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C-Band Radar Calibration Using Geos-3

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W.B. Krabill
and
C.F. Martin

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W.B. Krabill
Wallops Flight Center
Wallops Island, Virginia

and

C.F. Martin
EG&G, Washington Analytical Services Center, Inc.
6801 Kenilworth Avenue
Riverdale, Maryland

NASA
National Aeronautics and
Space Administration

Wallops Flight Center
Wallops Island, Virginia 23337
AC 804 824-3411

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SECTION 1.0
INTRODUCTION

C-Band radars have been used for more than 30 years for the determination of trajectories of rockets, spacecraft, aircraft, and various other objects, obtaining direct real time measurements of range, azimuth, elevation and, in a number of cases, range rate. Although varying somewhat with different applications, data utility depends, of course, upon the measurement noise level and upon the level of various systematic errors which can, to some degree, affect all measurement channels. Radar "calibration" is the process of determining the parameters which can be used to describe, and correct for, these systematic errors. When repeated over a period of time, it also determines the parameter stability and thus the need for frequent calibrations.

Before each mission, most radars undergo a static calibration (calibrating against targets at known distances and known directions). This process has several disadvantages, including

- The elevation angles are low, thus leading to potential clutter and multipath problems with angle calibration.
- The ranges are shorter than for most operations, leading to near field tracking and high signal strength returns which require the use of attenuators in the receiver circuits that are not used for normal tracking.
- Conditions are static, so that dynamic errors do not exhibit themselves.
- The radar timing system is not exercised.

These restrictions should be considered as somewhat limiting the accuracy achievable from static calibrations, rather than making them useless. Measurement biases, which can generally rather reliably be estimated from such calibrations, are usually the most significant error parameters and are among those most susceptible to time variation. But calibration parameters must also be correctly applied to measurements, frequently via software. It is thus highly desirable to have a radar's performance validated during an actual tracking mission. Otherwise, it may be necessary to accept the radar trajectory with no possibility of validating it even for gross errors which occasionally do arise.

C-Band radar calibration in the past has been performed with the use of several satellites, with the GEOS-2 satellite having been the most extensively used. GEOS-2 carried C-Band transponders to provide higher return signal strength for radars tracking and was used for various C-Band calibration activities up until the launch of GEOS-3 in April 1975.

The primary advantage of satellite calibration, or the checkout of a radar via satellite tracking, is the unforgiveness of Newton's laws. That is, the data taken during a satellite pass (~10-15 minutes for a typical GEOS-3 pass) must be consistent with the laws of orbital mechanics and, if the data does not fit an orbit, there is a problem with the radar data* or its preprocessing (assuming, of course, that the data reduction program does not have problems and that the data reduction run is set up properly). Determining the particular error source for a given anomalous set of data may not be particularly simple, but each radar systematic error source

*The process also is unforgiving to radar operators. Generally, the flipping of any switch during a pass is visible in the data. Frequently, variations in any operating conditions or switch settings from one day to the next are also visible in the data.

produces a calculable pattern in the measurement residuals for a pass.* Based on the pattern, the number of possible error sources can be greatly narrowed, and multiple passes with different geometries can be used to further pin down the true errors.

Another advantage of satellite calibration is that different systems can be readily intercompared, including systems of different types, such as radars and lasers. Such comparisons also bring into play the timing systems used at each site to apply time tags to the data. In many cases, timing problems at the sub-msec level are readily identified when data from different systems are used in the same orbital solution.

The GEOS-3 spacecraft added a new dimension to satellite calibration capabilities, with the inclusion in the spacecraft instrumentation of a coherent C-Band transponder, in addition to the non-coherent type of transponder utilized on GEOS-2. This allowed, for the first time, the satellite checkout of the range rate data channel on many of the C-Band radars. This dynamic checkout mode has proved itself to be quite valuable in evaluating not only biases, but data timing as well, even within the radar system itself.

In this report, summaries are given of the C-Band radar calibration activities that have been performed by NASA/Wallops Flight Center, involving the analysis of data from some 25 C-Band radars around the world. These radars were operated by a number of agencies, including NASA, DOD (Air Force Eastern Test Range, Air Force Western Test Range, Pacific Missle Range, Kwajelin Missle Range), the Australian Weapons Research Establishment, and the Deutsche Forschungs und Versuchsanstalt für Luft und Raumfahrt. Some of these agencies have performed

*The ORAN error analysis program [1] has been developed, in part, to calculate such patterns. For typical patterns, see Ref. [2].

extensive analyses of their own C-Band data, including that from a number of specially scheduled GEOS-3 tracks. In addition, several GEOS-3 investigators have performed data intercomparisons that included C-Band analysis. Although this report considers primarily work that has been performed at Wallops Flight Center, efforts have been made to maintain cognizance of results of the various analyses. In particular, a series of interagency GEOS-3 C-Band Working Group meetings were held during the first two years of operation of GEOS-3. Calibration techniques and results were reviewed at these meetings.

The report is organized by type of calibration, rather than by radar. In addition, certain calibration activities have been documented in detail elsewhere, and will only be summarized here.

SECTION 2.0
RANGE CALIBRATION - TECHNIQUES AND RESULTS

The overall radar calibration effort using GEOS-3 has emphasized range calibration, since range measurements normally provide the most accurate position coordinate at satellite distances. In fact, orbital solutions from radar data are frequently performed using only range data, due to the low weight which the angle data would have in the solution. On the other hand, the fact that orbits can be determined from range data to accuracies considerably higher than normal angle accuracies means that satellite tracking is a very fruitful method for calibrating angles. Angle calibration results will be considered separately in Section 4.

Before considering actual calibration, it is of some interest to examine the general nature and origin of radar biases. Radars are generally ground calibrated prior to each mission, which means that they are zero set* to be consistent with surveyed ranges to calibration targets. These targets are normally the equivalent of skin tracking targets, in that they return a pulse of the same length that they receive. Since most of the C-Band radars are centroid trackers,** the calibration range measured is based on the transit time of the pulse centroid to the target. In fact, however, the return pulse from GEOS-3 is of a fixed width, independent of the width of the received pulse. The relative pulse times are illustrated in Figure 1, assuming the leading edge of the received pulse to be quite sharp, and to initiate a return after a fixed delay which is only beacon dependent.

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*In fact, these zero sets are normally applied during data pre-processing, but the equivalent of making measured ranges equal to surveyed ranges is still done. Beacon delay is also included in the pre-processing.

**Only one radar analyzed was not a centroid tracker.

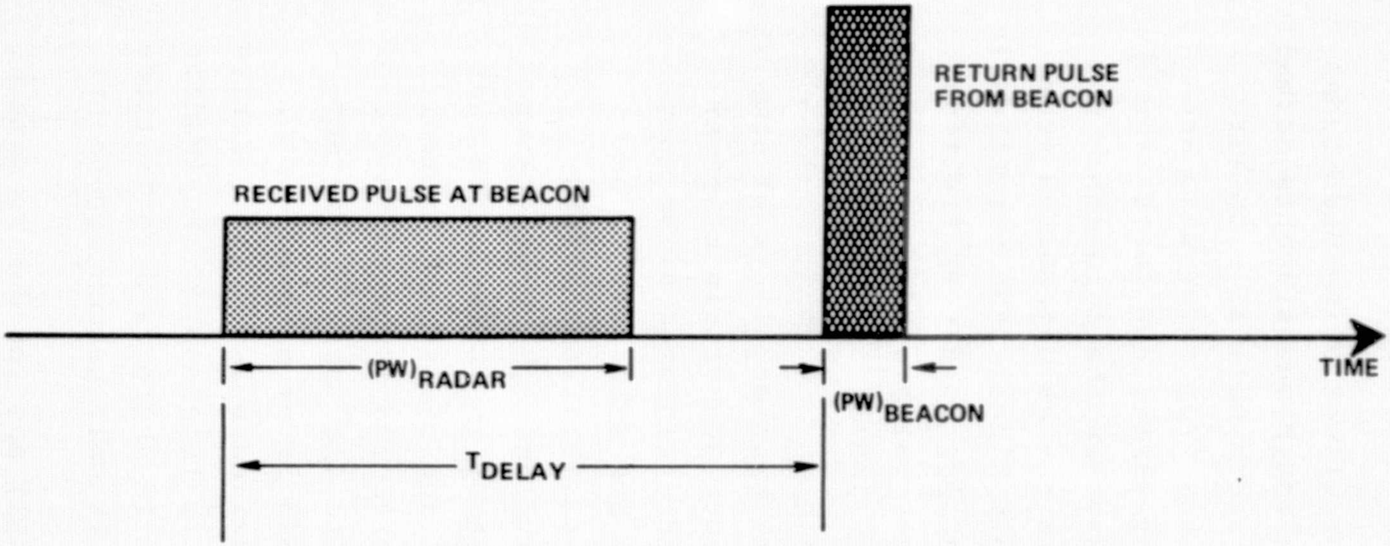

FIGURE 1. SIMPLIFIED TIME RELATIONSHIP OF RECEIVED AND TRANSMITTED PULSES AT SATELLITE BEACON

Considering that the radar actually measures the return time of the centroid of the pulse from the satellite beacon, although accounting for the known (pre-launch measured) beacon delay, the error in the measured range due to pulsewidth mismatch is

$$\Delta R = \frac{C}{2}\left\{\frac{(PW)_{beacon}}{2} - T_{delay} - \left[\frac{(PW)_{radar}}{2} - T_{delay}\right]\right\}$$

$$= \frac{C}{4}\left[(PW)_{beacon} - (PW)_{radar}\right] \qquad (1)$$

where

$(PW)_{radar}$ = radar pulse width

$(PW)_{beacon}$ = beacon pulse width

C = speed of light

T_{delay} = beacon delay

The nominal GEOS-3 coherent beacon pulsewidth is 0.5 μsec. Some radars, such as those on the Air Force Eastern Test Range (AFETR) cannot track in the matching nominal pulsewidth of 0.5 μsec, and they normally track with 1 μsec. For these radars, the nominal bias is expected to be

$$\Delta R = \frac{C}{4}\,[.5\text{x}10^{-6}\text{sec} - 1\text{x}10^{-6}\text{sec}] = -37.47 \text{ m}, \qquad (2)$$

and biases on this order have been observed for the AFETR radars. However, the GEOS-3 beacon pulsewidth is not exactly 0.5 μsec, and the actual radar pulsewidths do not exactly correspond to their dial settings, so a bias of a few meters could be expected from any radar solely on the basis of pulsewidth "mismatch." This mismatch is really no serious problem, and should be removable as simply as for beacon delay. It is, however, different for each radar, and may vary significantly after each major radar overhaul.

Several basically different types of orbital solutions have been used for radar bias estimation, ranging from the use of single station radar data alone to multiple station solutions in which the data from a particular radar has only a minimal effect on the estimated orbit. Several types of solutions have been exercised and will be discussed below.

2.1 TWO PASS MULTIPLE STATION SOLUTIONS

A number of calibrations of the Wallops Island and Bermuda radars were performed in support of the GEOS-3 altimeter calibration effort [3]. In general,* these solutions used the radar data taken from Wallops and Bermuda on two or three GEOS-3 satellite passes, with the solution for a radar bias for each station. The recovered range biases for the two Wallops radars are plotted in Figures 2 and 3 as a function of GEOS-3 revolution number. Because of daily adjustments to the Bermuda radar during this time period [4], these biases were stable only within a working day and are not plotted.

The Wallops Island FPQ-6 biases shown in Figure 2 have a mean value for 11 solutions of about -5 m, and a 1σ spread about the mean of less than a meter. Although there

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*Laser data from the NASA lasers at Goddard and Grand Turk was also used on several passes.

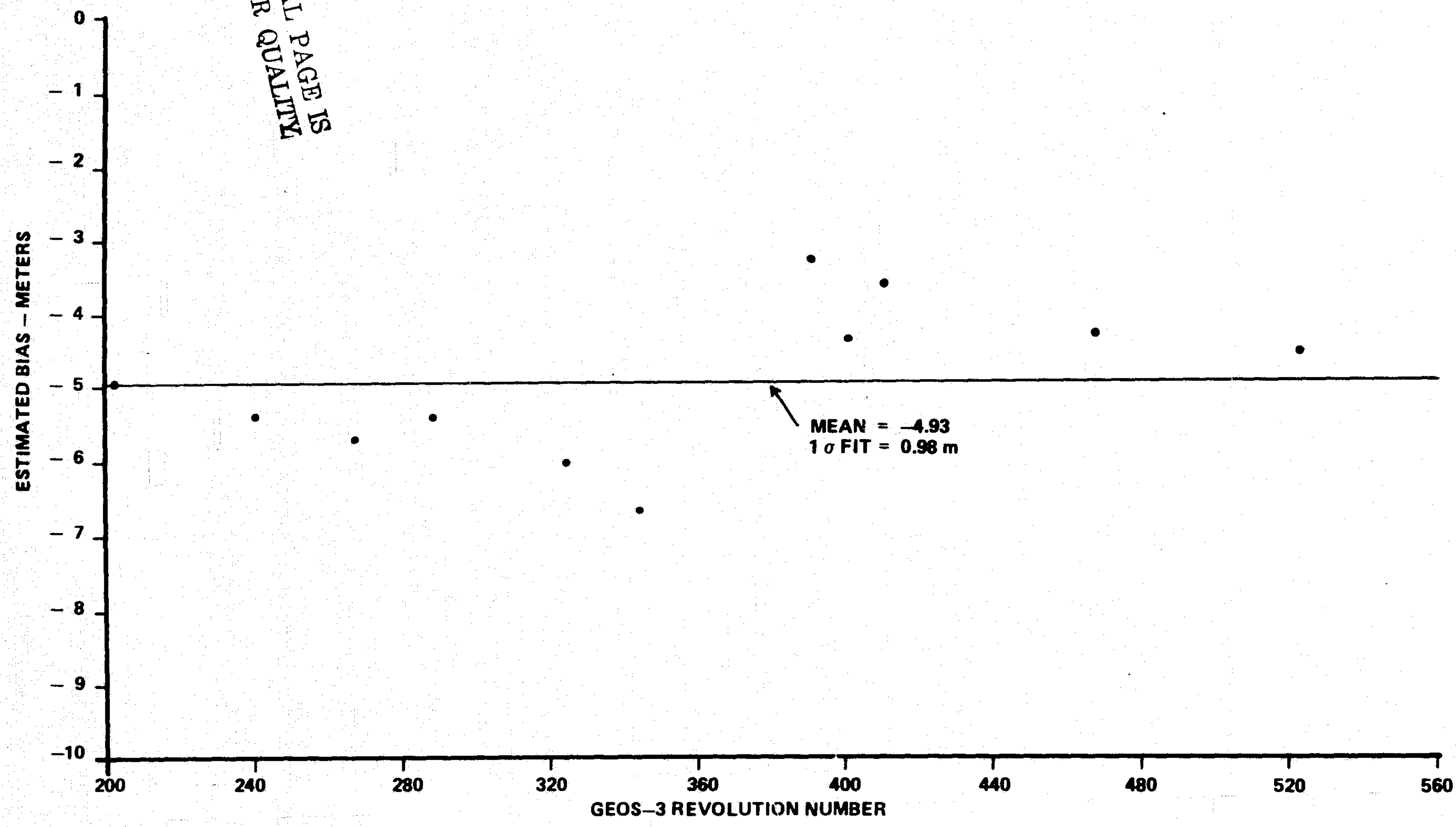

FIGURE 2. WALLOPS ISLAND FPQ–6 RADAR BIASES ESTIMATED FROM MULTI–STATION 1 AND 2 REVOLUTION SOLUTIONS

appears to be some slight increase in the biases during this interval, the time period is too short (~3 weeks) to reliably estimate a slope.

Figure 3 shows the 8 biases estimated for the same time period for the Wallops Island FPS-16 radar. These biases have a mean of -2.2 m, with a 1σ variation about the mean of some 73 cm. That the FPS-16 should be somewhat more stable than the FPQ-6 might be expected on the basis of the difference in the Range Machines for the two radars.*

Although the multi-station solutions produce bias estimates that are consistent between solutions, there may be systematic errors in all the recoveries. Primarily, systematic effects on the estimated biases would be expected from errors in the gravity model and station positions used.

2.2 TWO PASS SINGLE STATION SOLUTIONS

This type of calibration analysis involves an orbital solution which includes a single radar range bias, and the tracking data from two successive satellite passes. The global orbit estimated is not necessarily very accurate, but the orbital constraints are sufficient to allow a bias recovery which is limited primarily by the uncertainties in the geopotential model used, and not even greatly sensitive to this. Of course, if the radar bias is not stable from one pass to the next, the calibration results may not be meaningful for either pass. But there are indications that few of the C-Band radars involved in the GEOS-3 tracking program have pass-to-pass variations beyond the meter or so level.

*The FPS-16 has an Advanced Digital RANge (ADRAN) tracker.

