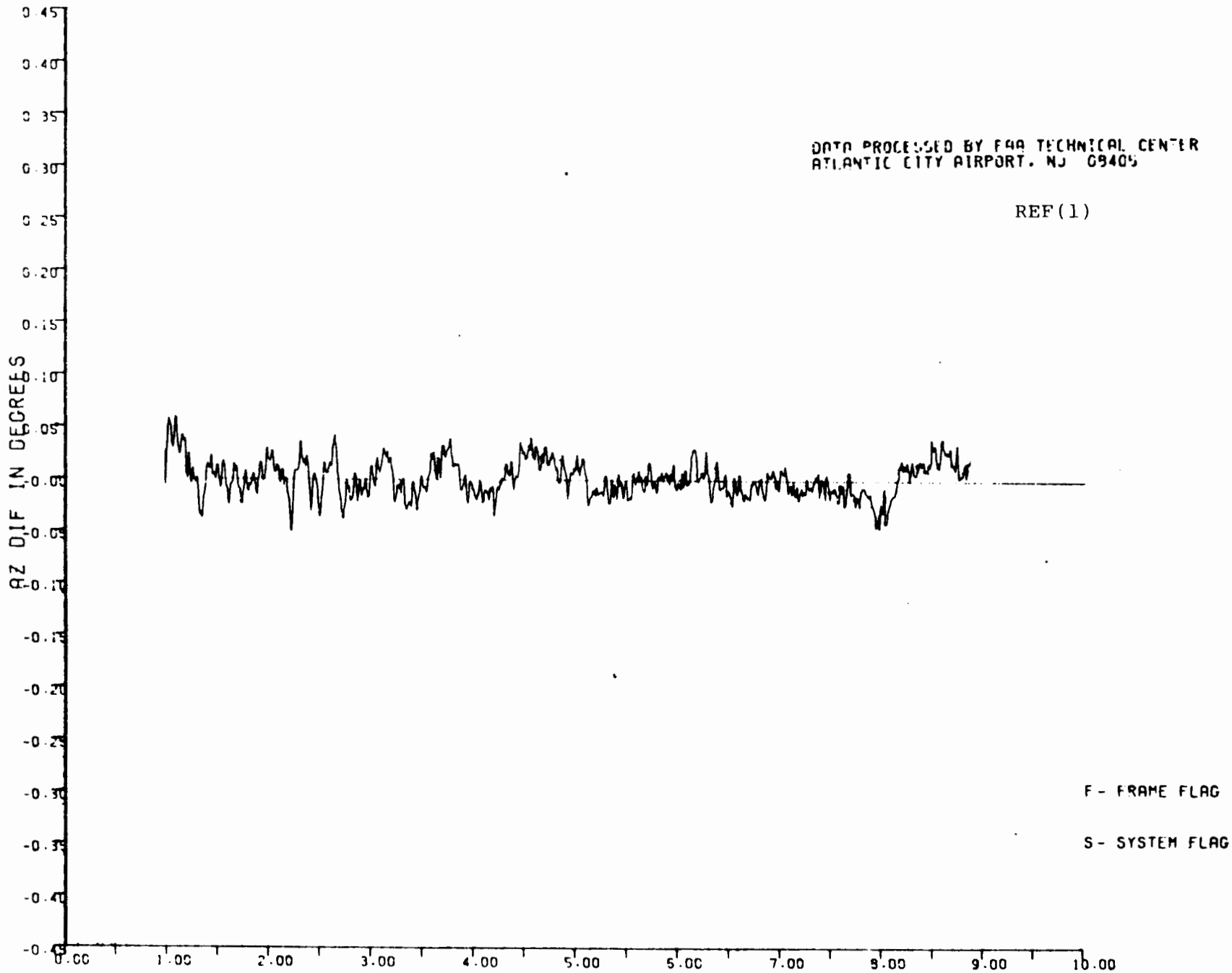

FIGURE 41 AZ DIFF; RUN 7, AUG 21, 1978, 9R RADIAL (AT ATLANTIC CITY, NJ) CMN

79-34-A-63

III. References

1. Test and Evaluation of Texas Instruments Small Community Microwave Landing System, Report No. FAA-RD-80-49; FAA-NA-79-34; May 1980 John Warren, NAFEC, Atlantic City, N.J. 08405

2. FAA-STD-022b; October 27, 1983; Microwave Landing System (MLS) Interoperability and Performance Requirements

3. TI. 6850.18; Instruction Book; Small Community Microwave Landing System (MLS); Texas Instruments Incorporated.

APPENDIX A

DIGITAL COMPUTER PROCESSING/FILTERING FOR ERROR COMPONENTS

The transfer function of the analog low pass filter used to extract the Path Following Error (PFE) from the raw data is:

$$H(S) = W_n^2/(S^2+2W_nS+W_n^2)$$

where, for AZ: $W_n = 0.78$ rad/sec and

for EL: $W_n = 2.34$ rad/sec

Implementation of this analog filter for computer processing is based on approximating an integral by the trapezoidal rule and Z-transform theory ("Digital Signal Processing," A. Oppenheim and R. Schafer). By making the following substitutions, the difference equation for the corresponding digital filter will result:

$$S = \frac{2}{T}\,\frac{(1 - Z^{-1})}{(1 + Z^{-1})}$$

$$Y(Z) = H(Z)\ X\ (Z)$$

$$X_{n-1} = X(Z)Z^{-1}$$

$$Y_{n-1} = Y(Z)Z^{-1}$$

where the Y's are the calculated filter outputs and the X's are the measured input values.

T is the sampling period (assumed constant)

$$Y_n = (4+4W_nT+W_n^2T^2)^{-1}\ (W_n^2T^2)\Big\{(X_n+2X_{n-1}+X_{n-2}) + (8-2W_n^2T^2)Y_{n-1}-(4-4W_nT+W_n^2T^2)Y_{n-2}\Big\}$$

AZ: $T = 2/13.5$
EL: $T = 2/40.5$

The filter is started by initializing all values to the first angular error difference measurement.

After the data filtered, they are compared to the 2-sigma maximum specification limits.

These Control Motion Noise (CMN) errors are generally of a frequency too high for the aircraft to track, but low enough for the control system to respond to. Thus, CMN results in rapid small-amplitude control surface shell and column motions and is undersirable in that it contributes to control surface and servo wear and diminishes flight crew confidence by presenting them with a "shaky stick". The transfer function of the bandpass filter used to extract the CMN error from the raw data is:

$$H(s) = \frac{S}{(S+W_1)} \quad \frac{W_2}{(S+W_2)}$$

AZ: $W_1 = 0.3$ rad/sec, $W_2 = 10$ rad/sec (3-dB points)

EL: $W_1 = 0.5$ rad/sec, $W_2 = 10$ rad/sec (3-dB points)

The corresponding digital filter difference equation is:

$$Y_n = (4 + 2W_1T + 2W_2T + W_1W_2T^2)^{-1} \left\{ 2W_2T\,(X_n - X_{n-2}) + (8 - 2W_1W_2T^2)\,Y_{n-1} - (4 - 2W_1T - 2W_2T + W_1W_2T^2)\,Y_{n-2} \right\}$$

Note that the $\frac{W_2}{(S+W_2)}$ term is the low pass filter term which may already be built into the receiver output.