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CALIBRATION AND EVALUATION OF THE WALLOPS AN/FPQ-6 RADAR UTILIZING THE GEOS-II SATELLITE

A STATUS REPORT

WALLOPS GEOS-B C-BAND SYSTEM
PROJECT GROUP
AND
WOLF RESEARCH & DEVELOPMENT
CORPORATION

AUGUST 1968

WALLOPS STATION
WALLOPS ISLAND, VIRGINIA

X-16-68-1

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Status Report

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1.0 INTRODUCTION

The purpose of this report is to document the current status of the Wallops Island AN/FPQ-6 radar calibration effort in support of the GEOS-B (GEOS-II) C-Band Systems Project objectives. It presents the development and evolution of procedures in radar operation and data handling, representative results of data reductions and analyses, and the state of the radar calibration to date.

Although procedures and results documented here are specific to the AN/FPQ-6 radar, they are also applicable to the Wallops AN/FPS-16 radar and quite possibly to any comparable C-Band radar system.

The methods and procedures evolved and the results described were obtained from AN/FPQ-6, AN/FPS-16 and LASER tracking of the GEOS-II satellite from the period 15 January 1968 to 30 June 1968. The primary purpose of this effort is to calibrate C-Band radars in an attempt to fulfill some of the objectives of the National Geodetic Satellites Program (NGSP) and the GEOS-B C-Band Systems Project.

2.0 PROJECT OBJECTIVES

The objectives of the GEOS-B C-Band Systems Project are to calibrate the C-Band radar systems to a degree which will qualify their use as geodetic data gathering systems and, if successful, to subsequently use the systems to provide geodetic data for use in the NGSP. Specifically, the project objectives are:

a. to better determine the accuracy of C-Band radar systems, develop refined methods for calibrating the systems, and improve the techniques employed in processing the data

b. to better determine the geodetic location of the C-Band radar sites and their intersite distances

c. to compare and correlate results obtained from the C-Band radars with emphasis on the evaluation of the possible contribution of C-Band data to the NGSP geodetic objectives

d. to make generally available the results of both the C-Band system calibration and the geodetic endeavor.

3.0 EQUIPMENT DESCRIPTION

3.1 Radar

Wallops Station has two C-Band radar systems, the AN/FPQ-6 radar and the AN/FPS-16 radar. The AN/FPQ-6 is a pulsed radar capable of non-ambiguous range measurements of up to approximately 32,000 nautical miles (nm). In addition to range measurements, the AN/FPQ-6 also provides azimuth and elevation angle measurements to the target. Using coherent signal processing (CSP), it provides range rate measurements. For this project, CSP can only be used in the skin track mode since a coherent beacon is not available on GEOS-II. The AN/FPQ-6 provides:

		Binary Bits	Least Count
AN/FPQ-6	R	25	~ 1.95 yards (yds)
	A,E	20	~ 1.24 seconds of arc
	$\dot{R}$	29	~ 0.00006 yds/sec

The AN/FPS-16 is a pulsed radar capable of non-ambiguous range measurements of up to ~ 32,000 nm. It also provides azimuth and elevation angle measurements to the target; however, it does not have CSP capability. The AN/FPS-16 provides:

AN/FPS-16	R	25	~ 1.95 yds
	A,E	17	~ 9.89 seconds of arc

3.2 Satellite Systems

GEOS-II, the second in a series of geodetic satellites, was launched in January 1968. It is equipped with memory controlled optical beacons, a U.S. Army SECOR transponder, a NASA Range and Range Rate transponder, NASA Minitrack beacon, U.S. Navy Doppler beacons, LASER corner cube retrodirective reflectors, two non-coherent C-Band transponders, and a retrodirective array for passive C-Band tracking. This combination of geodetic instrumentation on a single spacecraft provides a unique opportunity to calibrate the C-Band systems and evaluate their potential contribution to the geodetic sciences by comparing their measurements with the variety of others available.

3.3 C-Band Satellite Systems

The design criteria for the GEOS-II satellite called for C-Band transponders (beacons) with delays identifiable to the extent that residual variation and delay jitter would not cause a radar range noise greater than ± 1.5 yds RMS. To further insure this goal, the passive reflector was designed so that both skin and beacon tracks might be performed and compared to remove range bias caused by the beacon. The satellite system also provides numerous beacon monitoring devices that are telemetered to supporting ground stations for analysis.

The beacon antenna patterns were also an item of concern since any sharp nulls would be very detrimental to the angle tracking performance of amplitude comparison monopulse systems such as the AN/FPQ-6 and AN/FPS-16 radars. These patterns were found to have a few undesirable nulls; however, overall performance is considered acceptable.

Two beacons were installed to insure long life. These were given different fixed nominal delays (Beacon #1, 0.7 μsec; Beacon #2, 5.0 μsec) to explore the advantages of short and long delays in actual operating conditions and to insure that no mix-up in identification could exist. The beacons were given wide receiver bandwidths to avoid possible errors caused by the radar system shifting frequency. Solid state local oscillators were installed to increase stability and operating life.

While the beacon delay noise approached design criteria, the absolute delay bias, as determined from APL-VEGA calibration charts and test data, could not be established better than ± 2 yds RMS.

The possibility still exists, however, that this error may be calibrated as a result of the data analysis now being performed since it is generally believed to be a pure bias (not subject to diurnal changes or systematic drifts).

4.0 METHODS AND PROCEDURES

The primary objective in the GEOS-B C-Band System Project being calibration, the methods and procedures followed by Wallops were designed to most efficiently accomplish this task. We have assembled a task group with knowledge of the radar hardware and experience in the analysis of tracking data. The general philosophy adopted by this group is as follows:

1. Prior to the first tracking mission, a set of procedures for radar calibration, operation, and data handling was established to insure that all data would be gathered and reduced in a consistent manner.

2. Tracking data obtained on GEOS-II was to be reduced and analyzed to identify systematic trends in the residuals.

3. The nature of these errors was to be investigated to relate them to hardware, method of calibration, or human origin.

4. If such an origin could be identified, the appropriate adjustment to the hardware or procedures would be made.

5. Data collected following these changes would be evaluated to establish the effectiveness of the modification.

6. Systematic errors whose source is external to the radar hardware itself, such as refraction, transponder delay, and timing corrections would also be evaluated to insure the adequacy of their functional form.

7. Procedures and results would be documented in detail to assist us in performing future calibrations and to provide guidelines for the calibration of other C-Band systems.

Since the measurement channels are relatively independent, we have decided to investigate the systematic errors in each separately. We have addressed ourselves initially to the range channel. We now are beginning work on the angle measurements, and finally will attack the range-rate measurements which are available only in skin track mode. When the major errors in each channel have been identified and removed, an investigation will be conducted to determine whether any cross channel effects appear.

Systematic trends in the residuals whose source may not be traceable to the hardware or to known external causes are also possible. If such should appear, we intend to study their stability and attempt to establish their functional form. If stability can be established, these errors will be removed in postflight processing. We hope to avoid, whenever possible, the estimation of error model terms in the orbit determination process. Although our major analytical tool, the NONAME orbit determination system [1] has this capability, we feel that any calibration effort should use this only as a last resort.

The problem of combinatorial behavior of systematic error must be evaluated from two points of view. From the data reduction point of view it is only necessary to evaluate the overall form and stability of those systematic errors which affect the performance of the system. If a simple error model properly describes the form and function of the systematic errors and it can be shown that this model exhibits the necessary stability, then the data reduction problem can be considered solved. From the calibration point of view, however, it is important to identify the various sources which contribute to the total error in order to determine whether hardware modification or changes in procedures are indicated. With this in mind, Wallops has performed experiments and is planning more in order to identify and verify the various sources which make up the range bias error.

The results of the investigations to date are tabulated in Table IV Section 5.5. From time to time the results of this effort will be used in a previously determined solution to verify the fact that the total error tabulated does improve the RMS of fit of the data. This information will in turn be used to evaluate the completeness and validity of the tabulated information.

4.1 Radar Set-Up

As a point of departure prior to any data acquisition a radar set-up was established for both the AN/FPQ-6 and the AN/FPS-16 radars at Wallops Station. In the case of the AN/FPQ-6, two set-ups were initially established, one for beacon mode tracking, the second for passive (skin) tracking. This original set-up is shown in Table I.

ORIGINAL RADAR SETUP

TABLE I

Term	Radar Setup for Transponder (Beacon) Track		Radar Setup for Passive Reflector (Skin Track)
	FPS-16	FPQ-6	FPQ-6
Peak Power	1.0 MW	2.0 MW	2.8 - 3.0 MW
Transmitter Frequency	5690 MHz	5690 MHz	5690 MHz
Receiver Frequency	5705 MHz	5765 MHz	5690 MHz
Pulse Width	1.0 µsec	1.0 µsec	1.0 or 2.4 µsec
Pulse Code	2 pulse 8 µsec spacing	2 pulse 8 µsec spacing	single pulse
Polarization	Linear Vertical	Linear Vertical	Circular
PRF	160 or less	160	160 or 640
Beacon AFC	Yes	Yes	No
Beacon Delay Compensation	0, 0.07 or 5 µsec	0, 0.7 or 5 µsec	0

Early results of operational performance and data analysis dictated modifications to the set-up procedures. Our present operational set-up, reflecting these changes, is shown in Table II and includes a third mode of operation for beacon/skin tracking. This mode of tracking is used when both beacon and skin track data are to be gathered on a single pass of GEOS-II. It should be emphasized that changes in the operational set-up are made only after a careful analysis of the data and the hardware system indicate that such a change will enhance the C-Band radar performance. We have been using the current set-up for several months now, and it will not be changed until we have strong evidence from the data or the hardware evaluation experiment that such changes are necessary. The rationale for the current GEOS-II tracking set-up is described in the following paragraphs.