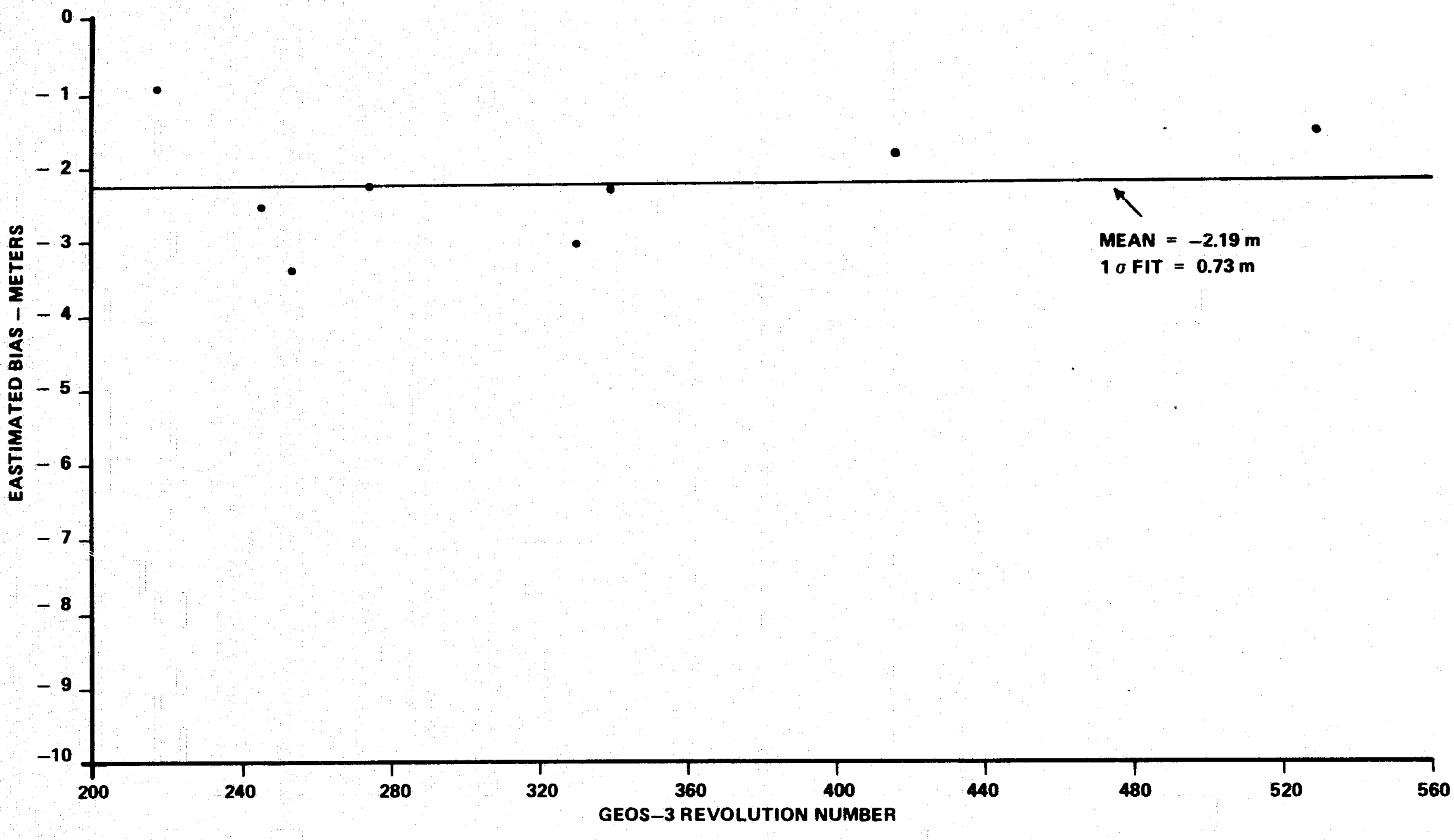

FIGURE 3. WALLOPS ISLAND FPS–16 RADAR BIASES ESTIMATED FROM MULTI–STATION 1 AND 2 REVOLUTION SOLUTIONS

The primary advantage of the single station calibration is, of course, that it allows self-calibration. No tracking data other than that for the single radar is used in the orbit and bias solution. There is no need to wait on S-Band or laser data to be received, pre-processed, reformatted, etc. In fact, with the use of limited data types and adjustment capabilities, special purpose calibration software can be developed which is sufficiently small to fit on many site computers. The radar site can maintain its own periodic calibration. In fact, this calibration can also include angles, since the two pass single station solution is generally accurate to within at least a few arc seconds within the coverage periods.

The error characteristics of single station two pass calibrations are typified by the ORAN sensitivities summarized in Table 1, a solution using two consecutive medium elevation passes, and a solution using a high elevation pass and a low elevation pass. As expected, both solutions are quite insensitive to station latitude and longitude errors. And both solutions are also insensitive to GM errors. The only error source contributing significantly to the medium elevation solution is gravity model error, with effects on the order of a meter to be expected. For the high elevation solution, gravity model errors appear to have a much lower effect, and the "dominant" error source is station height error. Even here, the effect is less than a meter for height errors near the maximum of what might currently be expected, even for an isolated station.

The individual pass sensitivities in Table 1 show the contribution of data from each pass in the overall bias solution. As might be expected, the solution including the high elevation pass is dominated by that pass. Thus, even if the bias for some reason is different on the second (or

TABLE 1. ESTIMATED ERROR CONTRIBUTIONS TO TWO PASS SINGLE STATION RANGE BIAS SOLUTIONS (Ref. 4)

		ERROR SOURCE AND MAGNITUDE						
	ELEV.	PASS ONE PASS BIAS 1m	PASS TWO PASS BIAS 1m	GRAVITY MODEL .10 APL-SAO	STA. λ 5m	STA. ϕ 5m	STA. h 5m	μ .2 ppm
SOLUTION 1	40^o 34^o	–1.56	.56	1.07	.00	.06	.30	–.05
SOLUTION 2	84^o 19^o	– .85	–.15	0.29	–.02	.11	.80	–.18

low elevation) pass, the estimated bias will still be very nearly that for the high elevation pass. The sensitivities for the medium elevation solution are somewhat different. Examples for both solutions are given in Table 2. The second solution, containing the high elevation pass, is seen to be a weighted sum of the two biases, if they are in fact pass-to-pass variable, but with much higher weight given to the high elevation pass. For Solution 1, however, the recovered bias will never be between two pass-to-pass varying biases, but will be approximately a meter away from the mean for each meter that either of the passes varies. However, the estimated bias is still closest to the true bias of the higher elevation pass.

Considering all error sources, we conclude that two pass single station calibration accuracy should be on the order of 1-2 m, with the accuracy most commonly determined by pass-to-pass stability. This uncertainty is somewhat higher than that observed above for the multi-station solution stability. However, some increase in sigma would be expected simply on the basis of less data input.

Figures 4 and 5 show a time history of Wallops FPQ-6 and Bermuda FPQ-6 biases, estimated primarily using the back-to back pass single station type solutions. In both cases, a linear variation of the biases with time has been assumed, and the lines best fitting this assumption determined. For the Wallops radar, the slope is ~4 cm/day, but with a 1σ scatter about this line which is slightly greater than 2 m. These results are consistent with an actual linear drift in the radar bias of 4 cm/day and the above estimates of the accuracy of the two pass single station calibrations, assuming

TABLE 2. BIAS RECOVERIES FOR DIFFERENT PASS GEOMETRIES WITH PASS VARIABLE BIASES

		CASE 1		CASE 2		CASE 3	
	MAXIMUM ELEVATION	TRUE BIAS	RECOVERED BIAS	TRUE BIAS	RECOVERED BIAS	TRUE BIAS	RECOVERED BIAS
SOLUTION 1	40^{o} (PASS 1)	0 m	0 m	1 m	1.56 m	0 m	–0.56 m
	34^{o} (PASS 2)	0 m		0 m		1 m	
SOLUTION 2	84^{o} (PASS 1)	0 m	0 m	1 m	0.85 m	0 m	0.15 m
	19^{o} (PASS 2)	0 m		0 m		1 m	

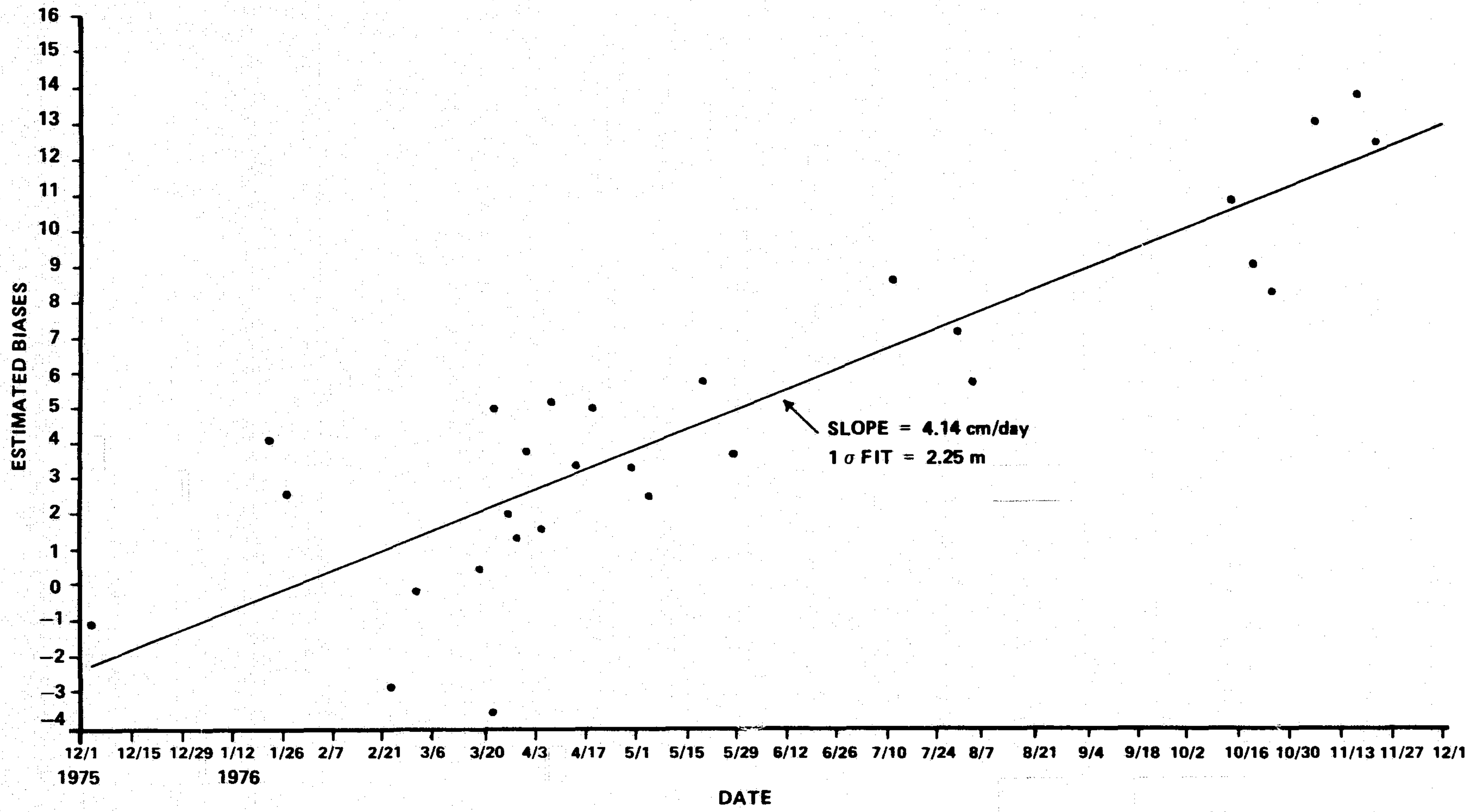

FIGURE 4. WALLOPS ISLAND FPQ–6 BIASES ESTIMATED FROM TWO REVOLUTION SINGLE STATION ORBITAL SOLUTIONS

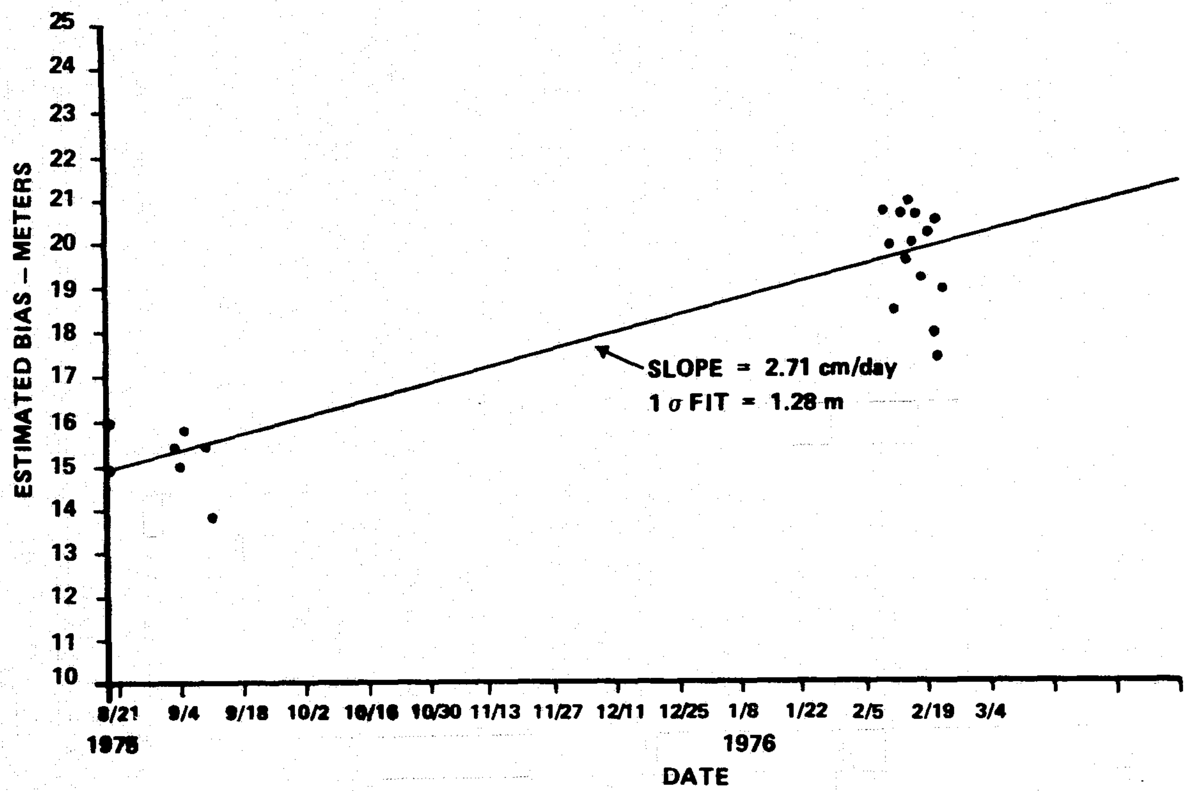

FIGURE 5. BERMUDA FPQ–6 BIASES ESTIMATED FROM TWO REVOLUTION SINGLE STATION ORBITAL SOLUTIONS

that most of the passes are moderate elevations and that there are pass-to-pass variations on the order of $\pm$ 1 m. A 4 cm/day drift in the radar bias is also consistent with what might be expected for the actual radar, considering that much of the station electronics is of the vacuum tube type. However, such a drift is still less than 1 m/month and, by most radar standards, is remarkably stable.

The Bermuda temporal variations shown in Figure 5, and the standard deviation of the fit about the linear variation, show an even smaller slope and a better fit about it. In both smaller temporal variation and low standard deviation, the Bermuda FPQ-6 results would be expected on the basis of the ADRAN range tracker utilized in the Bermuda radar. In fact, a significant portion of the slope shown in Figure 5 may possibly be attributed to long term variations in the return pulsewidth of the radar beacon itself, so that the radar is even more stable than suggested by the slope.

2.3 MULTIPLE STATION GLOBAL SOLUTIONS

The final category of orbital solution which we wish to consider involves multiple station tracking data from a global network of tracking stations. Most of the solutions of this type have utilized one day arcs of GEOS-3, and data taken during a two week period of concentrated tracking during the last week of February and the first week of March in 1976. The same data was also used to estimate the locations of the tracking stations, so the influence of tracking station location errors on the recovered biases is thus considered to be minimal. The dominant error source in bias estimation is expected to be geopotential model error, assuming that the range measurements input to the data reduction program contain only noise and a constant bias for each station.

The estimation of the bias for a single pass of an isolated station is limited by the accuracy of the orbit, which may be at the 10-15 m level. With the adjusted bias constrained to be the same for multiple passes, there is a considerable averaging-out of orbit error effects, particularly if the multiple passes include passes in different directions and on both sides of the tracking station. If there are multiple tracking stations in the same geographic area, these problems are somewhat minimized, since the orbit errors themselves are considerably smaller.

Most of the bias estimations using one day arcs did constrain the recovered biases to be the same throughout each day, but with independent estimates made for different days. The number of passes per day tracked by a station varied from one station to the next, although around the clock tracking generally produced four passes. However, each of the Wallops radars generally tracked only 2 passes per day, and the DFVLR radar at Wettzel, West Germany, sometimes tracked up to 7 passes. The results for the two week concentrated tracking period are shown in Table 3, tabulated by station for each of the 10 days. Overall, the bias stability shown in Table 3 appears quite good, although there are some anomalies and some unexpected behavior. The apparent instability of the Ascension radar (4045) may be due in part to the station's tracking alone and sometimes collecting only one pass per day, so that the bias estimation has substantial error. The scatter in the Ascension biases may also be real.

The variations in the WTRPPQ (Station 4260) biases for the last 4 days could not be explained on the basis of

TABLE 3. ESTIMATED C–BAND BIASES OBTAINED USING ONE DAY ARCS FROM CONCENTRATED TRACKING PERIOD (1976)

STATION \ DATE	2/23	2/24	2/25	2/26	2/27	3/1	3/2	3/3	3/4	3/5	MEAN	STANDARD DEVIATION	NOTES
AFETR													
4013 (FPQ–13)	–52.3	–55.5	–51.4	–51.4	–50.0						–52.1	2.1	
4045 (FPQ–15)	–17.9	–19.6	–11.6	–20.5	–19.9	–46.5	–38.6	–25.1	–37.7	–33.3	–27.1	11.3	
4061 (FPQ–14)	–30.1	–30.6	–30.1	–29.1	–28.5	–33.0					–30.2	1.6	
4082 (TPQ–18)	–23.7	–21.6	–19.3	–17.0	–19.0						–20.1	2.6	
WHITE SANDS													
4150 (FPS–16)	– 0.9	0.2	– 0.8	– 2.4	– 3.8	– 1.4	– 2.3	– 3.0	– 3.2	– 1.3	– 1.9	1.3	
4160 (MPS–36)	12.0	14.3	12.2	13.3	13.2						13.0	0.9	
4198 (MPS–36)						8.3	9.8	9.4	8.3	9.1	9.0	0.7	
AFWTR													
4260 (FPQ–6)	– 9.2	– 8.5	– 8.3	– 7.2	– 8.6	– 7.1	–13.3	–30.2	–27.7	–23.7	– 8.2/ –14.4	0.8/ 9.1	FIRST 6 PASSES/ ALL PASSES
4280 (TPQ–18)	12.1	10.8	12.3	7.8	12.9			8.2		6.3	10.0	2.6	
4282 (FPQ–14)	–22.0	–23.0	–25.0	–23.9	– 2.0	– 0.7	– 4.9	– 5.3			–13.4	11.0	
PMR													
4446 (FPS–16)	– 2.9	– 3.0	– 2.5	– 3.4	– 3.7		– 3.7	– 2.7	– 3.2		– 3.1	0.4	
4452 (MPS–25)			5.7	1.4	3.4	9.2	5.1	4.8	5.1	6.1	5.1	2.2	
ELY													
4610 (CAPRI)	– 5.2	– 4.2	– 7.1	– 7.3	– 5.7	– 4.9	– 6.9	– 6.2	– 5.4	– 4.5	– 5.7	1.1	
HAWAII													
4742 (FPS–16)	– 6.0	– 8.0	– 6.8	– 6.6	– 6.2	– 6.8	– 6.3	– 6.5	– 4.5	– 4.0	– 6.2	1.2	
BERMUDA													
4760 (FPQ–6)	18.8	18.3	17.2	17.6	17.4	18.4	20.1	18.7	17.8	18.5	18.3	0.8	
WALLOPS ISLAND													
4840 (FPS–16)	– 2.4	– 2.3	– 0.8	– 0.6	– 2.0		1.0	2.3	1.8	1.7	– 0.1	1.9	PRE & POST CALIBRATIONS USED
4840	– 2.7	– 2.4	– 0.3	– 0.5	– 2.1		– 0.1	– 0.4	– 0.2	– 1.0	– 1.1	1.1	PRE & POST CALS NOT USED
4841 (FPS–16)		– 5.8	– 7.3				– 2.2				– 5.1	2.6	
4860 (FPQ–6)	– 2.9	– 2.8	– 3.0	– 2.5	0.2	2.6		2.1	1.8	3.7	– 0.1	2.7	PRE & POST CALIBRATIONS USED
4860	– 2.2	– 2.7	– 2.8	– 0.3	– 1.6	– 4.1		– 2.8	– 2.1	– 0.4	– 2.1	1.2	PRE & POST CALS NOT USED
KWAJELIN													
4958 (MPS–36)				– 6.9	– 8.9	– 8.2	– 7.0	– 9.3		– 7.7	– 8.0	1.0	
4959 (MPS–36)			– 1.6	– 3.9	– 7.0	– 2.1	– 0.6	– 6.4		– 3.1	– 3.5	2.3	
DFVLR													
4960 (MPS–36)			13.1	11.9	14.2	13.4	14.9	13.0	11.8	12.1	13.1	1.1	
MIT													
4966		3.8	7.8	8.3	3.5		8.0	5.1		7.9	6.3	2.1	

any information received with the data, or about the data from WTR personnel. The first 6 days, however, show excellent stability and have been separately tabulated. It will be noted that the Vandenberg radar (Station 4280) also shows somewhat anomalously lower biases in the second week also. In this case, some reduction in the scatter could be achieved with the application of constant calibrations, in the manner discussed below for the Wallops radars. The Kaena Point radar (Station 4282) shows quite good stability (σ = 1.3 m) for the first 4 days, and fair stability for the last 4 days (σ = 2.2 m), but the difference between the means for these two periods is 20 m. The suspected reason for this difference is on-site compensation for pulsewidth/bandwidth mismatch, but this has not been completely verified.

The radars showing the highest degree of bias stability were a PMR radar (4446) and a White Sands radar (4198) with 1σ deviations from the mean bias of 0.4 m and 0.7 m, respectively. As expected, the Bermuda bias was also quite stable, with 1σ deviation about the mean of 0.8 m. Several radars had 1σ bias fluctuations around a meter.

Two bias summaries are given for the Wallops FPQ-6 and one of the FPS-16's. (A similar treatment could have been given to the other Wallops FPS-16, in which case the 1σ scatter would have been 1.5 m.) The second summary was attempted primarily because of the apparent systematic variation from the first week to the second, in spite of identical calibration and operating procedures throughout the two week period and no records of unusual conditions at any time. Subsequently, it has been determined that the FPQ-6 calibration target, a meteorological tower, had a lightning arrestor installed around this time period. Although the date of installation cannot be firmly established, it does present the possibility that there was physically something different between the beginning and end of the concentrated tracking period other than the radar itself. Unfortunately, the FPS-16 uses a different calibration target and an attempt to find some physical variation in it was fruitless.

The observation that the ground calibrations for the Wallops FPQ-6 underwent a systematic change during the concentrated tracking period, together with a possible physical explanation for it, led to an attempt to remove the trend by applying a constant calibration correction throughout the two week period. The application of the mean calibration for the first 4 days to the entire 2 week period led to the second row of estimated biases for Station 4860 in Table 3. The mean is reduced (in magnitude) by 2 meters, and the standard deviation is reduced by more than a factor of 2.

The technique was so successful with the FPQ-6 that it was also attempted with Station 4840, even though there was no physical reason to question the calibration variation from the first week to the second. For this radar the mean calibration for the two week period was applied to all the data, and again there was almost a factor of 2 reduction in the standard deviation about the mean bias.

Although the same technique was not applied systematically to other stations, it was noted that the radars with the most stable biases also had stable calibrations. We can thus conclude that there is substantial evidence in Table 3 that radar stability exceeds the accuracy of individual ground calibrations. Further attempts at validating this hypothesis appear definitely warrented, since it suggests that the normal mode of operations of almost all C-Band radars may need to be modified.

SECTION 3.0
TIMING CALIBRATIONS

In most applications of C-Band radars, the time tags as well as the radar measurements must be incorporated with those from other stations, or correlated with on board experiments or measurements. In all such cases, it is necessary that the timing systems utilized by the different instruments be synchronized with each other, or all be synchronized with a common timing source. In practice, the latter is normally attempted, with systems throughout the world attempting to maintain "UTC" time. In the United States, this may be done via several methods, although the incorporation of WWV receivers is a part of the timing system of most facilities. The use of transportable clocks to (or from) the Naval Observatory is also quite common at NASA facilities.

Regardless of the particular method used, however, the timing system for most C-Band radar sites should be accurate to within a few tens of microsonds ($\sim$ 50 μsec) provided everything is working properly. "Working properly" here must also include not only the correct synchronization of a facility timing system with some reference timing standard, but also the appropriate correlation of measured data with station timing signals. Furthermore, once the correlation has been made, software data handling should not be allowed to introduce timing or other errors.

As the above implies, timing problems can arise in numerous ways, almost all of which are unpredictable. E.g., during the GEOS-2 C-Band project, the major timing problems found [5] were:

- Two cases of radars having time tags in error by one data sampling interval. In these cases, the timing system was working properly, but the times were assigned to the wrong data samples.

- Occasional errors in the Wallops Island timing of multiples of 0.1 second. An error of this magnitude was easily corrected in the data, although the hardware problem responsible was not found until some two years later.

- Uncertainties as to whether data from the AFETR had been transit time (and refraction) corrected, since the corrections were applied to the measurements rather than the time tags. In some cases, both corrected and uncorrected data were supplied on the same data tapes.

For the most part, timing problems found with GEOS-3 have been different, although still frequently of an abstruse nature. Problems identified (and "solved") included:

- Occasional problems at Wallops Island during electrical storms during weekends in the summer of 1975. The timing error could be any amount, but remained constant between storms.

- An identification that the range rate measurements were being incorrectly time tagged. This identification, and the resolution thereof, was a major achievement in radar calibration using GEOS-3, and is discussed below.

- A time varying timing error in data from the Woomera radar, identified by R.L. Brooks [6] and subsequently verified-thus far unique in the annals of timing problems.

- Errors in teletype data from the DFVLR radar (Station 4960 - FRGM10) at Wettzel, West Germany, of multiples of 10 msec, later identified as software problems in the data sampling. The data received on magnetic tapes was free of this problem.

- Errors of ~ 500 μsec in the time tags of data from the Patrick AFB laser, which was used in some of the C-Band analysis. The origin of the error was never identified, although its existence was tacitly admitted. This error disappeared in April 1976.

In a few other cases, there were suspicions of timing problems, but these subsequently disappeared when more accurate station positions were obtained.

A discussion will be given of only two of these problems. The first, the range rate timing problem, was the more significant since it had been a problem with all radars with Coherent Signal Processor kits. The second, the FRGM10 10 msec problem, will be discussed to show the capability of the global orbit to identify and resolve timing errors for a remote site.

3.1 RANGE RATE TIMING

This subject will be discussed only briefly, since it has been documented in detail elsewhere [7]. The net result of the system analysis by RCA was that the range rate time tags applied by the radar were in error by approximately

$$\Delta t = (PRI)/2 \qquad (3)$$

where PRI = pulse repetition interval.

With the radars operating at the normal PRI of 1/160/sec, the timing error was

$$\Delta t = \frac{1 \text{ second}}{(160)(2)} = 3.125 \text{ msec} \qquad (4)$$

With the optional PRI of 1/640 sometimes used, the timing error was only 0.78 msec.

Using tracking of the coherent beacon on GEOS-3, the timing error was relatively easy to identify when compared against an orbit determined by the regular radar range and angles. The analysis mode for a new or questionable data type is normally to estimate a bias and timing error such that the new data has a best fit to the more validated data. Following this approach, a varying bias of 1-2 cm/sec was estimated along with a timing error near a constant 3 msec. The bias existence was expected and can largely be eliminated using pre/post mission calibrations similar to range calibrations as described, e.g., by Borman [8].

The consistency of the estimated timing bias, and the range rate consistency with the range and angle data after the timing adjustment was essentially impossible to refute as being other than a true timing bias. Confronted with cold hard facts, a hardware explanation was eventually forthcoming [7].

3.2 FRGM10 TIMING SOLUTIONS

As indicated above, teletype data (although not magnetic tape data) from the DFVLR radar at Wettzel, West Germany, contained timing errors which were multiples of 10 msec (corresponding to an internal radar update rate of 100/sec). This timing error was always constant throughout a pass, and frequently constant for several consecutive passes. Particularly for the two week concentrated tracking period in February-March, 1976, the proper 10 msec slot could be identified through pass by pass timing bias recoveries in the orbital data reduction.

Table 4 shows one day arc timing bias recoveries for FRGM10 for the week of 1 March 1976, first for pass by pass estimations, and then with common adjustments for biases which appeared to be the same on consecutive passes. On a pass by pass basis, the biases are generally within 1-2 msec of a 10 msec slot, corresponding to orbit errors on the order of 15 m alongtrack, which could be expected for a global one day arc away from the area of concentrated tracking stations (east coast of the U.S.). When the constraints are applied, the largest deviation from a 10 msec slot is 1.5 msec, and this for a pass unconstrained to either of the adjacent passes.

As the above discussion implies, timing errors of a few milliseconds are detectable during radar calibrations via satellite for an isolated station. With a higher concentration of tracking stations around a questionable station, the level of detection can be considerably higher.

TABLE 4. ESTIMATED TIMING BIASES FOR FRGM10 TELETYPE DATA FOR FIRST WEEK OF MARCH 1976

DATE	ESTIMATED PASS BY PASS BIASES		ESTIMATED CONSTRAINED BIASES
3/1/76	PASS 1	77 msec	78.8 msec
	2	97 msec	11.5 msec
	3	49 msec	
	4	50 msec	50.8 msec
	5	49 msec	
	6	48 msec	
3/2/76	PASS 1	41 msec	40.1 msec
		31 msec	
		31 msec	30.8 msec
		31 msec	
		30 msec	
3/3/76	PASS 1	29 msec	
		32 msec	
		31 msec	
		31 msec	29.8 msec
		30 msec	
		30 msec	
		30 msec	
3/4/76	PASS 1	33.5 msec	
		35 msec	30.5 msec
		32 msec	
		32 msec	
		81 msec	
		83 msec	79.4 msec
		79 msec	
3/5/76	PASS 1	81 msec	
		83 msec	
		82 msec	
		81 msec	80.3 msec
		81 msec	
		81 msec	
		78 msec	

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SECTION 4.0
ANGLE DATA ANALYSIS

Satellite calibration is particularly well suited for angle calibration, since orbit errors in a global arc will generally not exceed ~15 m using currently available gravity models and arc lengths on the order of 1 day. The accuracy of the reference orbits is thus ~2 arc seconds or better, and somewhat better than the specification accuracies for all known C-Band radars.

Angle measurements from two different days of the GEOS-3 concentrated tracking period were analyzed against reference orbits determined by the range measurements from C-Band radars and available NASA laser tracking data. Each pass of angle data was reduced to determine a mean bias and an rms about this mean. The results are summarized by radar in Table 5.

In general, the angle summaries show surprisingly good performance, especially considering the fact that angles are a relatively neglected measurement type at a number of radars. Most of the bias levels are well below the noise levels although, as will be discussed below, measurement errors (residuals) are not necessarily characterized by a simple bias and random noise about that bias. The noise levels for the same type of radar, even though operated by different agencies, appear to be about the same. Noise levels observed for the different radar types were typically in the following ranges:

TABLE 5. PASS BY PASS SUMMARY OF C–BAND RADAR ANGLE RESIDUALS FOR GEOS-3 TRACKING ON FEBRUARY 23 AND FEBRUARY 25, 1976

NAME	STATION NUMBER	TYPE	DATE	PASS START TIME	PASS STOP TIME	MAX EL	MEAN (SEC. OF ARC) AZ	MEAN (SEC. OF ARC) EL	RMS (SEC. OF ARC) AZ	RMS (SEC. OF ARC) EL
WTRKPT	4282	FPQ–14 (On Axis)	Feb 23	$0^h 58^m$	$1^h 08^m$	43°	– 8	2	10	19
			Feb 23	$2^h 38^m$	$2^h 45^m$	20°	– 11	16	25	11
			Feb 23	$15^h 08^m$	$15^h 19^m$	75°	– 5	– 10	16	13
ETRAS5	4045	FPQ–15 (On Axis)	Feb 23	$3^h 28^m$	$3^h 36^m$	23°	–171	– 3	42	22
			Feb 23	$5^h 06^m$	$5^h 15^m$	33°	– 17	8	39	34
			Feb 23	$16^h 06^m$	$16^h 15^m$	25°	–125	51	61	45
			Feb 23	$17^h 44^m$	$17^h 53^m$	29°	–958	149	2053	166
NBERO5	4760	FPQ–6	Feb 23	$8^h 20^m$	$8^h 29^m$	33°	19	14	22	17
			Feb 23	$18^h 00^m$	$18^h 10^m$	32°	25	11	23	22
			Feb 25	$9^h 29^m$	$9^h 40^m$	63°	– 13	81	93	15
			Feb 25	$17^h 34^m$	$17^h 40^m$	38°	12	15	18	10
			Feb 25	$19^h 10^m$	$19^h 20^m$	—	———	89	———	———
ETRANT	4061	FPQ–14 (On Axis)	Feb 23	$8^h 22^m$	$8^h 33^m$	89°	0	– 14	87	9
			Feb 23	$19^h 34^m$	$19^h 45^m$	65°	7	– 25	10	8
			Feb 25	$9^h 33^m$	$9^h 42^m$	26°	0	9	13	16
			Feb 25	$19^h 06^m$	$19^h 16^m$	47°	11	–125	56	179
			Feb 25	$20^h 46^m$	$20^h 53^m$	17°	– 2	– 32	9	17
ETRPAT	4060	FPQ–14	Feb 23	$10^h 01^m$	$10^h 12^m$	87°	– 9	9	27	5
ETR313	4013	FPQ–13 (On Axis)	Feb 23	$10^h 01^m$	$10^h 12^m$	72°	25	– 2	24	26
			Feb 23	$19^h 39^m$	$19^h 49^m$	52°	20	13	19	19
			Feb 25	$11^h 12^m$	$11^h 20^m$	24°	20	– 4	11	18
			Feb 25	$19^h 13^m$	$19^h 19^m$	22°	———	———	———	———
			Feb 25	$20^h 49^m$	$20^h 49^m$	48°	– 14	– 6	27	24
WSG219	4150	FPS–16	Feb 23	$11^h 41^m$	$11^h 52^m$	35°	– 17	70	25	34
			Feb 23	$13^h 20^m$	$13^h 29^m$	41°	10	47	24	38
			Feb 23	$21^h 24^m$	$21^h 35^m$	71°	11	87	21	26
			Feb 25	$12^h 49^m$	$13^h 02^m$	84°	4	104	41	37
			Feb 25	$20^h 56^m$	$21^h 06^m$	35°	18	88	54	39
			Feb 25	$22^h 23^m$	$22^h 44^m$	42°	6	53	21	26