We selected a wide transmitter pulsewidth (2.4 μsec) for skin tracking since it provides signal-to-noise enhancement and increases the reliability of CSP tracking. For the beacon portion of beacon/skin missions we reduced the pulsewidth to 1 μsec since in the wider pulsewidth, the coding required would have caused the radar transmitter to approach its duty cycle. Switching from single to double pulse operation while the radar is in this condition often causes transmitter overload. Therefore, the 1 μsec pulsewidth makes the beacon-to-skin-to-beacon transition more reliable. The AN/FPQ-6 has the capability of dual presentation of skin and beacon returns. This was omitted for all tracks and calibrations except the beacon-skin case where continuous mode was used to facilitate switching from beacon-to-skin-to-beacon.

PRESENT RADAR SETUP

TABLE II

	FPS-16	FPQ-6		
			BEACON/SKIN	
	BEACON ONLY	BEACON ONLY	SKIN PORTION	BEACON PORTION
PARAMPS	ON	ON	ON	ON (BOTH)
PULSEWIDTH	1 μsec	0.5 μsec	2.4 μsec	1 μsec
POLARIZATION	LINEAR VERTICAL	LINEAR VERTICAL	LINEAR VERTICAL	LINEAR VERTICAL
PRF	160	160	640	160
BEACON AFC	ON	ON	OFF	ON
BEACON DELAY COMPENSATION	809 yds.	809 yds	N/A	809/123 yds as appropriate
SKIN AFC	OFF	OFF	ON	ON
RANGE BANDWIDTH	4 cps	4 cps	4 cps	4 cps
ANGLE BANDWIDTH	3.2 cps	Pos.#9 3.2 cps	Pos.#9 3.2 cps	Pos.#9 3.2 cps
DATA CORRECTOR BANDWIDTH	N/A	2 cps	2 cps	2 cps
DATA RATE	10 PPS	10 PPS	10 PPS	10 PPS
RECEIVER BANDWIDTH	1.8 MC	2.4 MC	0.6 MC	1.6 MC
BEACON GATE	ON	ON	OFF	ON
BEACON LO	ON	ON	OFF	ON
SKIN GATE	OFF	OFF	ON	ON
SKIN LO	OFF	OFF	ON (COHERENT)	ON (COHERENT)
DOPPLER SYSTEM BANDWIDTH	N/A	N/A	160 cps	40 cps
DOPPLER LO LOOP BANDWIDTH	N/A	N/A	WIDE	WIDE
POSITION TRACK	N/A	N/A	GROSS	GROSS
DOPPLER SYSTEM	N/A	N/A	ON	ON (SKIN)
PULSE CODER	On 2 Pulse 8 μsec	On 2 Pulse 8 μsec	OFF	On 2 Pulse 8 μsec(both)

Since the parametric amplifier systems (paramps) at the Wallops AN/FPQ-6 and AN/FPS-16 can be pre-set and pre-phase delay corrected to provide instantaneous switching between two frequencies, they are used in all tracking applications to avoid the possibility of change in system alignment caused by by-passing the paramps.

Atmospheric phenomena can often cause conflicting re-polarization (signal fading) when systems are operated with like polarizations. To avoid the possibility of these deep signal fades, we operate the radar in linear-vertical although the transponder antenna polarization is circular.

When tracking the transponder, the radar automatic frequency control (AFC) loop uses the transponder return frequency as its reference. In the skin portion of the beacon/skin mode, the AFC references the range rate from the range system until the CSP acquires track whereupon the pulse doppler controls the loop.

The pulse repetition frequency (PRF) is held at 160 for all tracks and calibrations except skin tracking. In skin track, we use the 640 rate, since it furnishes significantly better track at low signal to noise ratio (S/N).

We set the range bandwidth at 4 cps for all tracks and calibrations. The 4 cps bandwidth is adequate for the dynamics of the GEOS-II satellite.

We have set the angle bandwidths at 3.2 cps to handle the dynamics expected from GEOS-II during 85° elevation tracks. We maintain this setting for all tracks to avoid the problem of having a large number of set-up variables. This makes the analysis of the tracking data somewhat easier.

The rationale for selecting the bandwidths was based on the analysis of servo lag vs. lag correction calibration curve accuracies in the GEOS-II dynamic range.

Throughout all operations, every effort has been made to maintain the radar set-up outlined. Any deviations from the recommended set-up in either track or calibration operations are documented so that the possible effect on the data can be evaluated and applied to the data if necessary.

4.2 Pre- and Post-Mission Calibration

Prior to the launch of GEOS-B, radar maintenance and alignment procedures were collected from all the ranges and studied to develop the best set possible for the Wallops AN/FPQ-6 radar. Many of the procedures were collected from all the ranges and studied to develop the best set possible for the Wallops AN/FPQ-6 radar. Many of the procedures already in use at Wallops were adopted, some from other ranges were chosen, and a few new ones were written. One of the chief weaknesses in our radar set-up procedures was in the collimation. The RCA radar manual [1] was used as a basis for writing a better defined procedure so that repeatability would be accomplished.

Also the maintenance and operating procedures were written in sufficient detail to insure day-to-day and operator-to-operator repeatability.

It is understood that the procedures thus produced are not final but merely represent the beginning point for an iterative process to be conducted in the GEOS-II Project.

Review of all available reports and documents pertaining to radar boresighting failed to yield sufficient historical data on the AN/FPQ-6 radar. Therefore, simultaneously with the procedure writing effort, a boresighting routine was developed that could be run on all Wallops missions to provide this vital data.

Analysis of this data established the mean and deviations that might be expected under normal operation. This data was very valuable in editing the GEOS-II boresight data. The most significant outcome of this procedure was the discovery that the boresight target being used to calibrate the range system was not sufficiently stable, and as a result new targets were studied and a replacement was eventually selected.

As the GEOS-II transponder was being tested for flight qualification, it was decided that a test of a sample unit with the AN/FPQ-6 radar at Wallops would be useful to confirm systems compatibility and transponder delay. These tests both confirmed some calibration problems expected and revealed some unanticipated problems. Pulsewidth, bandwidth, pulse coding, PRF, signal to noise, local oscillator mode, all affected the range measurement.

4.3 Minimization of Human Error

A system of site logs and reports is used to standardize set-up and calibration procedures and minimize the possibility of human error. Examples of some of these logs are shown in Figures 1-5.

In addition, quick-look data reduction feedback is provided to site personnel. This feedback has helped to convert would-be errors into identifiable quantities and has, on occasion, resulted in operational improvements. As an example, the location of a pulsewidth error in the beacon portion of the beacon/skin track discussed in Section 5.0 resulted from the rapid feedback of data reduction results to site personnel.

4.4 Data Pre-Processing

Data pre-processing is defined as all quality control and data correction processes applied to the radar data postflight but prior to its inclusion in the data reduction process.

Here again, we have followed the philosophy of establishing a consistent procedure, evaluating the efficiency and validity of this procedure through data reduction analysis and hardware evaluation experiments, and modifying the procedures as indicated. The initial procedure established to pre-process the AN/FPQ-6 data is described in the following paragraphs.

RADAR LOG

1 DATE	2 PRED. HOR. TIME	3 SITE	4 MISSION NUMBER

OPERATING PARAMETERS

5 PW 1.0 2.4 ___ us.	6 PRF 160 640 ___ PPS	7 RCVR. BW 1.6 0.6 ___ MHz	8 XMTR. FREQ. ___ MHz	9 RCVR. FREQ. ___ MHz	10 XMTR. PWR.% 100 ___ PERCENT	11 XMTR.PWR. 2.5 2.0 ___ MW

12 POLARIZATION CIRC LIN	13 NOISE FIGURE REF___ AZ___ EL___ db	14 INSERTED BCN.DLY ___ N/A YARDS	15 PULSE CODE ___,___N/A NBR us	16 SYSTEM K ___

17 SEC POT IN OUT	18 TCKING GATE SKIN BEACON	19 BEACON TRACKED LONG SHORT DELAY	20 DATE OF LAG ERROR CORRECTION CALIBRATION ___	21 EL Pos During Calibration Manual Locked-on

22 MEASURED ERROR GRADIENT

AZIMUTH___

ELEVATION___

23 SERVO BANDWIDTH SW POS VRS BW HZ

	POS 6	POS 7	POS 8	POS 9	POS 12
ELEVATION	___	___	___	___	___
AZIMUTH	___	___	___	___	___
RANGE	___	___	___	___	___

24 TRACK K_v

AZIMUTH___

ELEVATION___

mils/sec

25

K_0 ___	K_a ___	K_{es} ___
K_1 ___	K_e ___	K_{ab} ___
K_2 ___	K_{as} ___	K_{eb} ___
K_3 ___		

26 CALIBRATION SURVEY

BORESIGHT TWR AZ ___

BORESIGHT TWR EL ___

RANGE TARGET RNG ___

27 COMMUTATION FREQUENCY

28 DATA CORRECTION BANDWIDTH

OPERATION DATA

29 ACQUISITION USED ___ ___ ___	30 PREDICTED PCA EL___DEGREES RNG___KYDS TIME___ZULU	31 SIGNAL CHARACTERISTICS STEADY LOBING WITH DB NULLS REMARKS___ ___

32 ORIGINAL ON___Z OFF___Z ON___Z OFF___Z TRACKING TIMES

ON___Z OFF___Z ON___Z FINAL OFF___Z

33 REMARKS:___

___

___

___

___

Figure 1

CALIBRATION CODE SHEET

ROUTINE CALIBRATIONS

GENERAL - Record Minimum of 100 Samples for Each Function, Use 100 Series for Pre-Calibrations and 200 Series for Post-Calibrations

ID			ID		
PRE	POST	FUNCTION	PRE	POST	FUNCTION
101.	201.	LOCK-ON-NOISE	123.	223.	BORESIGHT TOWER NORMAL
102.	202.	0 DB	124.	224.	BORESIGHT TOWER PLUNGED
103.	203.	3 DB	125.	225.	RANGE TARGET - SKIN GATE
104.	204.	__________ DB	126.	226.	RANGE TARGET - BEACON GATE
105.	205.	5 DB	127.	227.	AZIMUTH - ONE MIL LEFT
106.	206.	6 DB	128.	228.	AZIMUTH - ONE MIL RIGHT
107.	207.	__________ DB	129.	229.	ELEVATION - ONE MIL BELOW
108.	208.	__________ DB	130.	230.	ELEVATION - ONE MIL ABOVE
109.	209.	__________ DB	131.	231.	XMTR - ATTN OUT
110.	210.	10 DB	132.	232.	XMTR - ______% PWR
111.	211.	15 DB	133.	233.	XMTR - ______% PWR
112.	212.	20 DB	134.	234.	RCVR - ATTN OUT
113.	213.	25 DB	135.	235.	RCVR - ______ DB ATTN IN
114.	214.	30 DB	136.	236.	RCVR - ______ DB ATTN IN
115.	215.	35 DB	137.	237.	RCVR - ______ DB ATTN IN
116.	216.	40 DB	138.	238.	TEST ROCKET
117.	217.	45 DB	139.	239.	SPHERE TRACK
118.	218.	50 DB	140.	240.	
119.	219.	55 DB	141.	241.	
120.	220.	60 DB	142.	242.	
121.	221.	65 DB	143.	243.	
122.	222.	70 DB	144.	244.	

SPECIAL CALIBRATIONS

RECEIVER GAIN - Bias antenna one mil right and above from boresight tower lock-on point. Run AGC calibration; recording AGC, azimuth error and elevation error.

ID	FUNCTION
301.	0 DB
302.	5 DB
303.	10 DB
304.	15 DB
305.	20 DB
306.	25 DB
307.	30 DB
308.	35 DB
309.	40 DB
310.	45 DB
311.	50 DB
312.	55 DB
313.	60 DB
314.	65 DB
315.	70 DB

ERROR CHANNEL LINEARITY - Maintain minimum of 50 DB signal from boresight tower. Bias antenna one mil from lock-on in elevation. Perturb antenna in azimuth from minus 3 to plus 3 mils, stopping and recording each and every one half mil. Repeat above, substituting azimuth for elevation and elevation for azimuth.

ID		
AZ	EL	FUNCTION
316.	329.	-3.0 mil
317.	330.	-2.5 mil
318.	331.	-2.0 mil
319.	332.	-1.5 mil
320.	333.	-1.0 mil
321.	334.	-0.5 mil
322.	335.	0.0 mil
323.	336.	+0.5 mil
324.	337.	+1.0 mil
325.	338.	+1.5 mil
326.	339.	+2.0 mil
327.	340.	+2.5 mil
328.	341.	+3.0 mil

Figure 2

ZERO TIME WEATHER OBSERVATION
WALLOPS ISLAND, VIRGINIA

WALLOPS MODEL NO.	HK-720
VEHICLE	GEOS-B
OTHER MODEL NO./REV.	
PASS DATE	
PASS TIME	Z

DISTRIBUTION

P.C.	
R.I.B.	
RADAR	

CLOUD COVER (BASES IN HUNDREDS OF FEET)		
VISIBILITY (IN STATUTE MILES) AND WEATHER		
SEA LEVEL BAROMETRIC PRESSURE	millibars	
TEMPERATURE AND DEW POINT (DEGREES F.)		
SURFACE WIND (30 FEET ABOVE GROUND, BLDG. X-85)	°/	MPH

REMARKS:

Data in Support of Radar: (GEOS Designation/Designations)	FPQ-6 4860	FPS-16 4840				
Distance from Observation Site to Radar Site/Sites:						
Direction from Observation Site to Radar Site/Sites:						
Height of Observation Site Relative to Radar Site/Sites:						

SUPPORT RADIOSONDE	Ascent No.	Release Time	Termination Pressure	Termination Altitude	Reason for Termination
				ft.	
				ft.	

Other Data or Remarks: ____________________

____

____

____

Figure 3

DATA PROCESSING LOG

GEOS SUPPORT

List any bit weight corrections made to any parameter with a full explanation: ____________________

List any bit count corrections made with full explanation: ____________________

List value of any timing bias applied to data: ____________________

Describe the data source and the method used for any leveling correction applied: ____________________

Other Comments: ____________________

Figure 4

LEVELING FORMAT

DATE ________________ INSTRUMENTATION NO. ____________

GEOS DESIGNATION ____________

SUPPORT INFORMATION

TIME READINGS STATED ________________Z ENDED ________________Z

WEATHER CONDITION AT TIME OF READINGS (circle one)

RAINING FOGGY HAZY OVERCAST PARTLY CLOUDY BRIGHT

TEMPERATURE AT TIME OF READINGS ________________deg. F.

AVERAGE WIND AT TIME OF READINGS ____________Kts. FROM ____________deg.

WIND CONDITION AT TIME OF READINGS (circle one) STEADY GUSTY TO ______Kts.

OBSERVATION DATA

Record values in seconds for azimuth given in mils.

AZIMUTH	CW	CCW	AZIMUTH	CW	CCW
0000			3600		
0400			4000		
0800			4400		
1200			4800		
1600			5200		
2000			5600		
2400			6000		
2800			6400		
3200					

REMARKS

____

____

____

____

Figure 5

The on-site RCA 4101 computer program is used to apply the static corrections (pedestal mislevel, droop, non-orthogonality, encoder bias, encoder non-linearity, and skew) to the raw data. We have chosen not to apply the dynamic lag corrections to the data at this point. However, we record the corrections which are calculated by the 4101 program. The 4101 output tape is then processed through the PASS-1 program which applies a time tag correction to the data, converts the data from radar bits to range in feet, and azimuth and elevation in decimal degrees. The PASS-1 program also reformats the data from 4101 format to a GE-625 compatible format. The PASS-1 output is then used to perform the following operations. First the R, A, E, $\dot{R}$ calibration (pre and post) are analyzed and calibration corrections are computed. The pre-processing program applies a transit time correction, nominal beacon delay correction, refraction correction and range calibration correction to the data.

The data used in obtaining the results reported here was pre-processed as described above. We have, however, designed a more sophisticated and automated pre-processing system during the course of our investigation. This new system, currently being implemented, reflects the knowledge gained during the earlier stages of the project. Again, our analysis of data has indicated where changes to our original system should be made. This pre-processing system is designed to use as input, the output of the modified PASS-1 program, and performs the functions discussed below.

a. Pre-Calibration

Computes pre-calibration information by comparing radar observed values with survey values. Using 100 calibration measurement samples, it computes the mean difference of radar and survey measurements and the standard deviation about this mean. A 3σ editing routine is used to eliminate rogue points in the calibration.

b. Data Quality Control Check

In addition the program compares radar operational modes with the mission requirements. The following comparisons are made and all inconsistencies noted:

the radar is in track mode
the target is detected
the automatic gain control (AGC) is on
the radar is not in coast/rate aid
the radar is in operate status
the range is verified
the radar is in appropriate track mode
  skin or beacon (mission dependent)
signal above 12db.

It compares the radar operational mode with the mission requirements. The following comparisons are made:

range servo BW
azimuth servo BW

elevation servo BW
azimuth data corrector BW
elevation data corrector BW.

When the radar is in skin track mode, the program verifies the following for CSP tracking:

radar is in CSP track
fine line lock-on
central line lock-on.

In addition, the AGC calibration function is computed and used to convert AGC voltage to S/N ratio using linear interpolation.

c. Post-Calibration

In post-calibration the same computations as in pre-calibration are performed and compared. If the difference in range calibration results exceeds a pre-set value, post-calibration data is used but is flagged as questionable. The post-calibration data is used since post-calibration is generally performed closer to the actual track time. This comparison is done with a statistical significance test.

We compute the quantity

$$Z = \frac{\sqrt{mn/(m+n)} \quad (\overline{X}_1 - \overline{X}_2)}{(\Sigma(X_{1i} - \overline{X}_1)^2 + \Sigma(X_{2j} - X_2)^2) \quad (m+n-2)^{1/2}}$$

where:

m = the pre-calibration sample size

n = the post-calibration sample size

$\bar{X}_1 = \Sigma \frac{X_{1i}}{m}$

$\bar{X}_2 = \Sigma \frac{X_{2i}}{n}$

X_{1i} = i^{th} reading of the pre-calibration

X_{2i} = i^{th} reading of the post-calibration.

Since m and n are usually large (approximately 100 samples) the computed quantity Z is normally distributed with zero mean and unit variance. Therefore, if Z is less than 2.54, the means are judged to be not significantly different at the 95% confidence level and the pre- and post-calibration results are averaged. If Z is greater than 2.54, the post-calibration data is used but flagged as questionable.

d. Data Correction

The following corrections are applied to the data which has passed the quality control.

Apply range bias correction obtained from pre- and post-calibration.

Apply doppler bias correction obtained from CSP skin calibration.

Remove the beacon delay inserted during the radar set-up and apply nominal delays for the appropriate beacon.

Apply transit time corrections to the measurement time as well as propagation delays so that time is naval observatory synchronized.

Apply refraction corrections to range and elevation angles. The ground level index of refraction is computed from meteorological data.

Compute and apply lag correction if requested. The pre-processor will determine whether the 4101 radar lag corrections are in general agreement with lag calculations based on a priori angle rates and accelerations. If this agreement is acceptable, the 4101 radar corrections will be applied. If not, they will be computed in the pre-processor.

Compute S/N ratio from AGC voltage calibration.

The thermal noise equations [2] are used to compute range, azimuth, elevation, and range-rate noise for each data point for use in the weighting scheme.

> Using the corrected data, we compute nominal elements (inertial rectangular) for use in our data reduction program, NONAME.
>
> Finally, we re-format all the data in the Geodetic Satellite Data Service format which is compatible with NONAME.

Further, we do not preprocess every data point but select every n^{th} point. Recently, we have been using a one per second sampling rate which is generously within the bandwidth constraints for independent measurements. The independent measurements sampling restraint is approximately the reciprocal of the servo bandwidth.