TABLE 5. (continued)

NAME	STATION NUMBER	TYPE	DATE	PASS START TIME	PASS STOP TIME	MAX EL	MEAN (SEC. OF ARC) AZ	MEAN (SEC. OF ARC) EL	RMS (SEC. OF ARC) AZ	RMS (SEC. OF ARC) EL
WSM350	4160	MPS–36	Feb 23	$11^h 42^m$	$11^h 52^m$	67°	– 12	144	84	70
			Feb 23	$21^h 22^m$	$21^h 33^m$	60°	– 33	149	71	105
			Feb 25	$11^h 14^m$	$11^h 23^m$	28°	25	257	88	100
			Feb 25	$12^h 52^m$	$13^h 02^m$	42°	60	102	156	98
			Feb 25	$20^h 55^m$	$21^h 03^m$	28°	– 5	232	102	113
			Feb 25	$22^h 32^m$	$22^h 42^m$	44°	75	154	85	113
NELHAR	4610	CAPRI	Feb 23	$11^h 42^m$	$11^h 49^m$	24°	45	46	12	21
			Feb 23	$13^h 20^m$	$13^h 30^m$	58°	21	66	20	58
			Feb 23	$21^h 25^m$	$21^h 35^m$	52°	42	60	31	18
			Feb 25	$12^h 50^m$	$13^h 03^m$	69°	60	29	51	52
			Feb 25	$14^h 29^m$	$14^h 40^m$	25°	26	40	11	32
			Feb 25	$20^h 56^m$	$21^h 07^m$	27°	38	90	15	11
			Feb 25	$22^h 34^m$	$22^h 46^m$	60°	17	26	20	28
PMRPM4	4446	FPS–16	Feb 23	$11^h 44^m$	$11^h 52^m$	22°	– 20	– 18	64	48
			Feb 23	$13^h 26^m$	$13^h 30^m$	54°	———	———	———	———
			Feb 23	$21^h 25^m$	$21^h 34^m$	28°	– 12	– 1	65	56
			Feb 23	$23^h 03^m$	$23^h 13^m$	47°	6	– 10	58	49
			Feb 25	$12^h 52^m$	$13^h 06^m$	69°	– 2	– 19	44	37
			Feb 25	$14^h 30^m$	$14^h 43^m$	21°	37	– 7	63	67
			Feb 25	$22^h 33^m$	$22^h 44^m$	75°	32	108	64	74
WTRVAN	4280	TPQ–18	Feb 23	$11^h 44^m$	$11^h 52^m$	19°	– 8	– 24	54	10
			Feb 23	$13^h 21^m$	$13^h 32^m$	62°	– 17	– 36	40	21
			Feb 23	$21^h 26^m$	$21^h 32^m$	26°	14	– 3	33	20
			Feb 23	$23^h 03^m$	$23^h 08^m$	50°	– 22	– 17	38	18
			Feb 25	$22^h 35^m$	$22^h 48^m$	71°				
WTRPPQ	4260	FPQ–6	Feb 23	$13^h 21^m$	$13^h 32^m$	84°	25	– 7	255	28
			Feb 23	$15^h 01^m$	$15^h 08^m$	18°	14	– 22	11	12
			Feb 23	$21^h 29^m$	$21^h 35^m$	29°	10	– 5	17	13
			Feb 23	$23^h 04^m$	$23^h 14^m$	51°	– 10	– 20	16	16
			Feb 25	$12^h 51^m$	$13^h 06^m$	44°	16	– 6	64	419
			Feb 25	$14^h 30^m$	$14^h 44^m$	33°	10	1	18	16
			Feb 25	$20^h 58^m$	$21^h 09^m$	16°	– 5	10	60	26
			Feb 25	$22^h 33^m$	$22^h 49^m$	74°	2	25	25	32

TABLE 5. (continued)

NAME	STATION NUMBER	TYPE	DATE	PASS START TIME	PASS STOP TIME	MAX EL	MEAN (SEC. OF ARC) AZ	MEAN (SEC. OF ARC) EL	RMS (SEC. OF ARC) AZ	RMS (SEC. OF ARC) EL
KWAJM3	4958	MPS–36	Feb 23	$16^h 54^m$	$17^h 05^m$	83°	89	– 20	83	229
			Feb 25	$3^h 48^m$	$3^h 57^m$	34°	–145	–219	317	204
			Feb 25	$16^h 26^m$	$16^h 35^m$	35°	81	–153	71	110
			Feb 25	$18^h 05^m$	$18^h 13^m$	22°	81	–235	85	131
KWAJM4	4959	MPS–36	Feb 23	$16^h 54^m$	$17^h 05^m$	83°	144	–137	157	103
			Feb 25	$3^h 48^m$	$3^h 57^m$	34°	100	–228	57	154
			Feb 25	$16^h 26^m$	$16^h 35^m$	35°	61	–170	52	101
			Feb 25	$18^h 05^m$	$18^h 13^m$	22°	71	–246	53	115
ETRMRT	4082	TPQ–18	Feb 23	$19^h 40^m$	$19^h 50^m$	49°	9	78	22	425
			Feb 23	$21^h 20^m$	$21^h 27^m$	21°	– 1	– 9	19	13
			Feb 25	$9^h 33^m$	$9^h 42^m$	35°	– 14	– 1	19	12
			Feb 25	$11^h 11^m$	$11^h 21^m$	31°	1	– 17	17	14
			Feb 25	$19^h 12^m$	$19^h 20^m$	21°	3	36	45	15
			Feb 25	$20^h 49^m$	$21^h 00^m$	53°	– 7	17	16	13
WTRKAU	4742	FPS–16	Feb 25	$0^h 32^m$	$0^h 38^m$	16°	– 0	28	39	37
			Feb 25	$2^h 08^m$	$2^h 18^m$	60°	2	25	27	34
PMRMR3	4452	MPS–25	Feb 25	$0^h 32^m$	$0^h 38^m$	16°	51	87	74	52
			Feb 25	$2^h 12^m$	$2^h 18^m$	60°	1	41	41	47
			Feb 25	$14^h 40^m$	$14^h 50^m$	36°	– 28	1	32	28
			Feb 25	$16^h 19^m$	$27^h 55^m$	27°	96	26	374	127
KALCOR	4466		Feb 25	$3^h 49^m$	$3^h 57^m$	35°	– 4	–190	7	62
FRGM10	4960	MPS–36	Feb 25	$5^h 59^m$	$6^h 09^m$	52°	–––	152	–––	247
			Feb 25	$7^h 38^m$	$7^h 46^m$	22°	25	149	107	127
			Feb 25	$9^h 16^m$	$9^h 22^m$	17°	– 9	126	121	120
			Feb 25	$10^h 54^m$	$11^h 01^m$	24°	23	159	123	125
			Feb 25	$12^h 29^m$	$12^h 40^m$	64°	– 5	–––	66	–––
			Feb 25	$14^h 09^m$	$14^h 18^m$	32°	– 11	–––	95	–––

TABLE 5. (continued)

STATION NAME	STATION NUMBER	TYPE	DATE	PASS START TIME	PASS STOP TIME	MAX EL	MEAN (SEC. OF ARC) AZ	MEAN (SEC. OF ARC) EL	RMS (SEC. OF ARC) AZ	RMS (SEC. OF ARC) EL
NWAL13	4860	FPQ–6	Feb 23	$18^h 02^m$	$18^h 13^m$	24^o	36	27	24	10
			Feb 23	$19^h 40^m$	$19^h 53^m$	66^o	24	24	21	10
			Feb 25	$9^h 30^m$	$9^h 39^m$	33^o	19	13	15	18
			Feb 25	$11^h 08^m$	$11^h 18^m$	42^o	27	19	50	11
NWAL18	4840	FPS–16	Feb 23	$9^h 57^m$	$10^h 10^m$	75^o	– 31	43	46	33
			Feb 23	$11^h 36^m$	$11^h 47^m$	22^o	7	34	30	56
			Feb 25	$19^h 10^m$	$19^h 25^m$	59^o	– 27	32	24	33
			Feb 25	$20^h 50^m$	$21^h 04^m$	22^o	– 81	– 6	42	36
NWAL49	4841	FPS–16	Feb 25	$19^h 12^m$	$19^h 25^m$	59^o	– 39	50	30	30
			Feb 25	$20^h 50^m$	$21^h 03^m$	22^o	– 70	–144	43	66

FPQ-6 and TPQ-18	10" - 30"
FPS-16	30" - 50"
MPS-36	100" - 200"
On-Axis Radars	Variable

Except for very high elevation passes, azimuth and elevation results were not significantly different.

Aside from measurement biases, there are several other forms of systematic errors expected to significantly influence azimuth and elevation data. These include:

- Servo lags (azimuth and elevation, essentially independent)
- Pedestal mislevel (affecting both azimuth and elevation)
- Antenna droop (affecting elevation only)
- Tropospheric refraction (affecting elevation only)

Some other effects, such as collimation error, are also possible. Servo lag effects are visible in azimuth residuals for all high elevation passes, as might be expected. No elevation residual patterns were observed which appeared to have the characteristics expected of either droop or tropospheric refraction, suggesting that these effects are well accounted for, either at the radar or in data processing. The residual patterns that were observed seemed to have the characteristics of:

- Servo lags,
- Pedestal mislevel, or
- None of the normal radar angle errors.

Examples of each of these will be briefly discussed below.

4.1 SERVO LAGS

Azimuth lags are very significant on high elevation passes, since the azimuth rates can exceed the rotation rates possible for the servo system. Two reasonably typical examples of this problem are shown in Figures 6 and 7 for a White Sands FPS-16 radar, and the Bermuda FPQ-6 radar, respectively. In both cases, there is loss of track around PCA, but the residual patterns are quite flat otherwise, having a mean near zero for WSG219 and a mean around 25" for NBER05.

Figures 8 through 11 show examples of elevation residuals which are reasonably well modeled by a combination of bias and velocity servo lag errors. Figure 8 is for an FPQ-6 radar, with an estimated K_v of 85/sec. The estimated rate coefficient for the FPS-16 radar residuals shown in Figure 9 corresponds to a K_v of 29/sec. and the corresponding K_v's for the estimated rate coefficients for the on-axis

FIGURE 6. WSG219 AZIMUTH RESIDUALS (FEBRUARY 25, 1976)
(MAX EL = 83.63°)

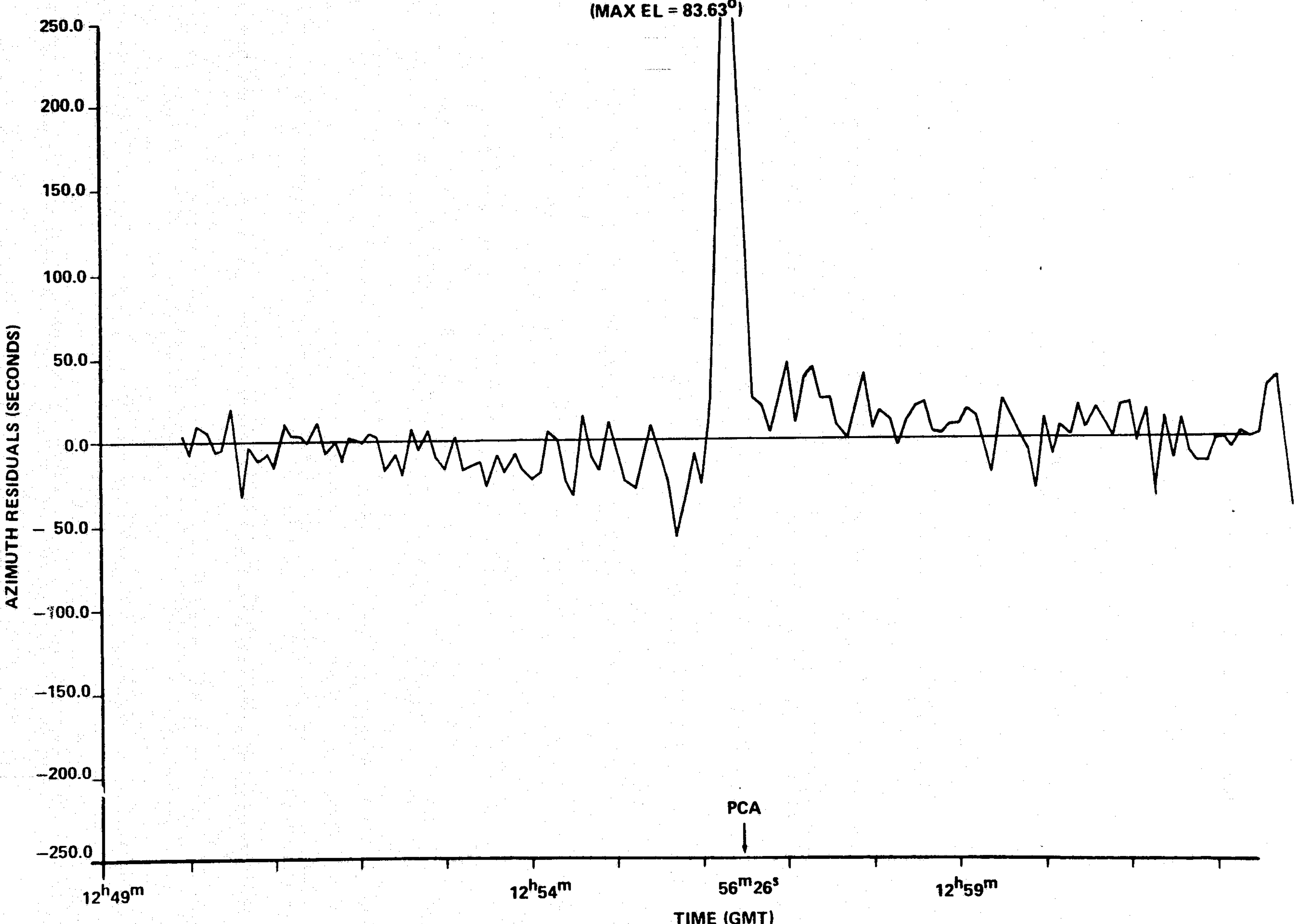


FIGURE 7. NBER05 AZIMUTH RESIDUALS (FEBRUARY 25, 1976)
(MAX EL = 81.02°)