The original pre-processor was not as sophisticated as the current system. However, each modification to the original system satisfied a particular requirement indicated by the data reduction results or hardware evaluation experiments. A continuing effort is in progress to analyze and evaluate all of the terms of the radar error model to determine which systematic errors exhibit characteristics which will allow for their correction in the pre-processing system. The system will be expanded and modified as necessary until we are satisfied that all major errors which can be successfully "pre-processed" from the data are handled by the system.

4.5 Data Reduction Procedure

Another important aspect of the calibration effort is the method used to reduce the tracking data after it has been "pre-processed." Wallops uses the NONAME program as its primary GEOS-II satellite tracking data reduction computational tool. This program, written in FORTRAN IV for the GE-625 computer facility at Wallops, is a Bayesian least squares adjustment program. The program uses a 10^{th} order predictor-corrector integrator which operates on the Cowell formulation of the equations of motion. This same integrator is used to integrate the variational equations to obtain the necessary partial derivatives. The current version of the program accepts gravitational coefficients up to and including degree and order 20. We currently use the SAO-determined M-1 gravity model which includes all terms up to degree and order 8 plus additional higher order terms including the GEOS-I and II resonant terms. The use of a comprehensive gravity model such as this allows us to perform "long arc" reductions. The program is modular in design which allows the user to substitute or add individual terms as well as complete gravity models in a simple and efficient manner. The program accepts all classes of data obtained by the GEOS-II tracking systems. The capability of handling various data classes allows us to reduce and analyze the data on a quick "turnaround" basis.

4.6 Use of GSFC Laser in C-Band Calibration

The C-Band Calibration efforts have been enhanced by the presence of the GSFC LASER during the period 1 April 1968 to 30 June 1968 as a participant in the Wallops Island Collocation Experiment.

The GSFC LASER has undergone extensive intercomparison with both optical and doppler systems and was found to be an accurate ranging system. The present best estimate of its accuracy is that its range noise is on the order of 1.5 meters or less and that it has an apparent range bias of 3 meters or less [3,4]. It is for this reason that this system has been chosen by the geodetic community as a ranging standard. In the GEOS-II program the LASER system has been restricted to tracking when the station is in darkness and the satellite illuminated by the sun. In addition, the configuration of the LASER reflectors on the spacecraft and the geometry of the orbit combine to limit the tracking to elevation angles above 30°.

Approximately 30 passes of LASER data were obtained at Wallops. During most of these passes, the Wallops AN/FPQ-6 and AN/FPS-16 were also tracking. This affords us the opportunity to reduce AN/FPQ-6, AN/FPS-16 data and LASER data simultaneously in both short and long arc reductions and to analyze and evaluate the systematic errors in the radars using the LASER data as a comparison standard. Section 5.0 contains the results of some of these comparisons.

5.0 DATA ANALYSIS RESULTS

The data analysis was divided into five general categories. (1) The short arc analysis of AN/FPQ-6 data was performed to determine noise levels and their stability. (2) The short arc intercomparisons were done to ascertain the agreement and consistency between C-Band and LASER systems. (3) Long arc intercomparisons were conducted to investigate systematic trends. (4) To determine the validity of the orbital solutions long arc predictions were compared against actual tracks. (5) In addition to the above, radar systems experiments were carried out to determine how calibration methods affected range measurements. These five areas will be discussed in the following sections.

5.1 Short Arc Analysis - AN/FPQ-6 Only

The object of short arc single station solutions is to estimate the noise on a given measurement channel without influencing the estimate with systematic errors which may be present in this channel.

A total of 36 passes of GEOS-II data have been analyzed in this manner. Table III summarizes the results of these short arc fits. These arcs represent a wide variety of types of passes with the maximum elevation angle ranging from 88.8° to 23.6°. Both daytime and nighttime passes are included as well as passes using both the long and short delay transponder. The data was used at a sampling rate of one sample per second. As can be seen from the table, a very small number (i.e., <1%) of the data points were edited out of the solutions. The only significant editing occurs in the azimuth data during high elevation passes (i.e., >65°).

Date	Rev #	Test	Time Start	Max El.	RMS R	RMS A	RMS E	No Az WTD Out	No El WTD Out	No R WTD Out	Mean Range Differences	
											AN/FPS-16	LASER
4-1	1039	1	16^h22^m	46°								
4-2	1044	2	01 16	51°								
4-3	1057	3	01 35	68°								
4-4	1070	4	01 55	88°8	0.70	25.8	43.1	71	1	3	-2	
4-5	1083	5	02 14	69°5	0.84	26.1	32.7	13	0	1	+4	-1
4-6	1096	6	02 32	51°								
4-9	1134	7	01 40	62°								
4-9	1142	8	17 05	32°								
4-10	1147	9	01 59	82°								
4-11	1160	10	02 00	82.7	1.585	22.8	41.25	13	11	7		
4-12	1173	11	02 37	56°								
4-13	1186	12	02 58	41°3	0.85	18.2	16.6	2	2	2	-2	-1
4-15	1219	13	17 12	34°1	1.330	20.1	17.1	1	0	1		
4-16	1224	14	02 04	77°								
4-17	1237	15	02 23	82°								
4-18	1250	16	02 42	61°								
4-19	1263	17	03 03	45°5	0.52	13.6	13.3	0	0	0		
4-20	1275	18	01 32	41°2	0.770	14.7	19.1	1	1	1	+9	+2
4-21	1288	19	01 52	54°1	0.868	26.1	28.5	1	1	1	+6	
4-21	1296	20	17 17	36°9	1.280	29.6	20.8	0	0	0	+7	
4-22	1301	21	02 10	71°3	0.850	30.9	41.4	24	1	0	+8	
4-22	1309	22	17 36	29°7	1.432	22.8	17.0	15	13	14		
4-23	1314	23	02 30	87°								
4-24	1327	24	02 48	67°3	0.712	27.6	37.6	2	2	3	+7	
4-24	1334	25	16 24	76°2	1.404	31.4	38.7	22	0	0	+10	

SUMMARY OF COLLOCATION TESTS
TABLE III

Date	Rev #	Test	Time Start	Max. El.	RMS R	RMS A	RMS E	No Az WTD Out	No El WTD Out	No R WTD Out	Mean Range Differences	
											AN/FPS-16	LASER
4-26	1352	26	01^h42^m	38°8	0.812	6.2	10.0	0	0	0	+12	+2
4-26	1353	27	03 27	36°5	0.792	14.7	10.0	1	1	1	+8	+3
4-28	1378	28	02 17	66°4	0.940	30.4	31.2	0	0	0	+7	
4-28	1386	29	17 43	32°0	1.075	19.6	10.5	0	0	0	+7	
4-29	1391	30	02 33	86°								
5-1	1417	31	03 13	55°1	0.854	13.7	18.8	0	0	0	+10	
5-2	1429	32	01 43	36°8	0.73	13.8	13.7	0	0	0	+6	
5-2	1430	33	03 32	41°1	0.74	11.8	16.1	1	1	1	+9	
5-3	1442	34	02 01	47°7	0.74	16.1	19.3	0	0	0	+7	+0
5-3	1450	35	17 27	42°3	1.2	33.6	28.7	0	0	0	+3	
5-4	1455	36	02 20	61°8	1.05	22.2	32.2	9	6	7	*+42	*+34
5-6	1488	37	16 34	85°0	1.46	27.4	49.4	42	0	0	+7	
5-7	1494	38	03 17	60°4	0.83	17.9	16.6	1	0	0	+8	+3
5-8	1506	39	01 48	35°1	0.69	8.6	8.9	1	1	1	+6	
5-8	1507	40	03 37	45°4	0.70	13.8	11.9	0	0	0	+4	-2
5-9	1519	41	02 06	45°2	0.70	15.3	17.7	0	0	0	+7	
5-10	1540	42	17 49	37°								
5-13	1578	43	16 56	73°								
5-16	1616	44	16 04	56°								
5-17	1629	45	16 25	70°6	1.4	34.6	42.4	59	3	0	+7	
5-18	1635	46	03 06	87°								
5-21	1673	47	02 16	40°9	0.84	11.9	9.3	0	1	2	+8	-1
5-21	1674	48	04 10	42°								
5-22	1686	49	02 36	52°2	0.80	18.4	18.0	0	0	1		0

SUMMARY OF COLLOCATION TESTS

TABLE III

Date	Rev #	Test	Time Start	Max El.	RMS R	RMS A	RMS E	No Az WTD Out	No El WTD Out	No R WTD Out	Mean Range Differences	
											AN/FPS-16	LASER
5-22	1687	50	04^h26^m	31°.5	0.8	11.5	10.3	0	0	0		
5-22	1693	51	16 12	52°.8	1.3	18.4	17.2	0	0	0	+5	
5-23	1699	52	02 54	66°.7	0.76	25.3	21.9	6	7	3		+6
5-23	1700	53	04 46	23°.6	0.82	12.7	9.9	0	0	0		
5-24	1712	54	03 13	84°.3	0.98	26.4	46.7	71	6	4	*+38	+6

NOTE: A priori weights used in reduction:

σ_R = 2 m

σ_A = 50m

σ_E = 50m

SUMMARY OF COLLOCATION TESTS

TABLE III

* - 1 μsec pulsewidth used by AN/FPQ-6

Figures 6 through 14 show range, azimuth and elevation residuals for tests 38, 47 and 54. These tests are representative of the class of geometries encountered in tracking GEOS-II. The maximum elevation angles during these passes were 60°, 40° and 84° respectively. The range residuals in each case have an RMS and a noise level of approximately 1 meter.

The tendency for the azimuth residuals to be large near the point of closest approach (PCA) can be observed on the plots. It can also be observed that this tendency is much more pronounced on the high elevation passes. There are several possible sources of errors of this type in the azimuth data. Indications are that the two largest contributors to this azimuth problem are errors in the leveling coefficients and dynamic lag. Recent leveling tests have shown a peak-to-peak variation in a single day of 7 seconds of arc in amplitude and 8 degrees in phase in the leveling correction coefficients (K_2, K_3). This could contribute as much as 70 seconds in azimuth error at an elevation angle of 84°. Another possible source for this error was discovered when it was found that the gain of the azimuth servo amplifier was below nominal due to a faulty tube. This problem was corrected as of 21 May 1968, and we are studying its effects on the azimuth residuals.

The results of these short arc analyses demonstrate the low noise and inherent stability of the AN/FPQ-6 radar. Thus, it is clear that the AN/FPQ-6 is a system of geodetic precision.

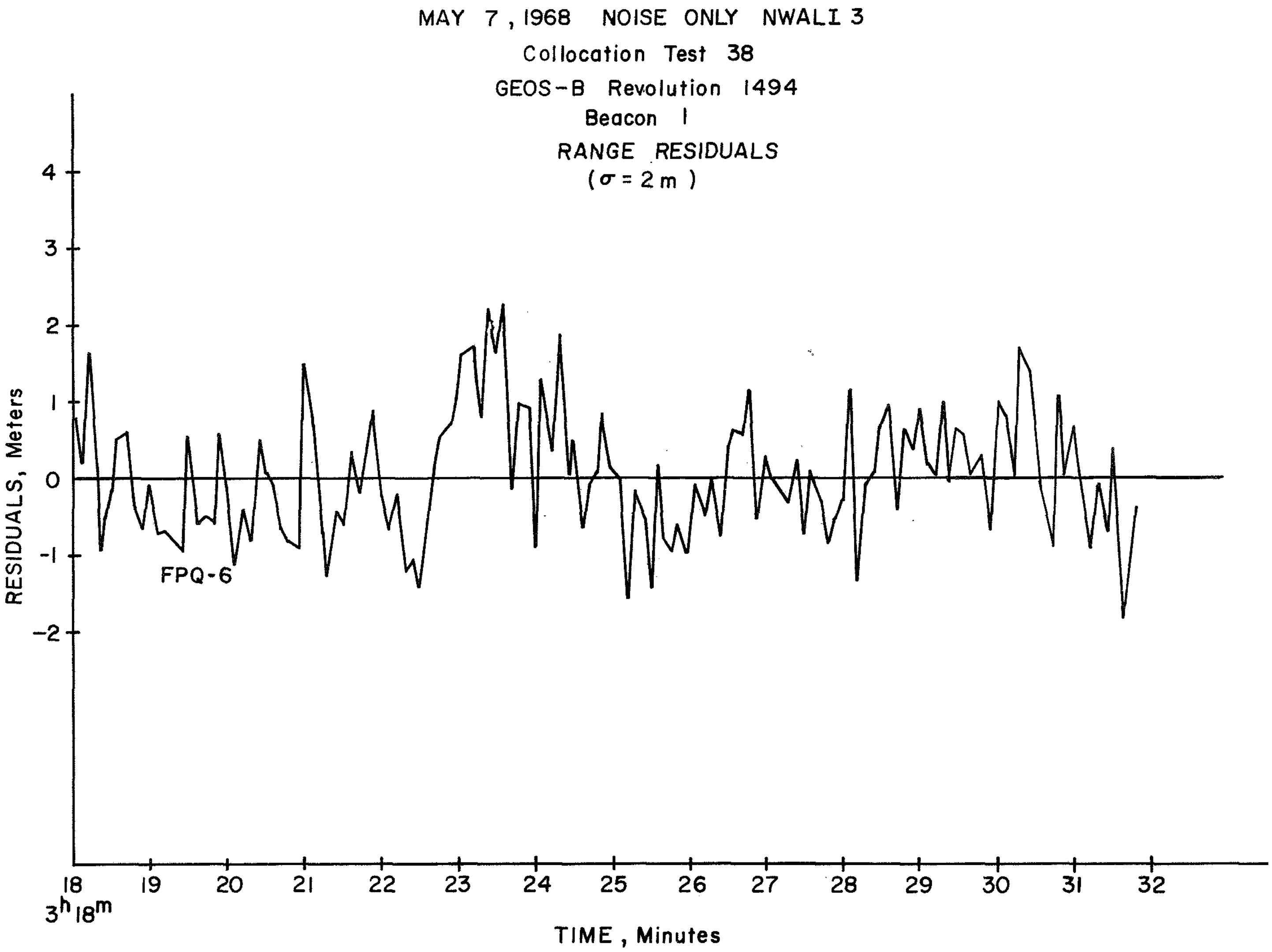

MAY 7, 1968 NOISE ONLY NWALI 3
Collocation Test 38
GEOS-B Revolution 1494
Beacon 1
RANGE RESIDUALS
(σ = 2 m)
RESIDUALS, Meters
4
3
2
1
0
-1
-2
FPQ-6
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
$3^h 18^m$
TIME, Minutes

Figure 6

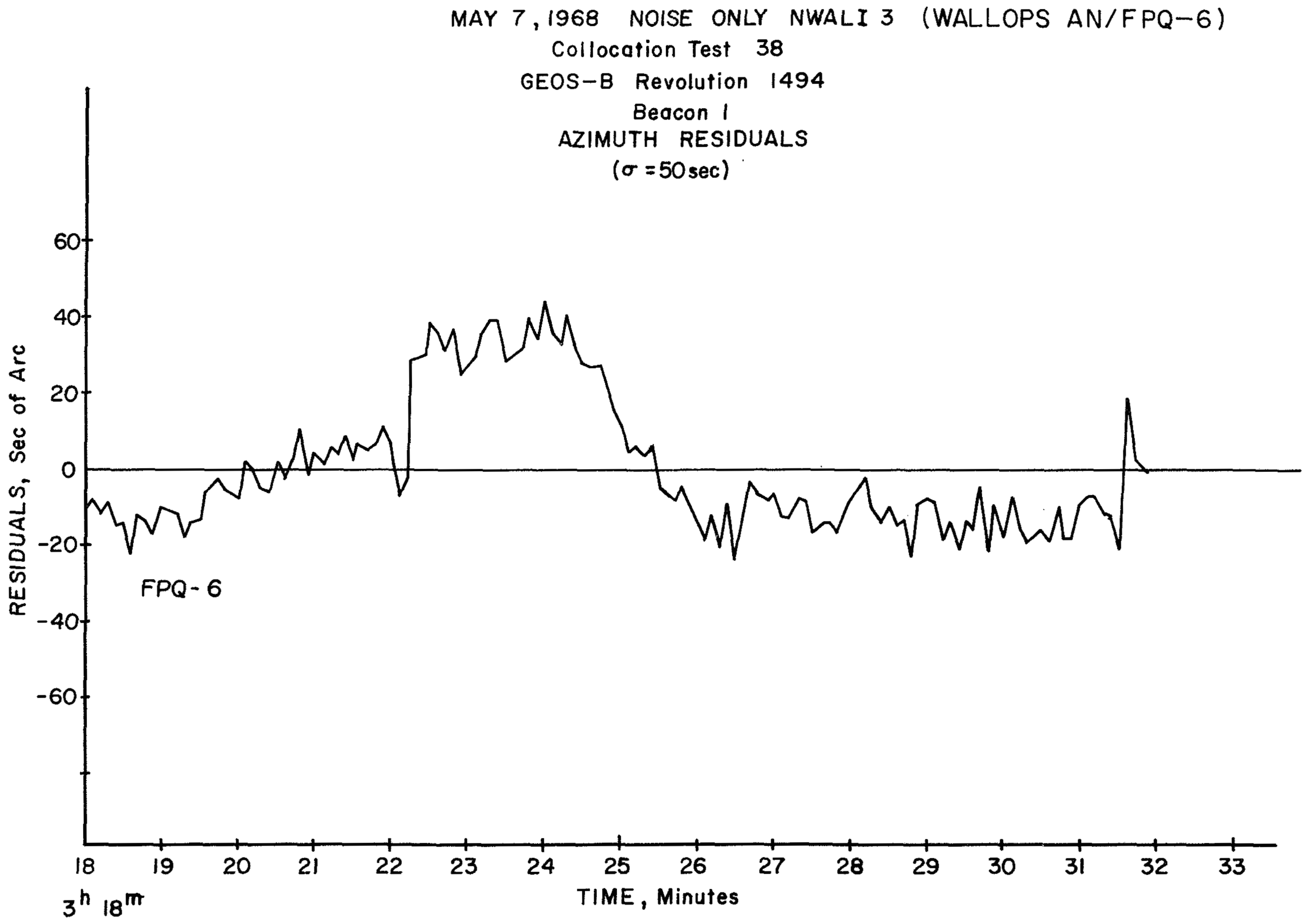

MAY 7, 1968 NOISE ONLY NWALI 3 (WALLOPS AN/FPQ-6)
Collocation Test 38
GEOS-B Revolution 1494
Beacon I
AZIMUTH RESIDUALS
(σ = 50 sec)
RESIDUALS, Sec of Arc
60
40
20
0
-20
-40
-60
FPQ-6
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
3h 18m
TIME, Minutes