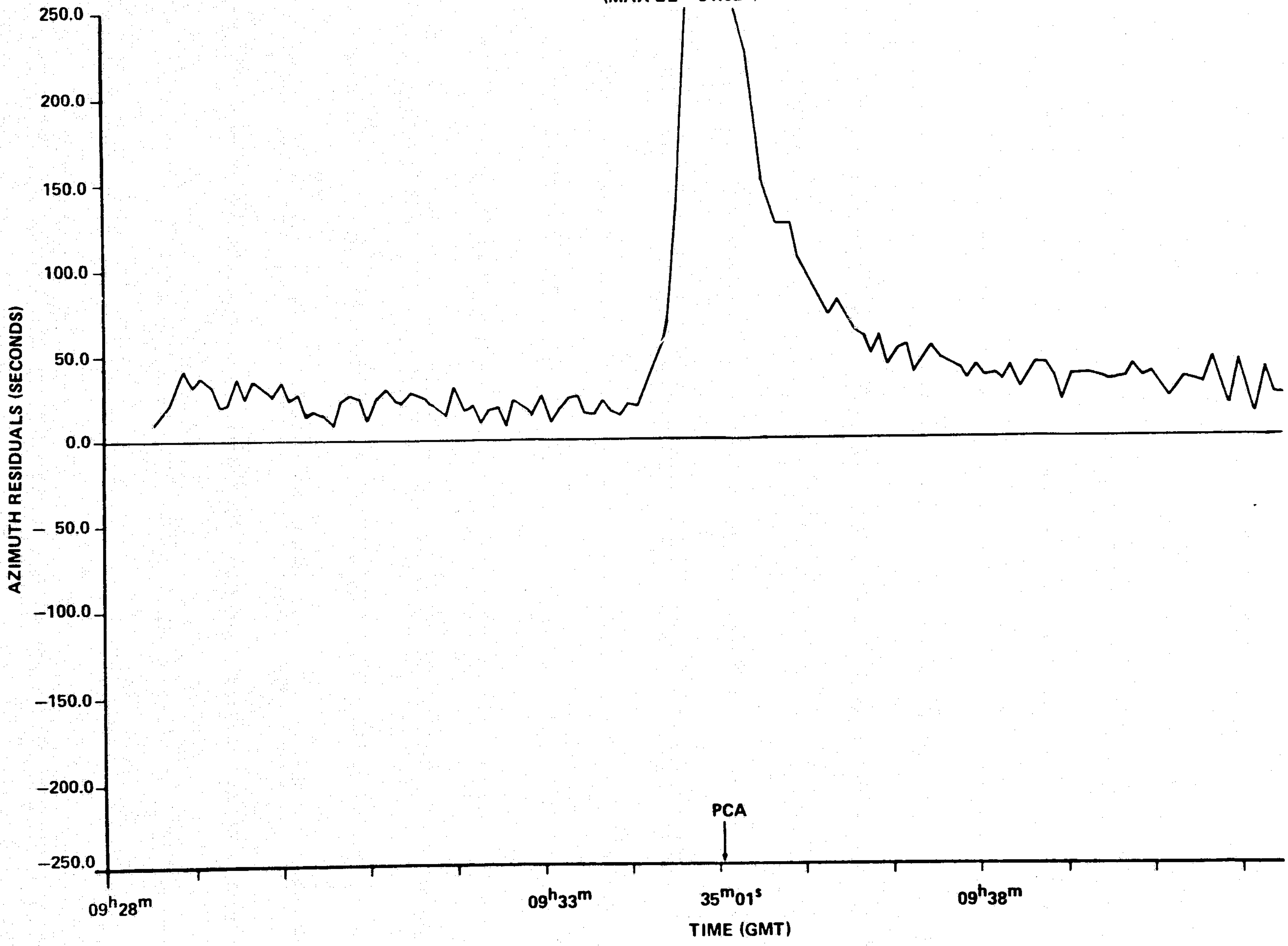


FIGURE 8. NBERO5 ELEVATION RESIDUALS (FEBRUARY 25, 1976)

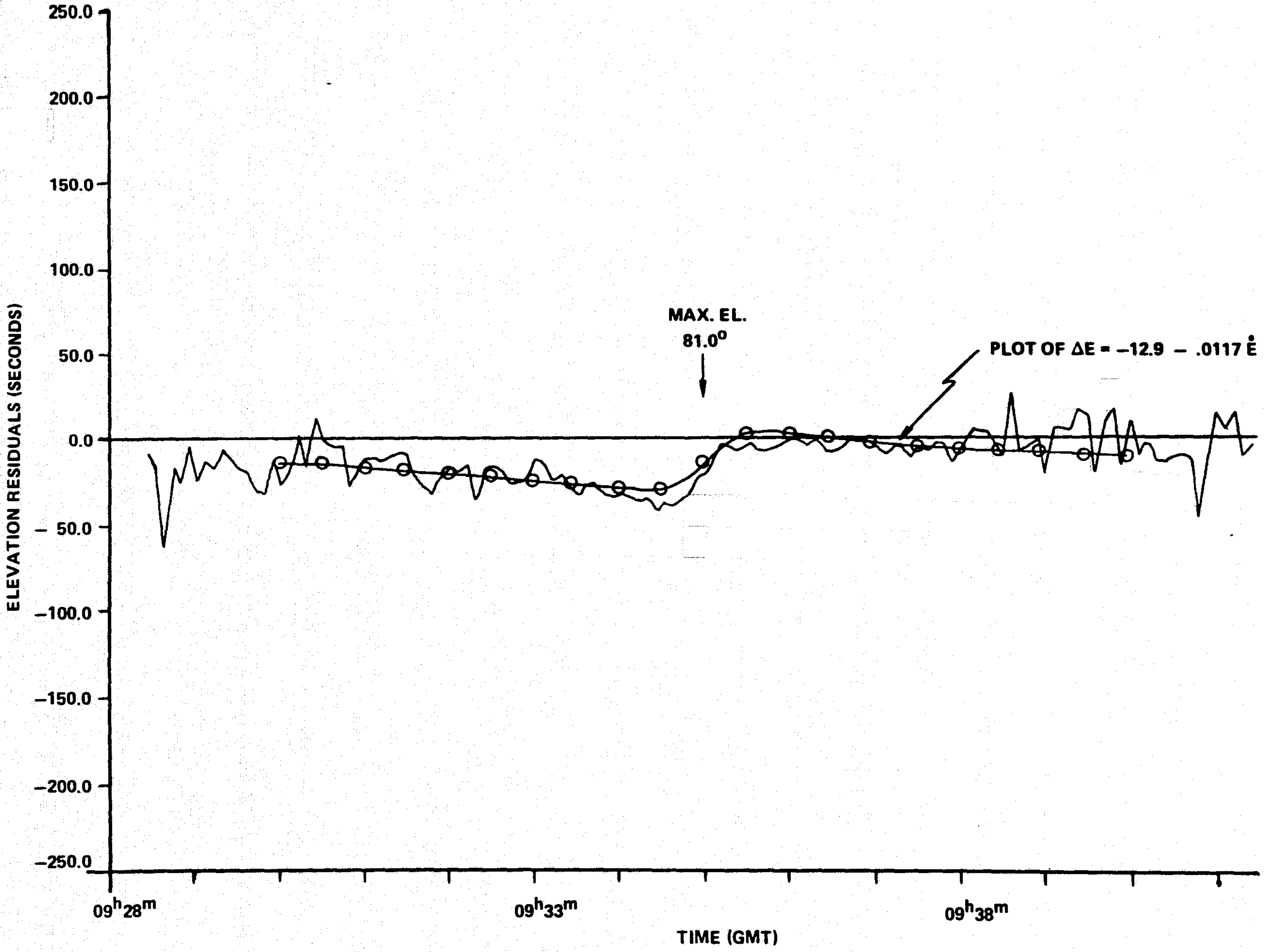


FIGURE 9. WTRKAU ELEVATION RESIDUALS (FEBRUARY 25, 1976)

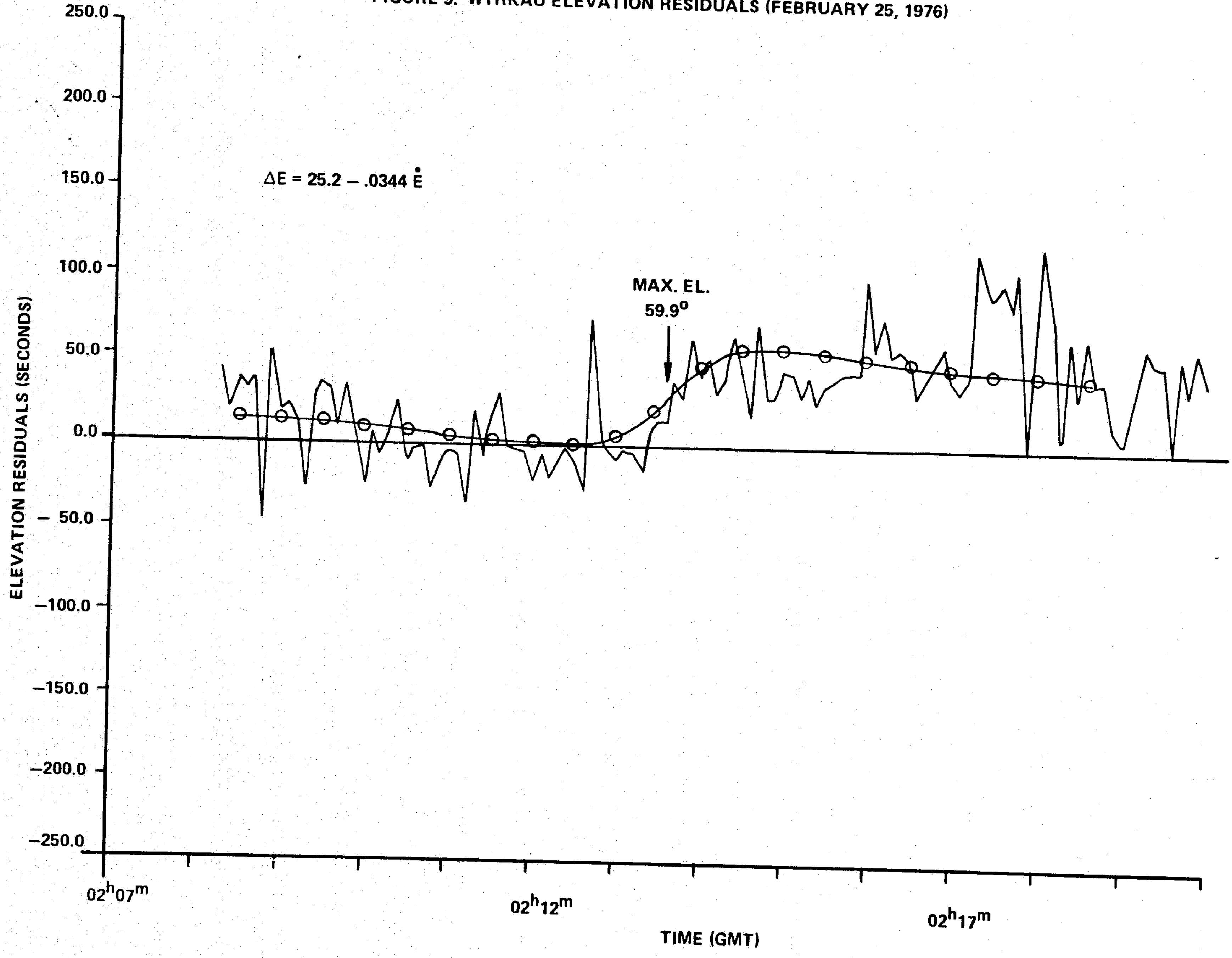


FIGURE 10. ETR313 ELEVATION RESIDUALS (FEBRUARY 23, 1976)

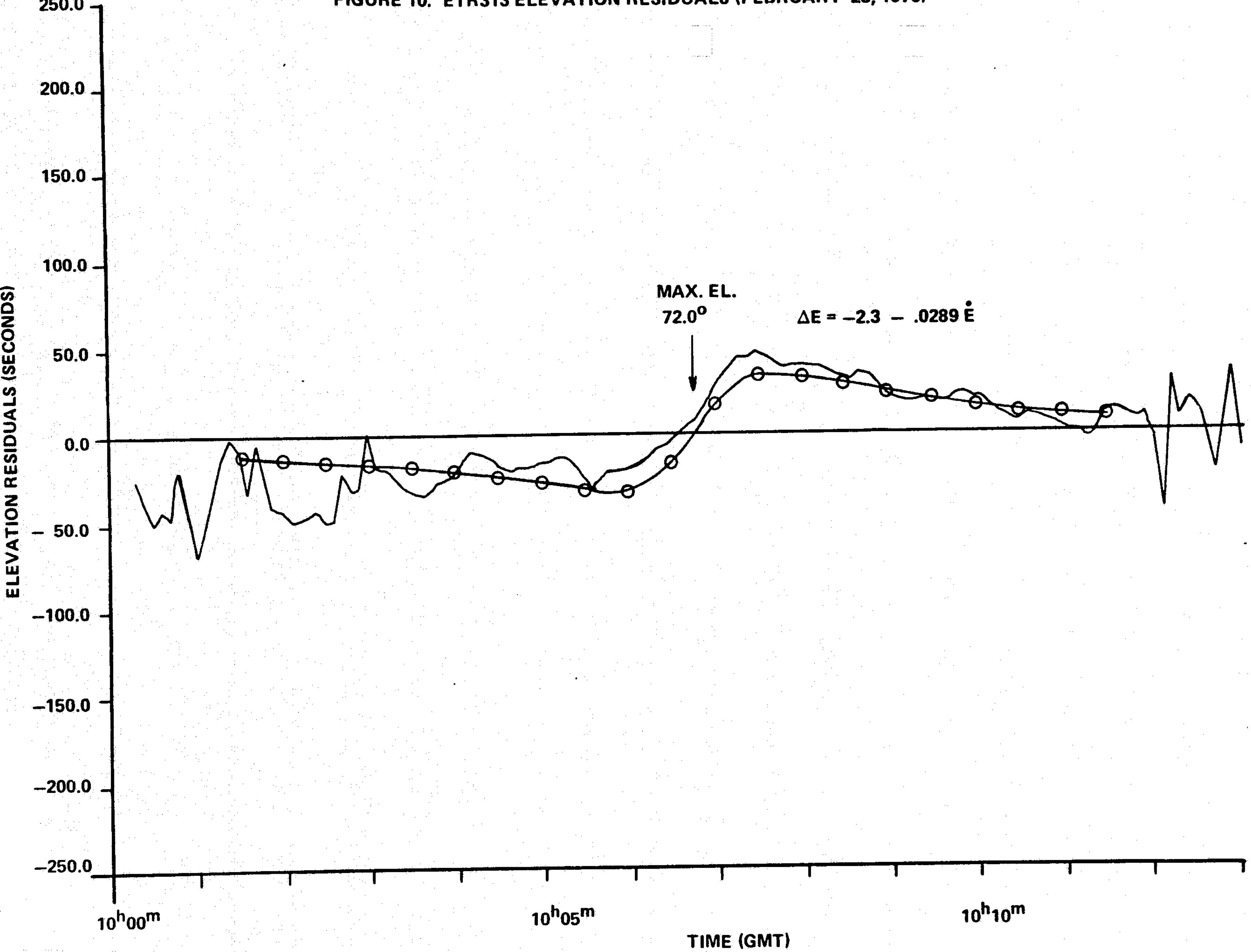
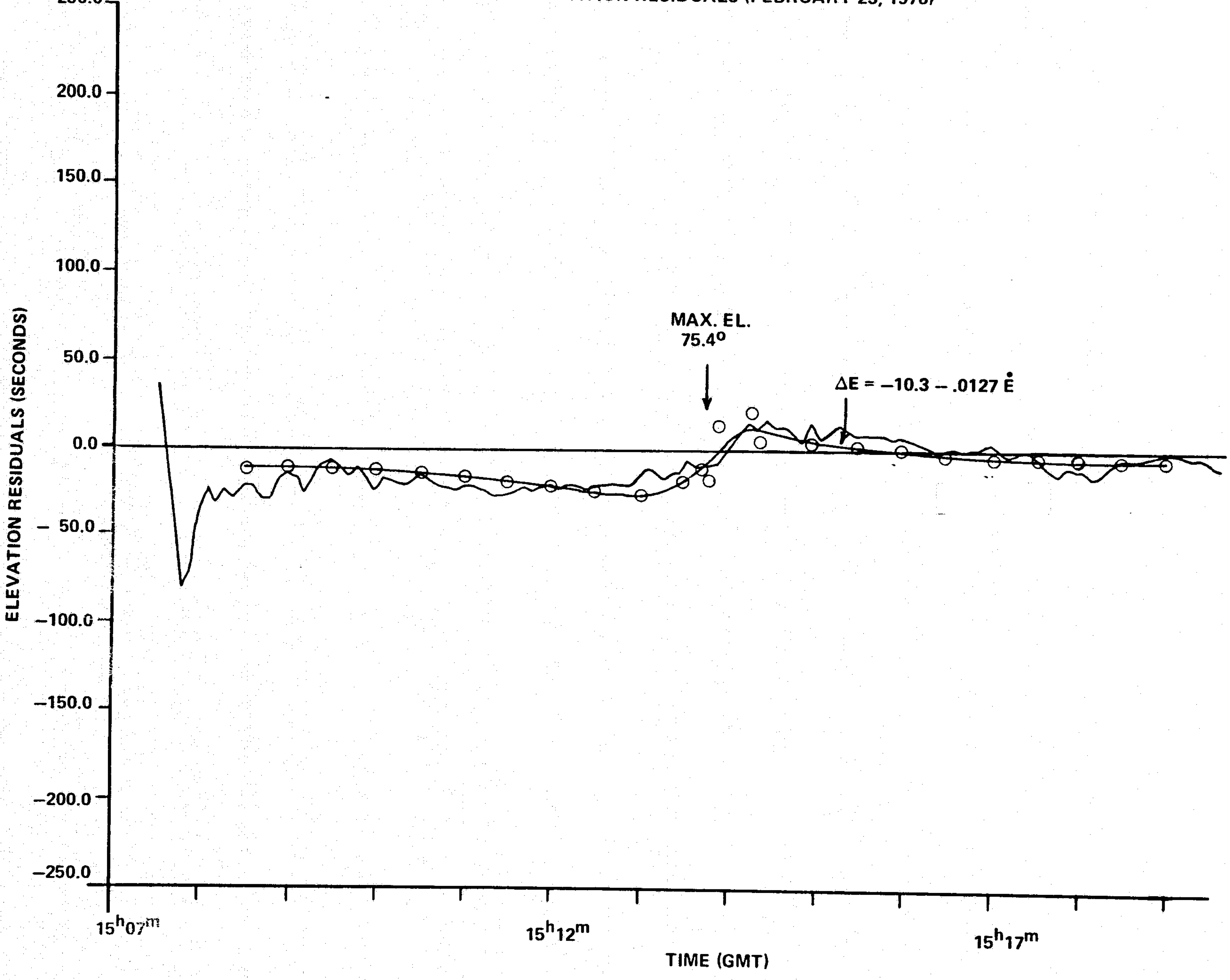


FIGURE 11. WTRKPT ELEVATION RESIDUALS (FEBRUARY 23, 1976)



radars with residuals shown in Figures 10 and 11 are 35/sec and 79/sec. These numbers are all somewhat smaller than the commonly quoted coefficients of ~350/sec for FPQ-6 and FPS-16 radars [9], and probably arise from tracking with different radar parameters than was expected.

It may be noted that the elevation lag is not always evident in the residuals, as is exemplified by the WTRVAN residuals shown in Figure 12, which has only a very slight indication of trending around PCA. Furthermore, the repetition of the characteristic lag pattern for the Bermuda radar in Figure 13 for another pass, showing residuals almost identical to those in Figure 8, indicates both a nearly constant bias and lag parameters.

We thus conclude that lags are present in the angles of most radars, whether they are supposed to be or not. Furthermore, there is no apparent distinction between the lags experienced by on-axis radars, and non-on-axis radars, except that there was no evidence of an on-axis radar without lag indications.

4.2 PEDESTAL MISLEVEL

Pedestal "mislevel" can exist in radar data if the angles are not transformed at some stage of processing to be equivalent to measurements made from an instrument whose base was parallel to the local ellipsoid. The correction process would have to account for:

FIGURE 12. WTRVAN ELEVATION RESIDUALS (FEBRUARY 25, 1976)

(MAX EL = 70.64°)

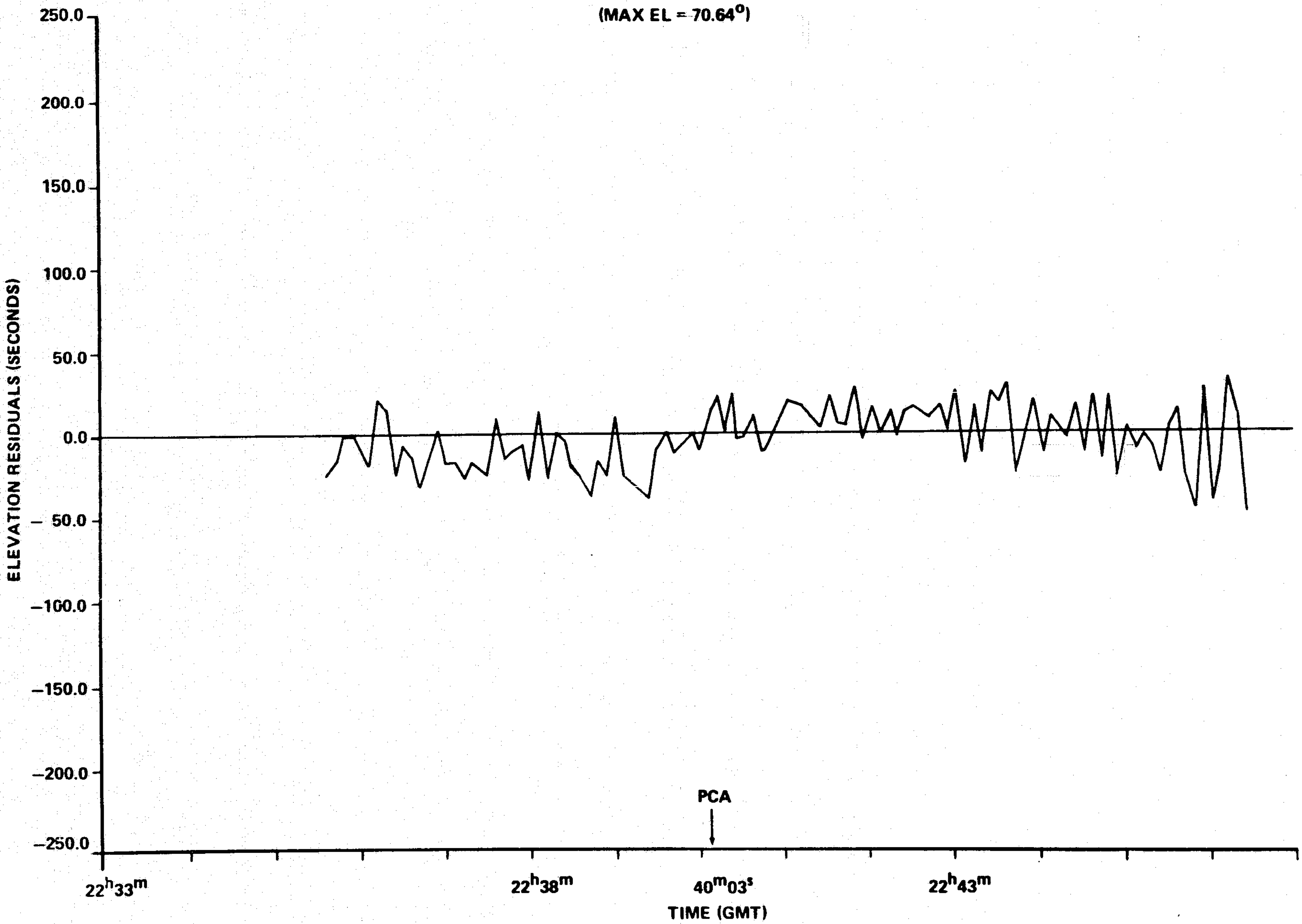
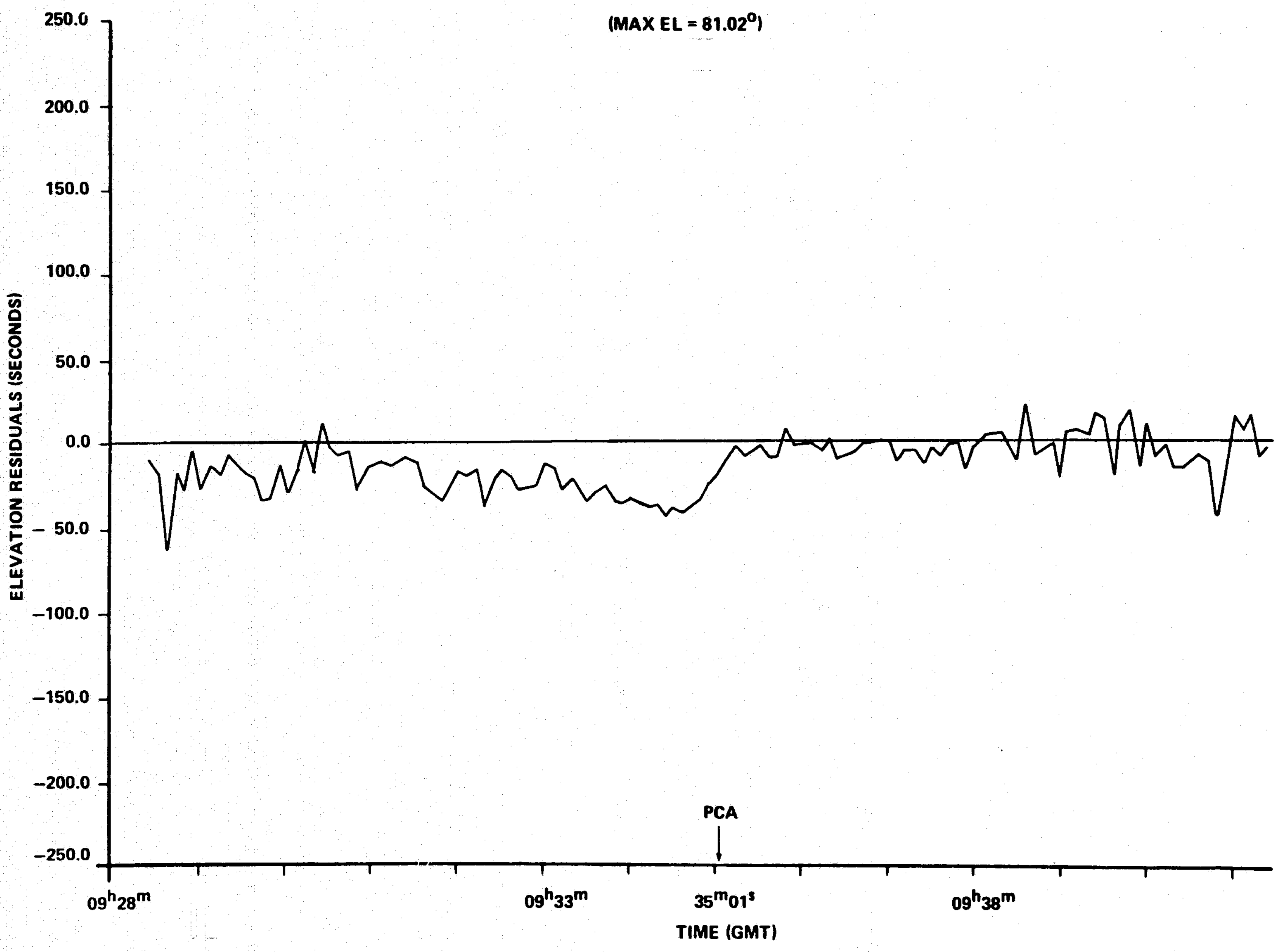


FIGURE 13. NBER05 ELEVATION RESIDUALS (FEBRUARY 25, 1976)

(MAX EL = 81.02°)



1. Deviations of the pedestal normal from the local gravity vector, and

2. Deviations of the local gravity vector from the normal to the ellipsoid.

These operations can, of course, be simultaneously accounted for via star calibrations, as is frequently done with on-axis radars.

No evidence was found of gross pedestal mislevel, but some patterns were observed for which pedestal mislevel appeared the most satisfactory explanation. An example for one such radar is shown in Figures 14 through 20, which give the azimuth and elevation residuals for 4 passes of the MPS-36 radar 350 at White Sands Missile Range on February 25, 1976. A best fit was made to the 8 sets of residuals (elevation residuals for the first pass are not given because they are predominantly off scale), with the solution for an azimuth bias for each pass, an elevation bias for each pass, and a common mislevel amplitude and angle of rotation. The estimated mislevel parameters were:

$$\text{Mislevel} = 47''.7 \ \underline{/-20^\circ.9}$$

Azimuth biases were around 50", and the elevation biases in some cases exceeded 200". As is seen by the fit curves drawn in Figures 14 through 20, the mislevel behavior does a reasonably good job of explaining the systematic behavior of the measurement errors.

FIGURE 14. WSM350 AZIMUTH RESIDUALS (FEBRUARY 25, 1976)

(MAX EL = 27.79°)

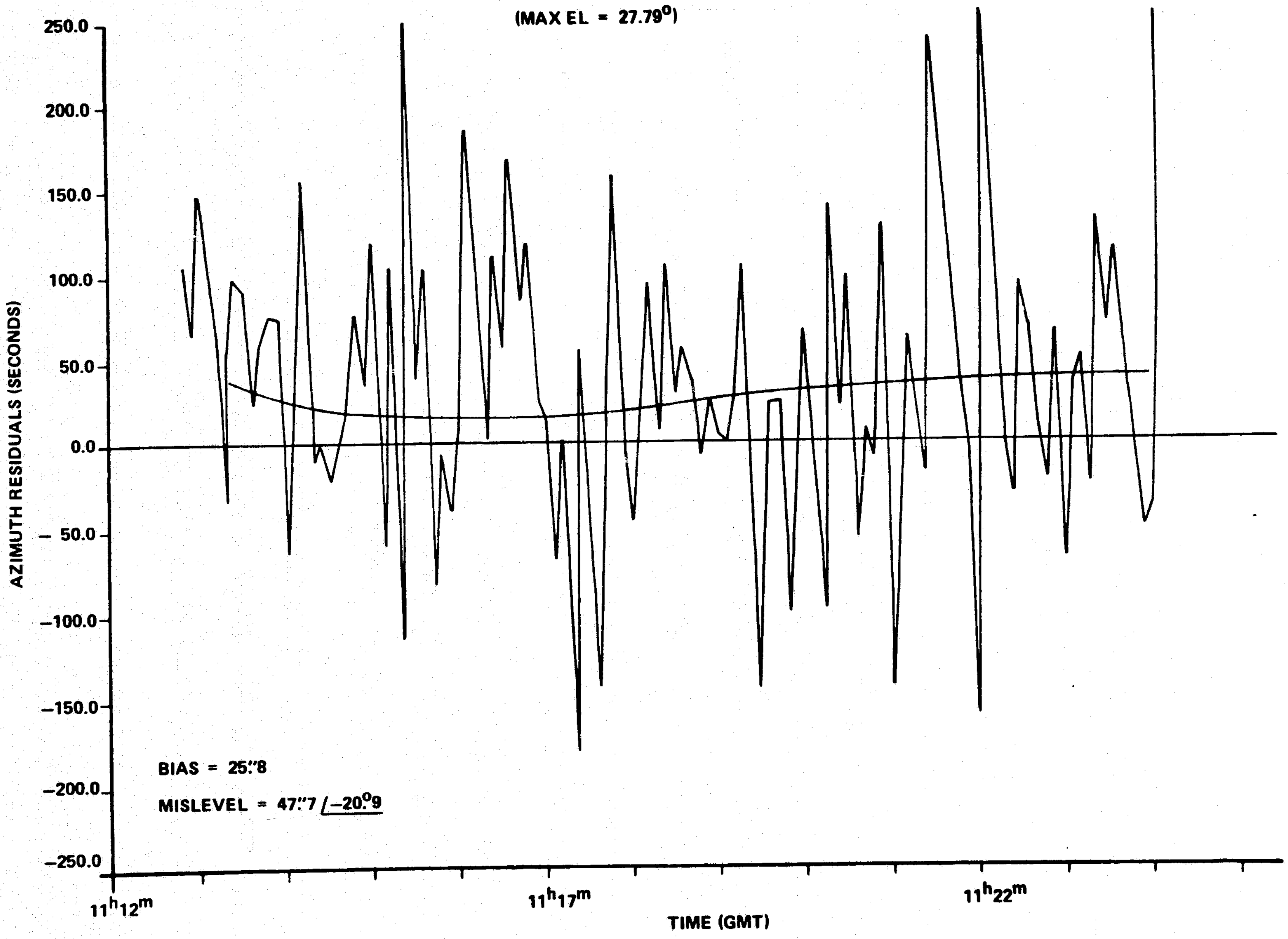


FIGURE 15. WSM350 AZIMUTH RESIDUALS (FEBRUARY 25, 1976)
(MAX EL = 41.69°)

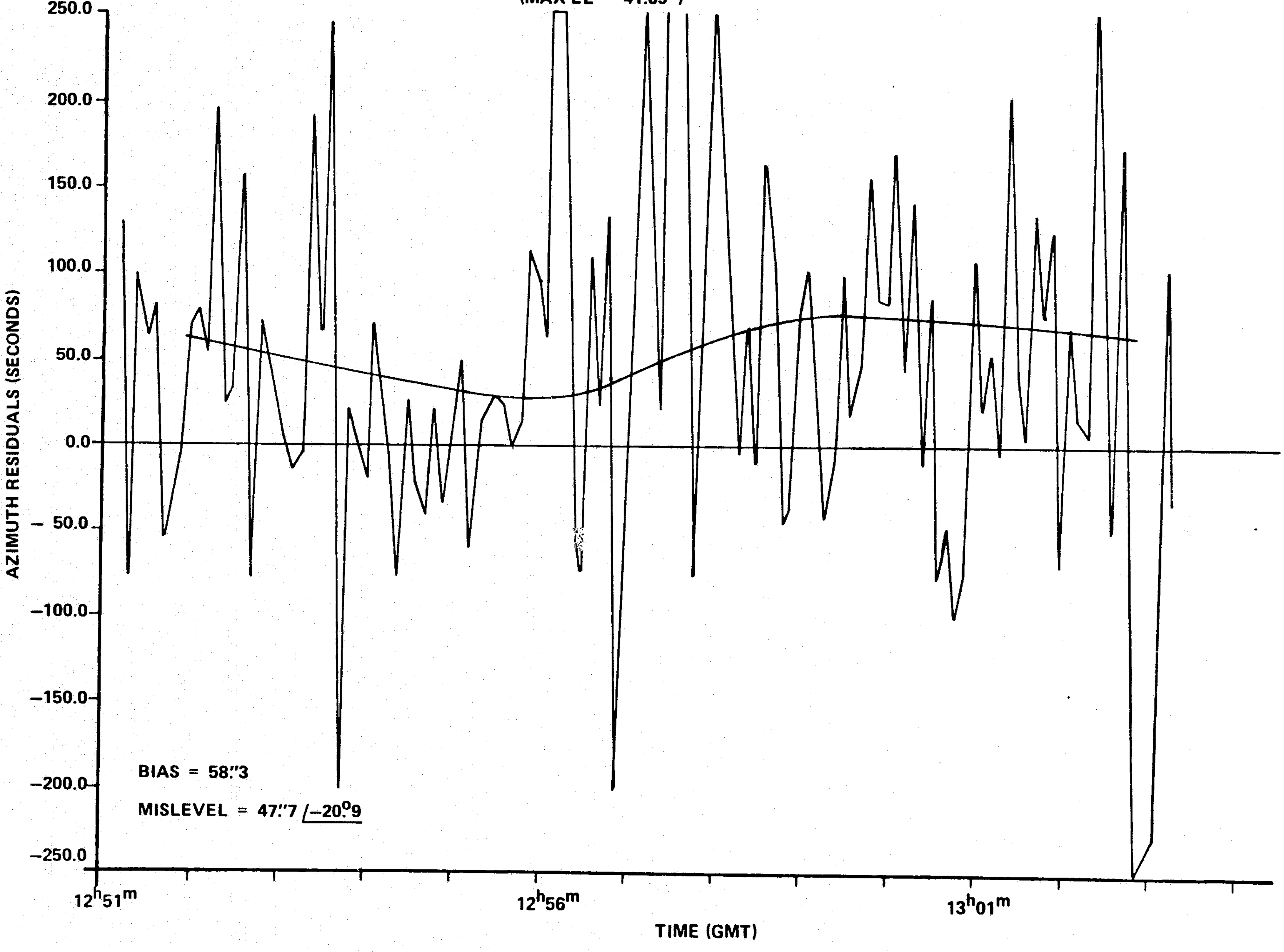


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FIGURE 16. WSM350 ELEVATION RESIDUALS (FEBRUARY 25, 1976)
(MAX EL = 41.69°)