Figure 7

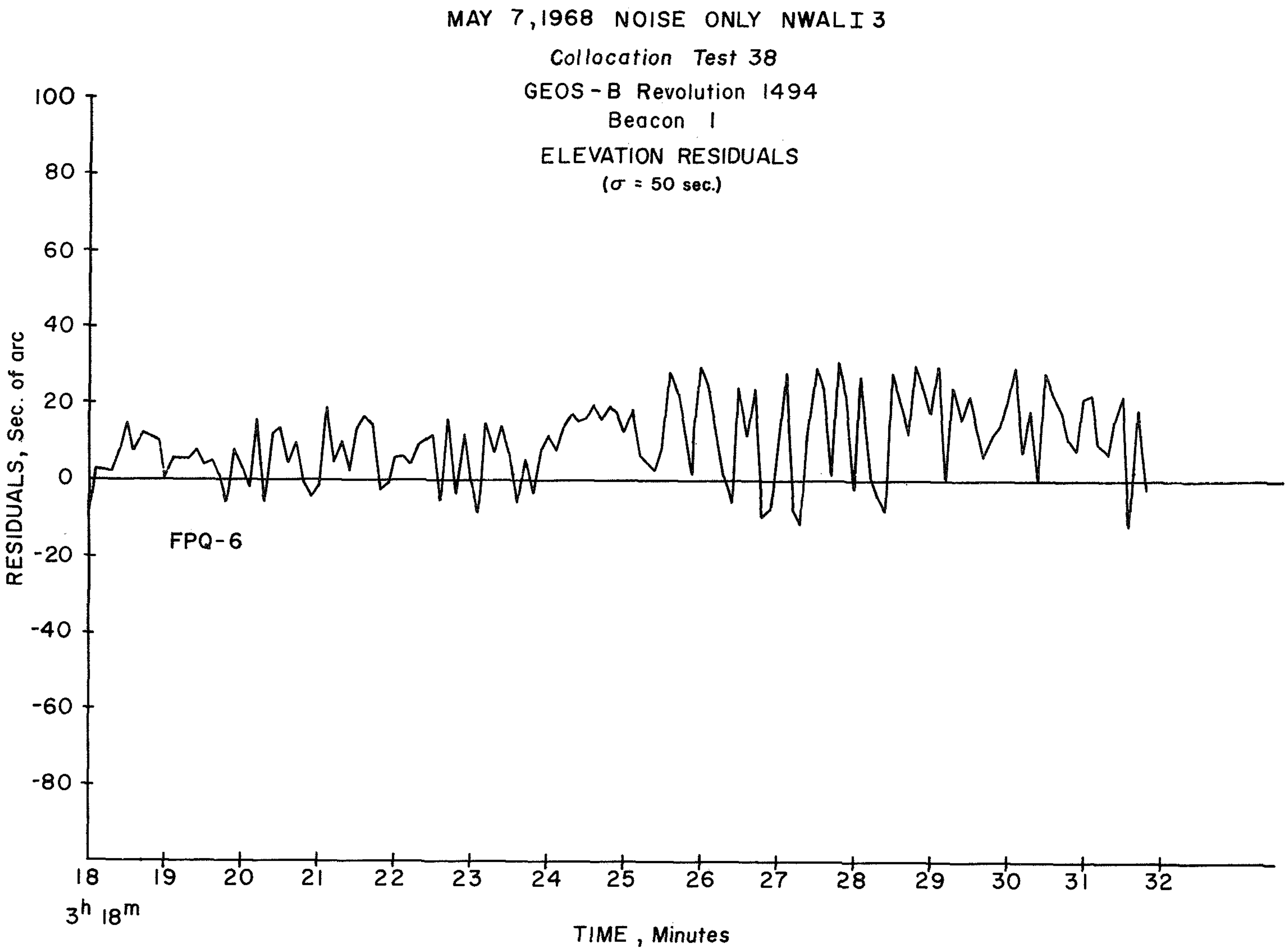

MAY 7,1968 NOISE ONLY NWAL I 3
Collocation Test 38
GEOS - B Revolution 1494
Beacon 1
ELEVATION RESIDUALS
(σ = 50 sec.)
100
80
60
40
20
0
-20
-40
-60
-80
RESIDUALS, Sec. of arc
FPQ-6
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
3h 18m
TIME, Minutes

Figure 8

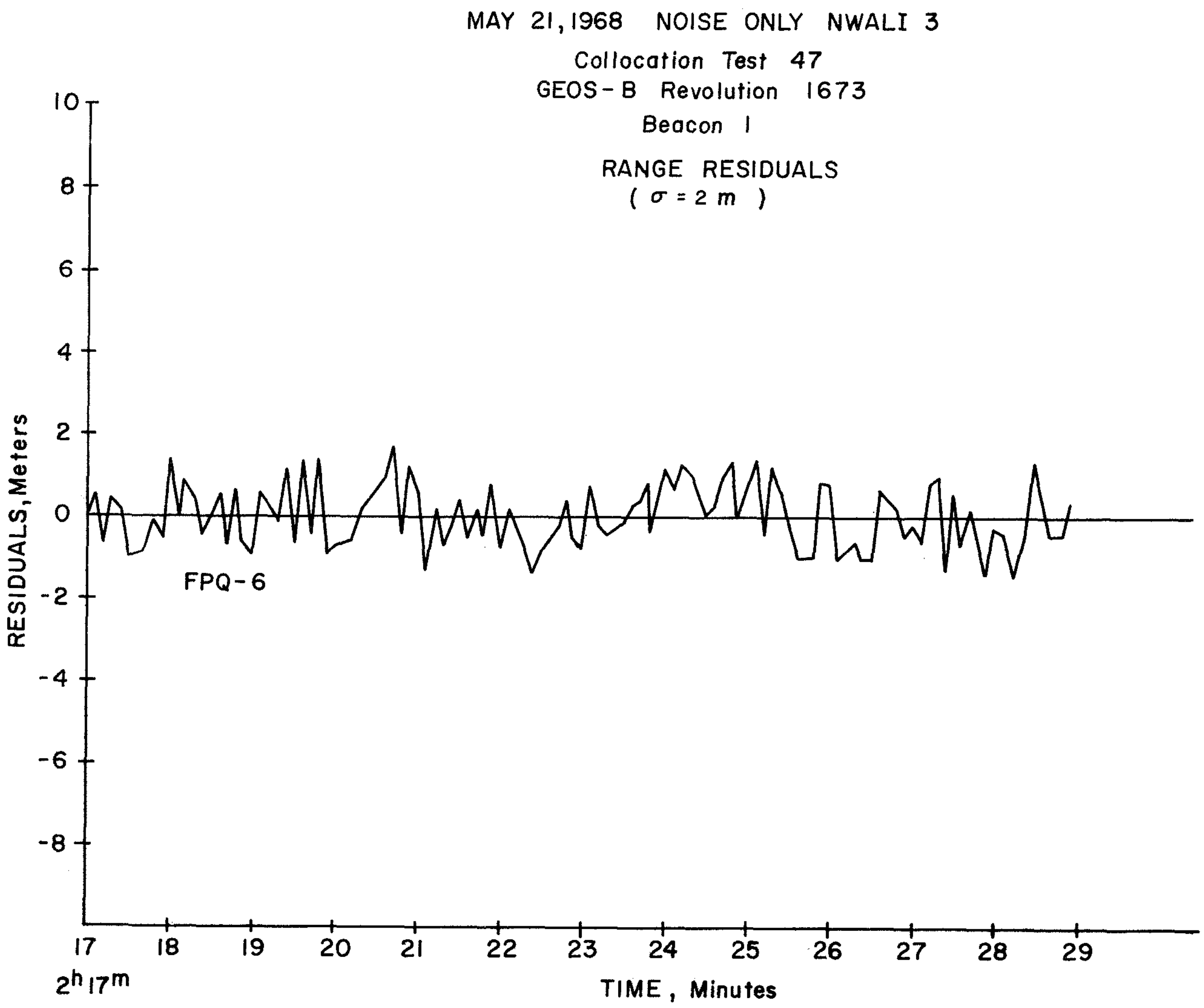

MAY 21, 1968 NOISE ONLY NWALI 3
Collocation Test 47
GEOS-B Revolution 1673
Beacon 1
RANGE RESIDUALS
(σ = 2 m)
RESIDUALS, Meters
10
8
6
4
2
0
-2
-4
-6
-8
FPQ-6
17
18
19
20
21
22
23
24
25
26
27
28
29
2h 17m
TIME, Minutes