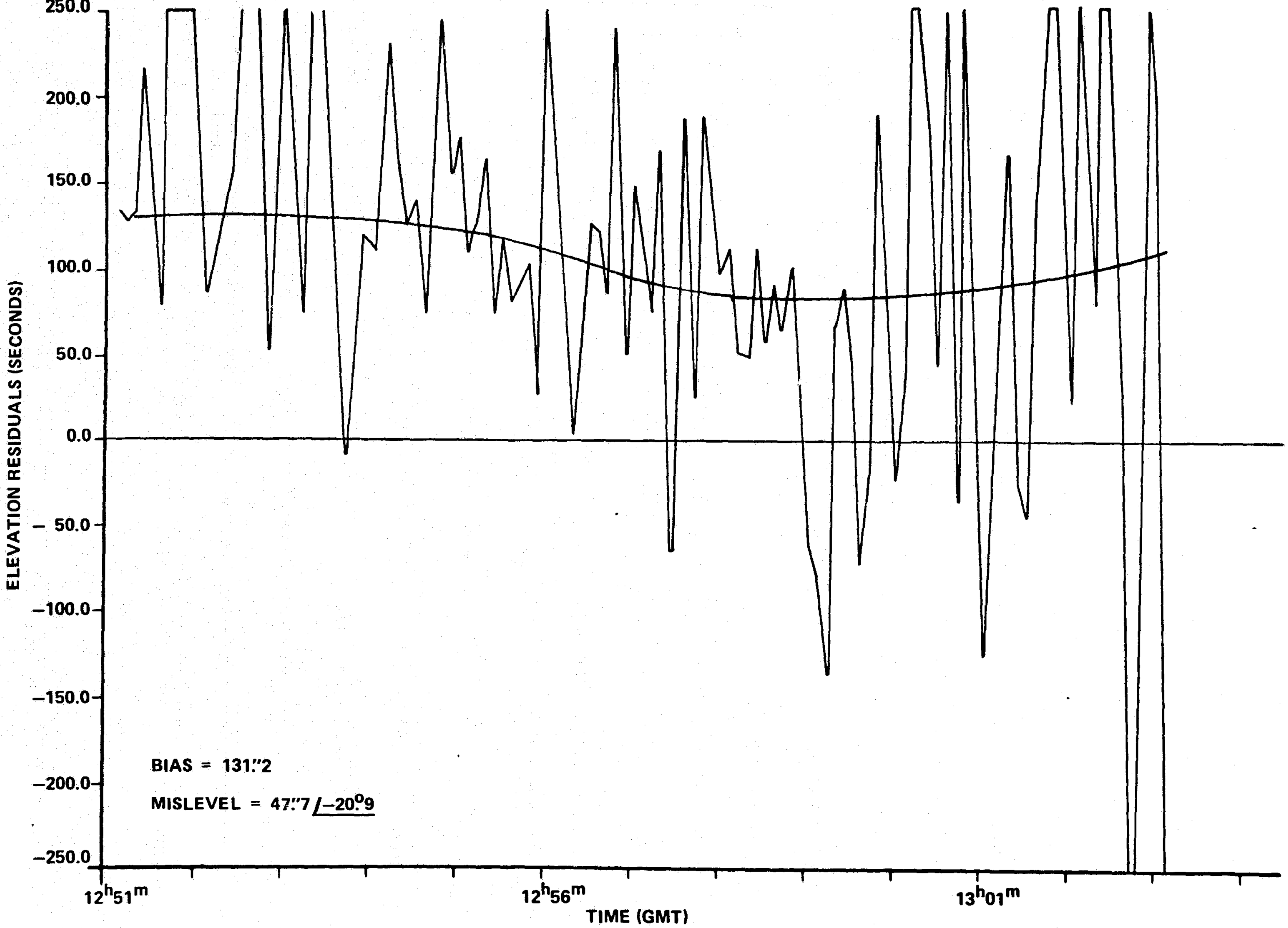


FIGURE 17. WSM350 AZIMUTH RESIDUALS (FEBRUARY 25, 1976)
(MAX EL = 27.46°)

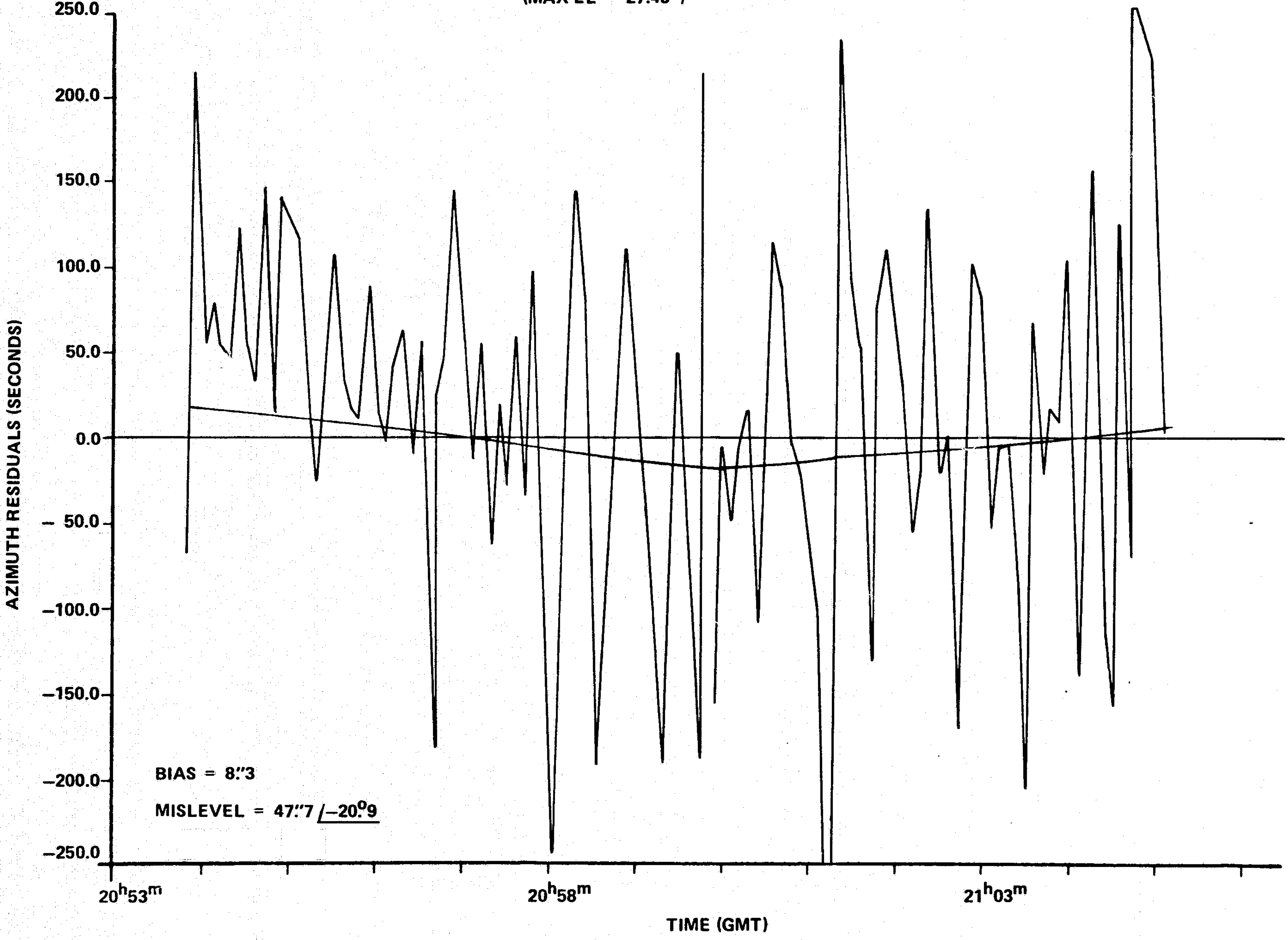


FIGURE 18. WSM350 ELEVATION RESIDUALS (FEBRUARY 25, 1976)
(MAX EL = 27.46°)

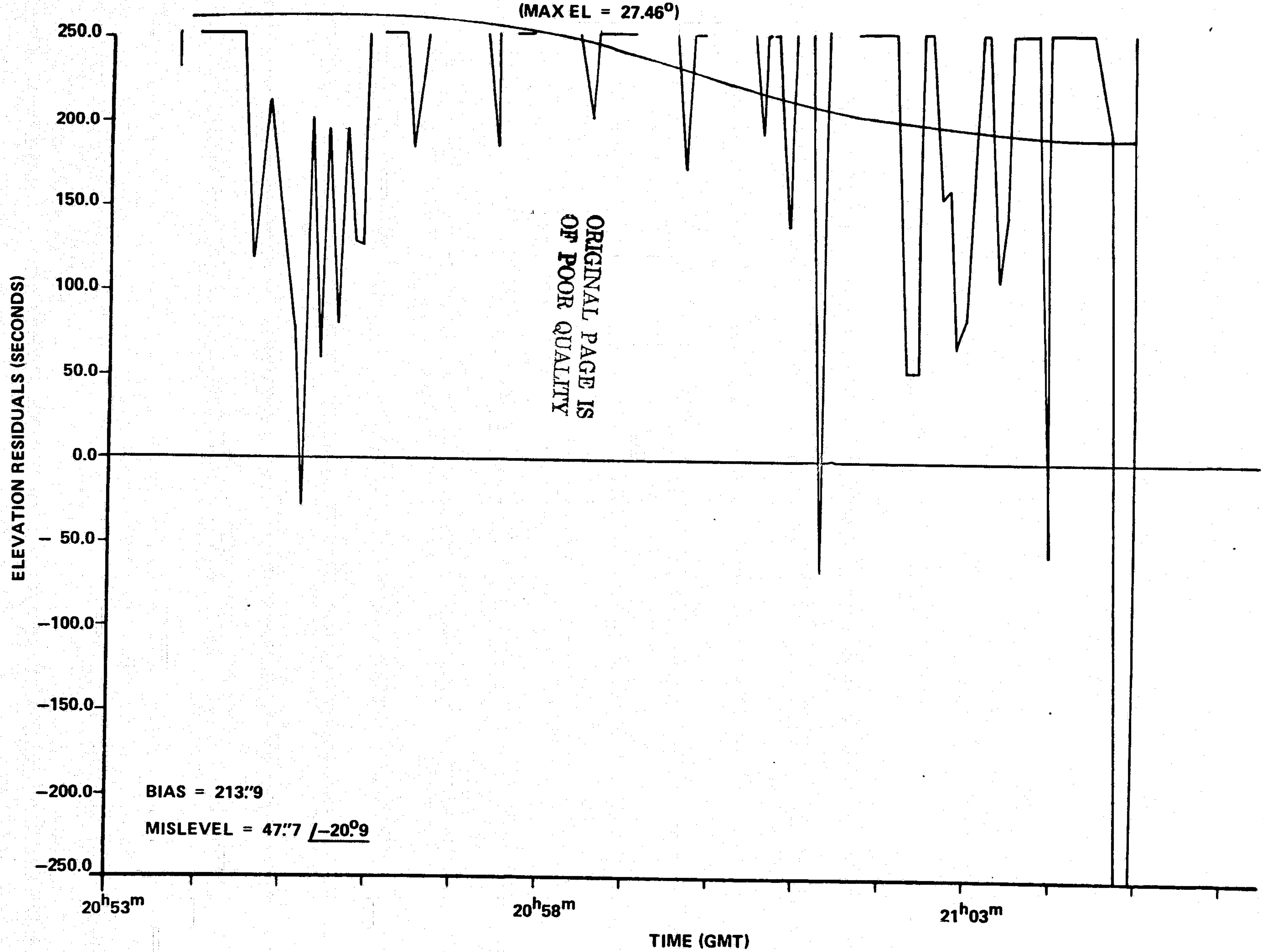


FIGURE 19. WSM350 AZIMUTH RESIDUALS (FEBRUARY 25, 1976)

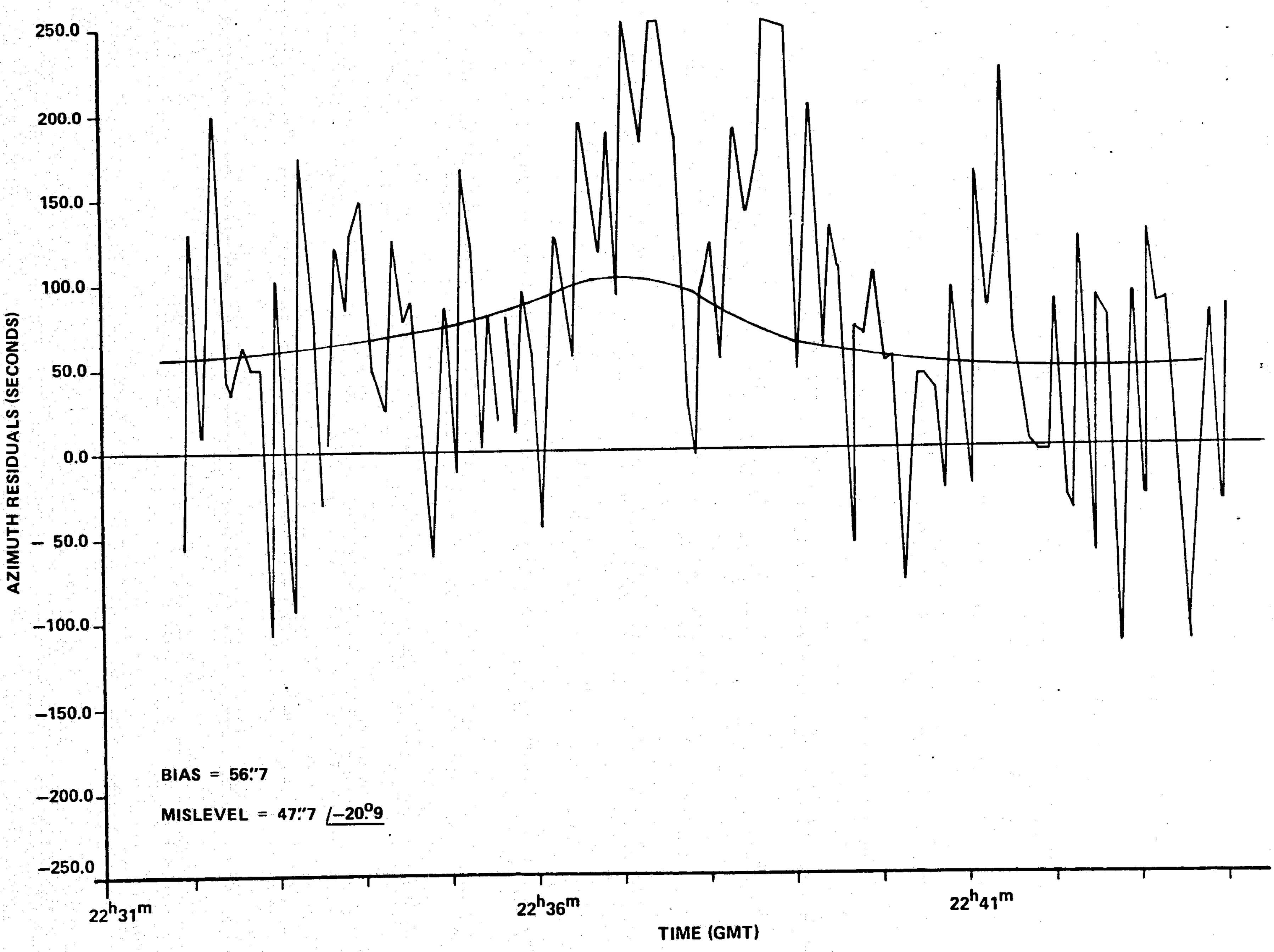
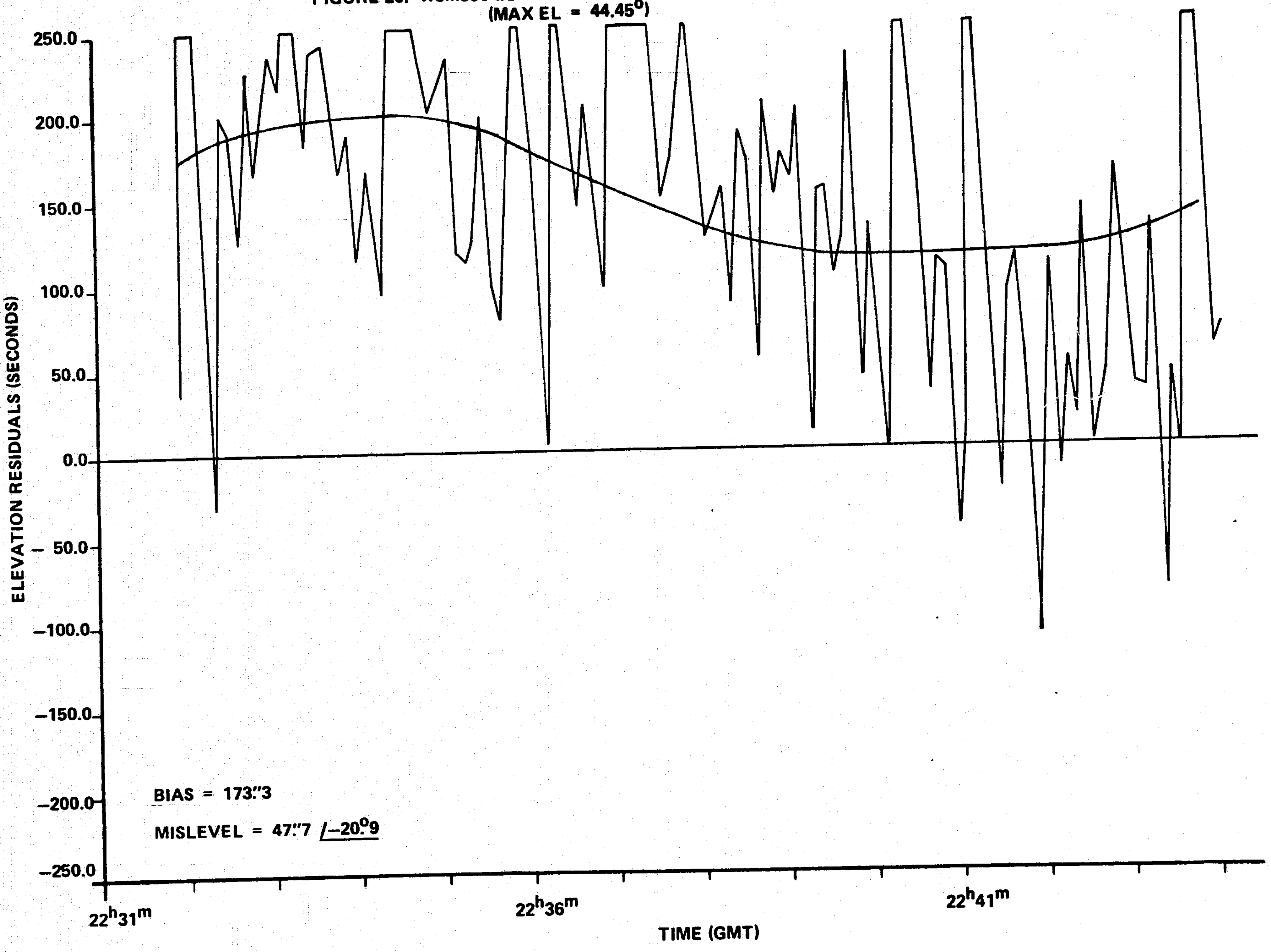