Figure 9

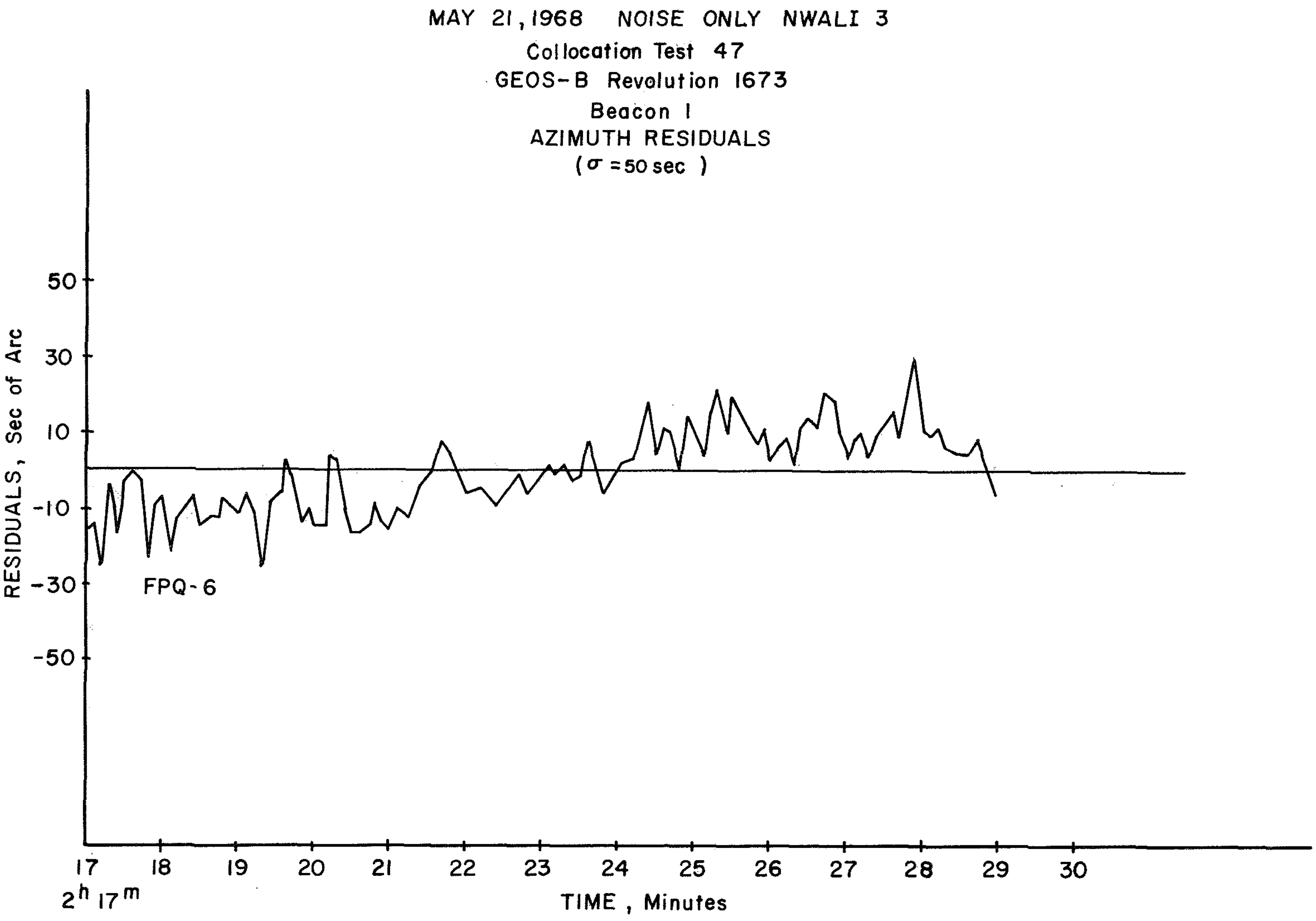

MAY 21, 1968 NOISE ONLY NWALI 3
Collocation Test 47
GEOS-B Revolution 1673
Beacon I
AZIMUTH RESIDUALS
(σ = 50 sec)
RESIDUALS, Sec of Arc
50
30
10
-10
-30
-50
FPQ-6
17
18
19
20
21
22
23
24
25
26
27
28
29
30
$2^h 17^m$
TIME, Minutes

Figure 10

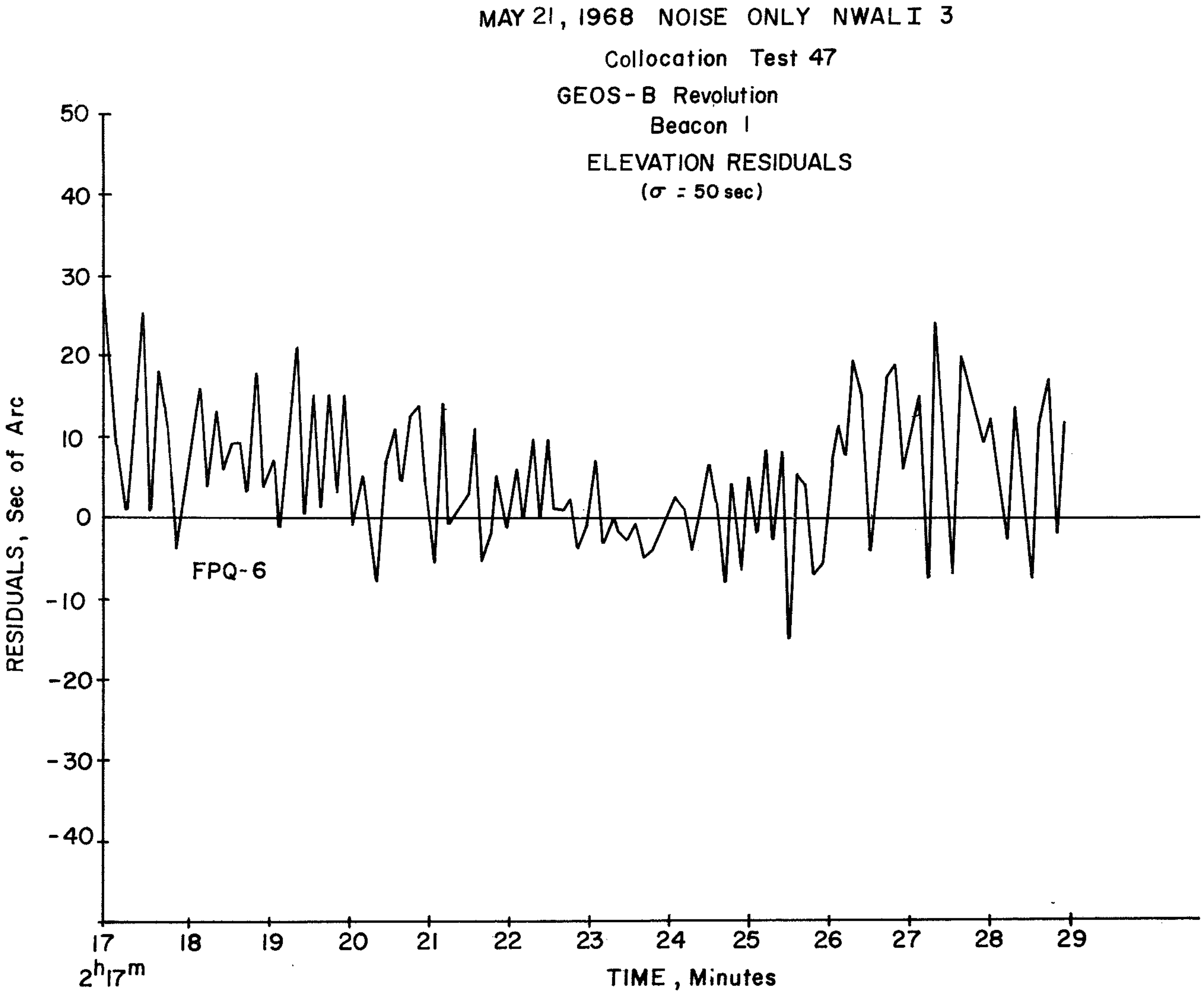

MAY 21, 1968 NOISE ONLY NWALI 3
Collocation Test 47
GEOS-B Revolution
Beacon 1
ELEVATION RESIDUALS
(σ = 50 sec)
RESIDUALS, Sec of Arc
50
40
30
20
10
0
-10
-20
-30
-40
FPQ-6
17
18
19
20
21
22
23
24
25
26
27
28
29
2h17m
TIME, Minutes

Figure 11

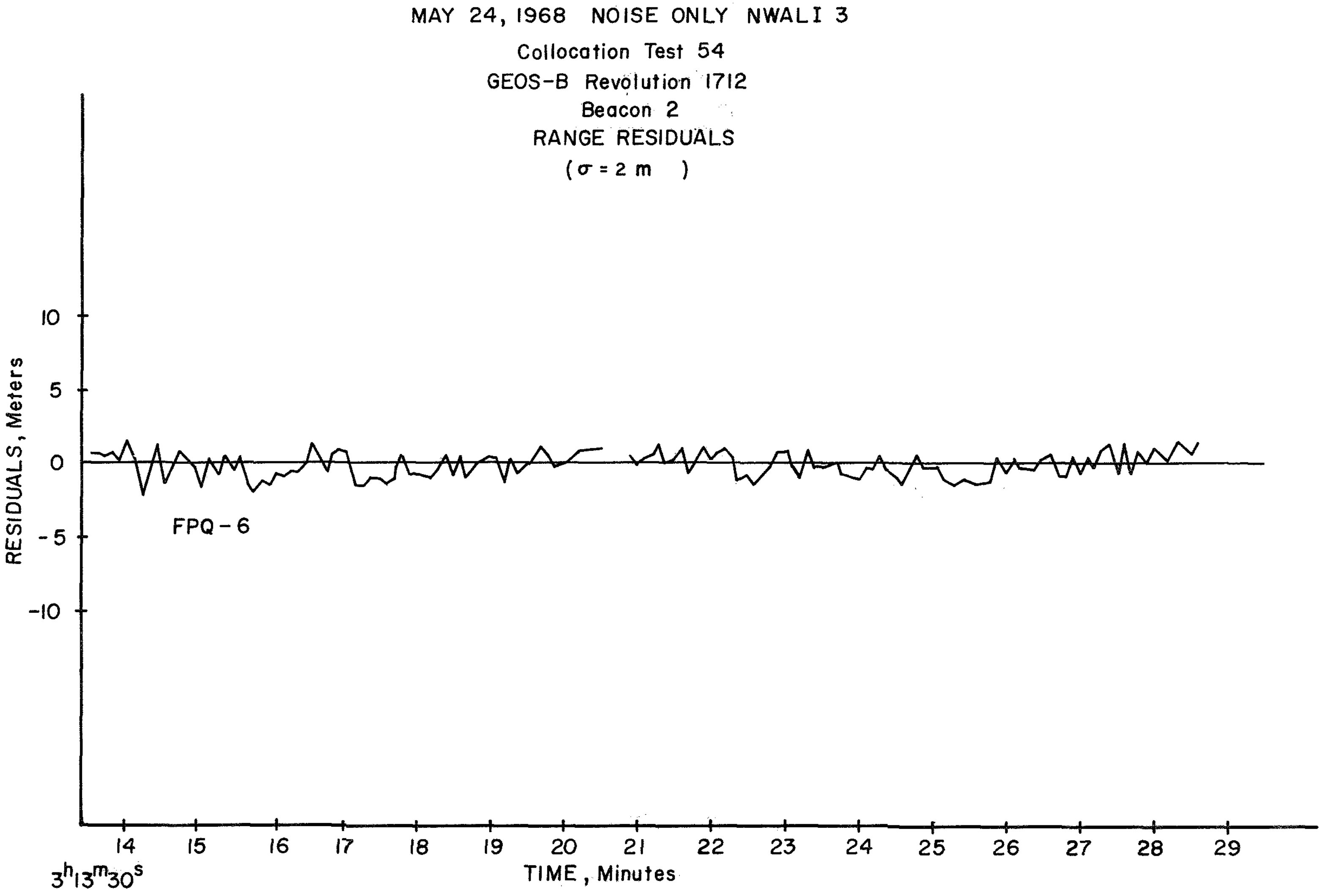

MAY 24, 1968 NOISE ONLY NWALI 3
Collocation Test 54
GEOS-B Revolution 1712
Beacon 2
RANGE RESIDUALS
(σ = 2 m)
RESIDUALS, Meters
10
5
0
-5
-10
FPQ-6
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
3h13m30s
TIME, Minutes