FIGURE 20. WSM350 ELEVATION RESIDUALS (FEBRUARY 25, 1976)
(MAX EL = 44.45°)



4.3 ANOMALOUS RESIDUAL PATTERNS

With the possible exception of the Ascension radar, which was known to experience occasional hardware problems, most of the residual patterns appeared explicable in terms of familiar error sources (lag, mislevel, etc.) discussed above, provided one is willing to accept anomalously large lag coefficients. One example of a problem residual is shown in Figure 21 for the WTRPPQ, where attempts were made to explain the pattern as due to velocity lag. Obviously, the residuals for the early portion of the pass do not fit the lag pattern very well. No other explanation is readily at hand, although an over-correction for tropospheric refraction is a possibility.

Finally, lacking a large number of examples of anomalous behavior, Figure 22 shows the azimuth residuals for a PMR radar, PMRPM4 (Station 4446), which is anomalous only in comparison to what was expected of the angle data in general. From Table 5, the mean of these residuals is -2", and with an RMS of 44". From Figure 22, the residual amplitude appears somewhat larger at the lower elevation angles, but there appears to be little, if any, overall systematic pattern to the residuals. In other words, they are nearly random, as they are supposed to be.

FIGURE 21. WTRPPQ ELEVATION RESIDUALS (FEBRUARY 23, 1976)

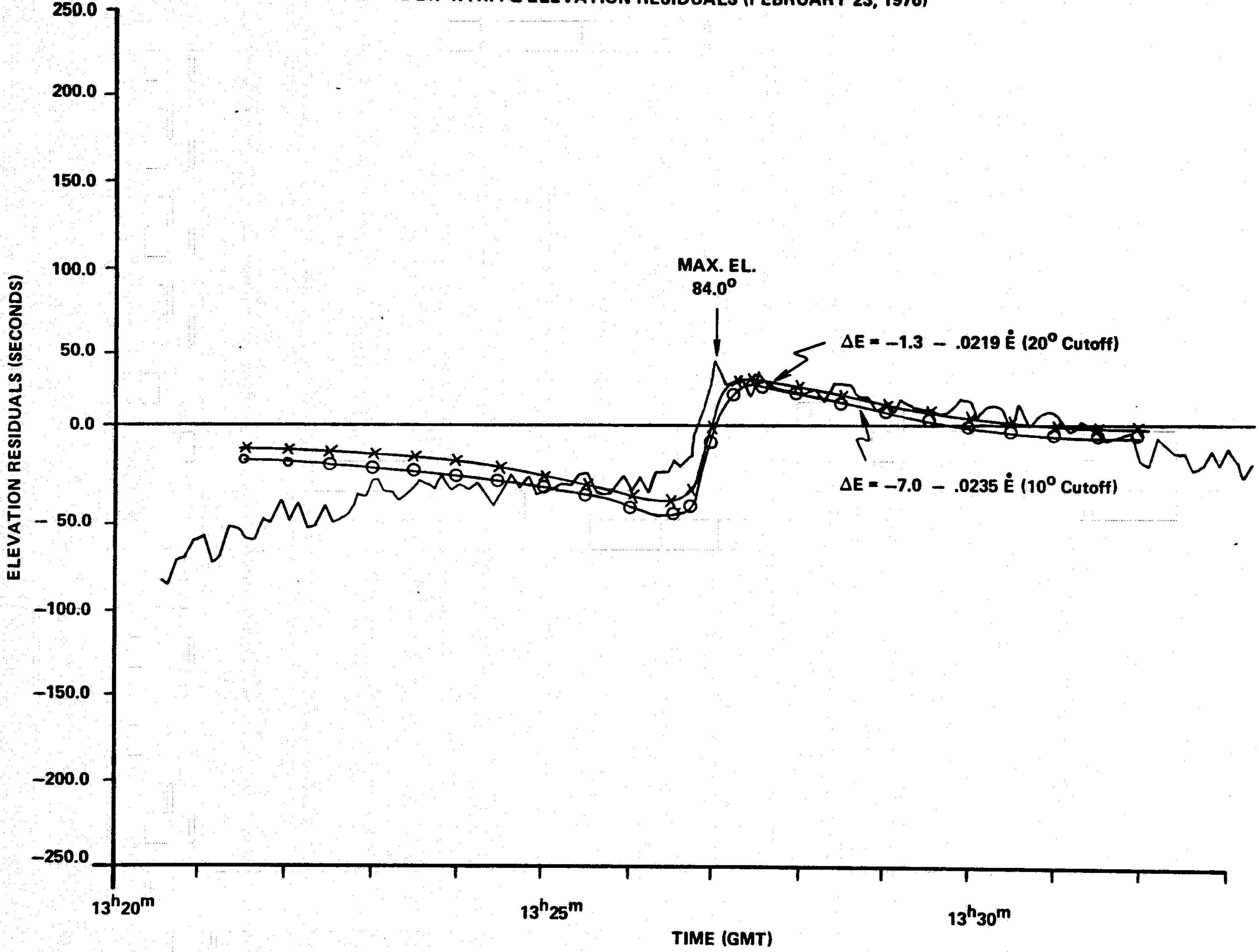
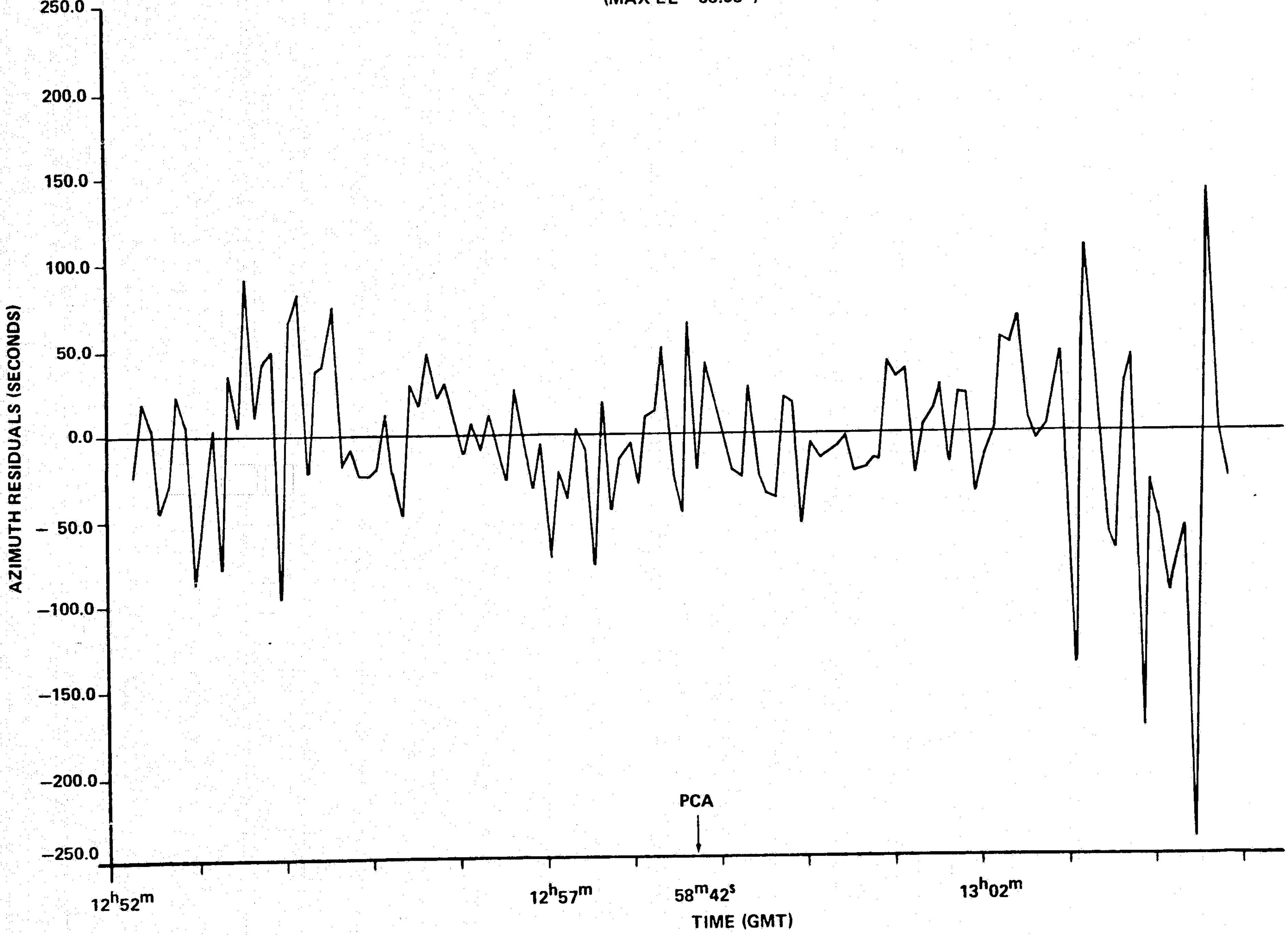


FIGURE 22. PMRPM4 AZIMUTH RESIDUALS (FEBRUARY 25, 1976)

(MAX EL = 68.98°)



SECTION 5.0
CONCLUSIONS AND RECOMMENDATIONS

The use of GEOS-3 has made major contributions to the calibration of a number of C-Band radars around the world. The major findings for the different measurement types are:

A. Range Rate Measurements

1. Timing
The major result for range rate measurements was conclusive evidence that the time tag for the measurement was in error. Prior to GEOS-3, it was known that there were problems with CSP data, but the existence of a timing error could not be pinned down because of the lack of a good range rate target and reference trajectory.

2. Biases
The resolution of the timing problem increased the accuracy of range rate measurements to the stage where biases became one of the more significant error sources. The utility of pre and post mission calibration was then investigated, with the conclusion that a major portion of the bias could be removed via this manner.

3. Integrated CSP Measurements
The technique of integrating range rate data to produce ambiguous range measurements was investigated [8] and found to be useful for integrating the effects of various systematic error sources so that they become visible above the noise level. Servo lag errors, residual timing and bias errors, and ionospheric propagation effects were studied in this manner. The actual noise level of the integrated CSP measurements is at the 2-3 cm level.

B. Range Measurements

1. Bias Stability

   Based largely upon calibrations using 2 pass bias solutions for Wallops and Bermuda, long term bias stability of 2-4 cm/day has been observed using normal ground calibrations to surveyed range targets. Day to day bias stability of much better than 1 m has been observed for some radars, based on one day arc calibrations, and should be possible for other radars.

2. Ground Calibration Accuracy

   Based on a limited analysis of normal radar calibrations (i.e., calibrations to surveyed range targets) as compared with satellite calibrations, it is strongly suggested that the true radar bias is more stable than are the ground calibrations. This would suggest that the normal radar calibration procedure prior to a mission needs to be re-examined.

C. Angle Data

Although only a limited analysis of angle data was performed, the overall level and prevalence of systematic errors were considerably lower than expected. Noise levels were consistent with that expected for the various radar types, with on-axis radars having the lowest noise levels, followed by radars with FPQ-6 (or TPQ-18) mounts. With regard to systematic error levels, the following was observed:

1. Bias Levels

   Bias levels observed were generally below the noise levels, with typical values in the 10"-20" range for FPQ-6 type radars and sometimes for FPS-16's.

2. Pedestal Mislevel
Some systematic patterns in angle and elevation residuals appeared to be largely explicable on the basis of biases and pedestal mislevel. One White Sands MPS-36 was analyzed in this manner with an estimated mislevel amplitude of 48".

3. Servo Lags
Servo lags in azimuth on high elevation passes are unavoidable, and the observed patterns are consistent with that expected. Lags in elevation for a number of radars are some 3-10 times the amount expected from servo rate lag, and have not been explained. Errors in time tagging the angle data (by amounts from 10-25 msec) would also explain the observed residual patterns for those cases where the same timing error is consistent with the azimuth residual patterns. It appears that such was sometimes the case, but the question has not been pursued to a definite conclusion.

4. No Detectable Patterns
It should be noted that there were passes for which some angle residuals showed no apparent trends, indicating that systematic errors had been corrected to well below the noise level.

5. On-Axis Radars
Although on-axis radars showed generally much lower noise levels than non-on-axis radars, there was no comparable lack of systematic patterns, particularly for lags.

The primary recommendation for further analysis is pursuit of the question of inherent radar range stability vs. the accuracy of ground calibration using surveyed range targets.

For the Wallops FPQ-6, there was a possible physical reason to question the stability of the ground calibrations, and improvement in results with a constant calibration might be expected. But the improvement for other radars for which there was no such physical justification strongly suggests that the reasons for time varying calibrations may be both numerous and elusive, and that only one of these reasons is a time drift in the radar itself. Several methods of approach are possible in identifying whether the radar is, or is not, actually varying. These include:

- Single pass range calibrations for a number of passes (A number of passes through the GEOS-3 calibration area had sufficient tracking and now have sufficiently good station positions to accomplish this.), with the results correlated with the normal ground calibrations.

- Use of constant calibrations for a network of radars, compared in (e.g.) one day arcs to the normal calibrations to see which method produces the best residual fit.

Regardless of the approach, the question of actual radar stability vs. errors in ground target calibration should be pursued for all radars for which maximum range accuracy is desired.

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15. Supplementary Notes

16. Abstract

The calibration of C-Band radars using satellites is discussed. The various methods of determining tracking radar measurement error parameters are described, along with the projected accuracy of results. Typical examples and results for calibration of radars tracking the GEOS-3 satellite are presented.

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