Figure 12

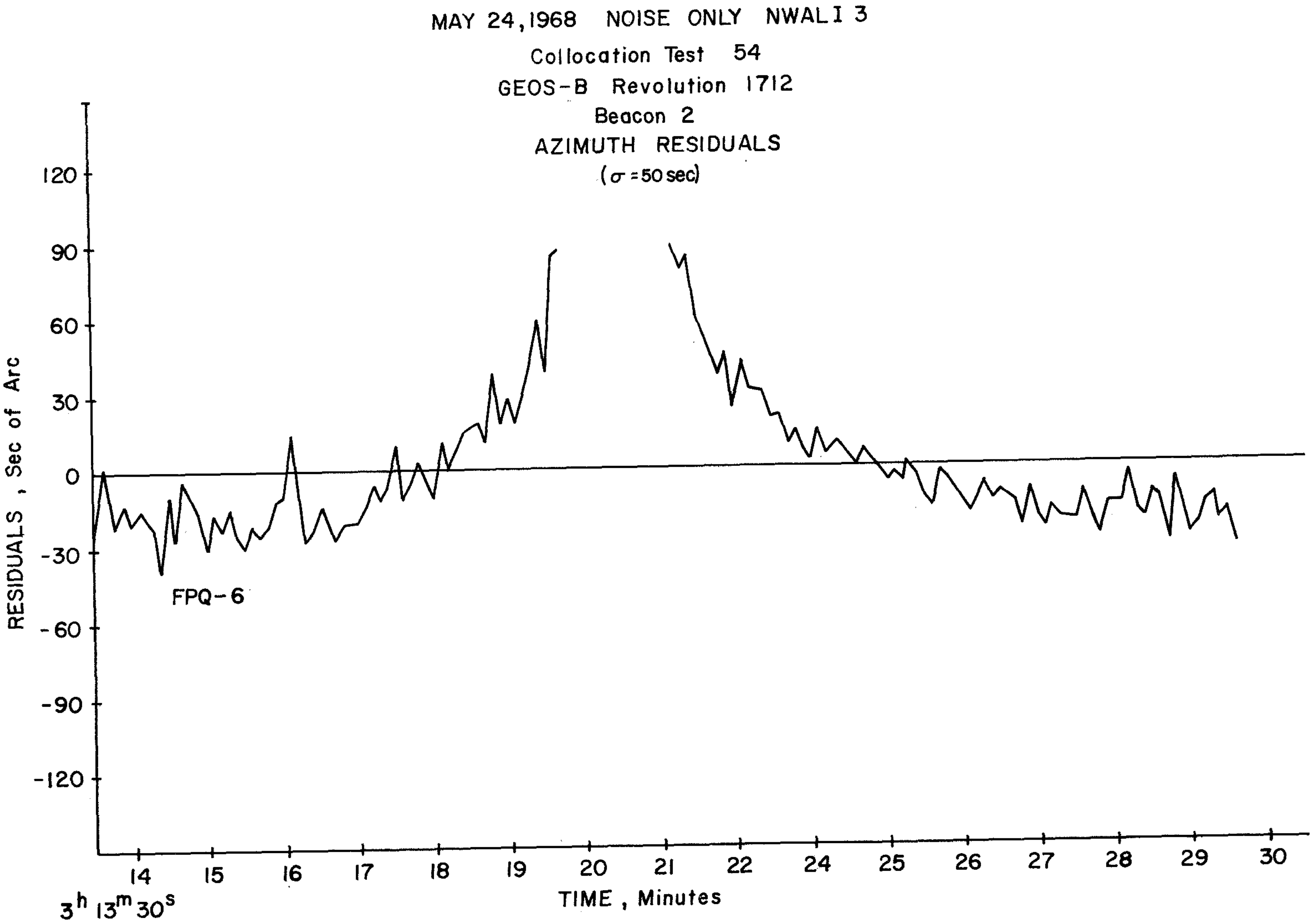

MAY 24, 1968 NOISE ONLY NWAL I 3
Collocation Test 54
GEOS-B Revolution 1712
Beacon 2
AZIMUTH RESIDUALS
(σ = 50 sec)
120
90
60
30
0
-30
-60
-90
-120
RESIDUALS , Sec of Arc
FPQ-6
14
15
16
17
18
19
20
21
22
24
25
26
27
28
29
30
3h 13m 30s
TIME , Minutes

Figure 13

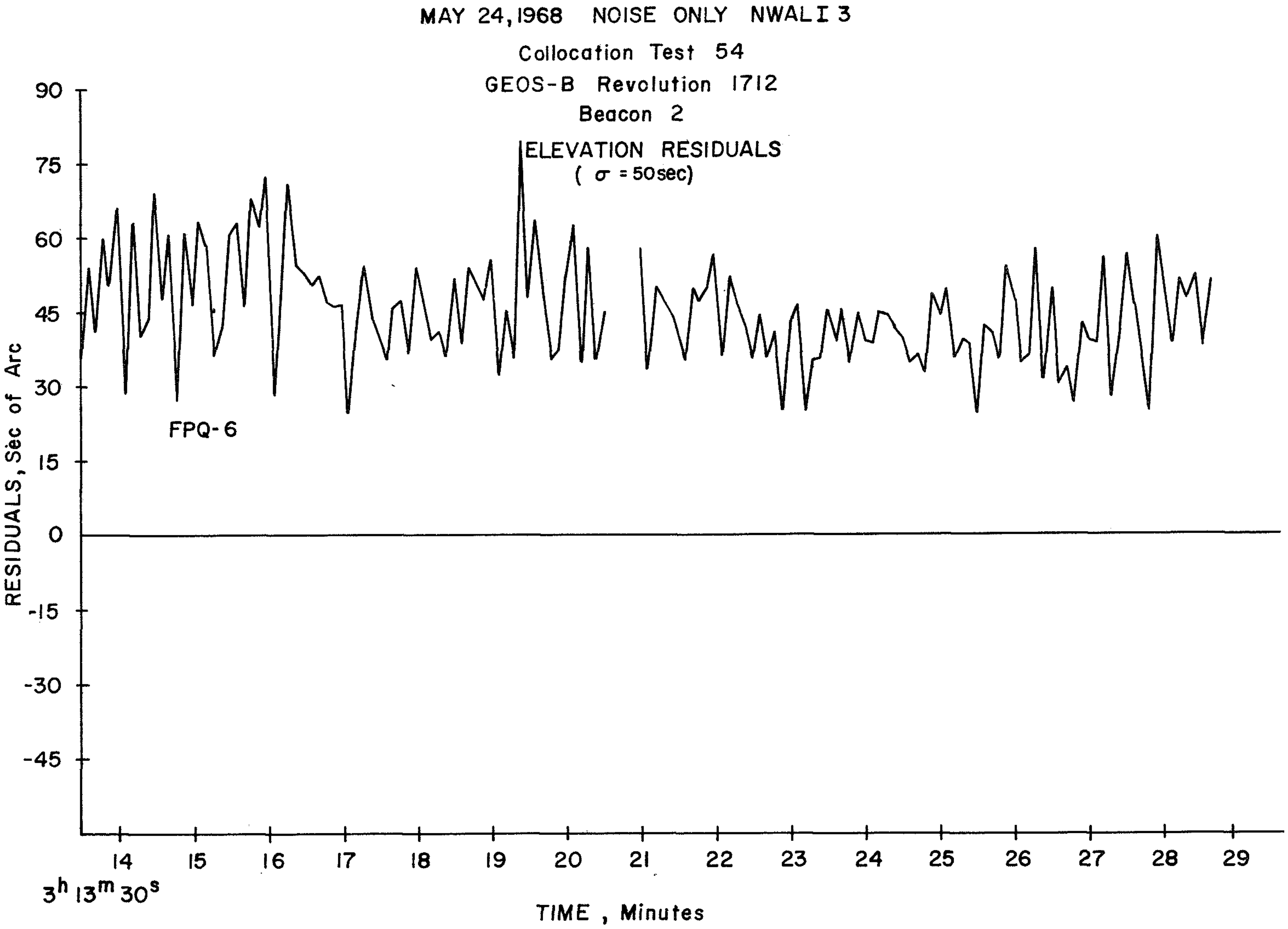

MAY 24,1968 NOISE ONLY NWAL I 3
Collocation Test 54
GEOS-B Revolution 1712
Beacon 2
ELEVATION RESIDUALS
(σ = 50sec)
FPQ-6
RESIDUALS, Sec of Arc
90
75
60
45
30
15
0
-15
-30
-45
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
3h 13m 30s
TIME , Minutes

Figure 14

5.2 Short Arc Intercomparison

The GSFC LASER is the accepted range standard in the geodetic community. For this reason we chose to use it for our short arc intercomparisons. In our first investigation only the LASER data was used to generate the reference orbit. It is important to mention in this connection that the orbit derived from a short arc of data is definitive only over the data span. Consequently, one can only expect to compare the radar measurements with the LASER-determined short arc over the LASER data interval. The valid intercomparison interval is appropriately marked in Figure 15. A short arc solution was determined using the LASER data on 5 April 1968 where we chose the epoch of the elements to correspond to the radar data at 8.8° elevation. As can be seen the radar and LASER residuals agree extremely well over the LASER data span, and the AN/FPQ-6 residuals deteriorate where no LASER data exists. This was a beacon only mission with the radar set-up as indicated in Table II. Figure 15 is an example of the agreement which we have consistently found between these two systems.

Having gained this confidence, we chose to reverse the role of the radar and the LASER data in the short arc solutions, thus gaining the added strength of orbital geometry obtained from the radar system which can track from horizon to horizon. Figures 16-18 show such an intercomparison where radar data above 10° in elevation was used in the solution. This again was a beacon only mission. In this case the LASER and the AN/FPS-16 residuals are also shown but neither of these data sets was weighted in the solution. The maximum elevation angle during this pass was $60^\circ\!.4$.

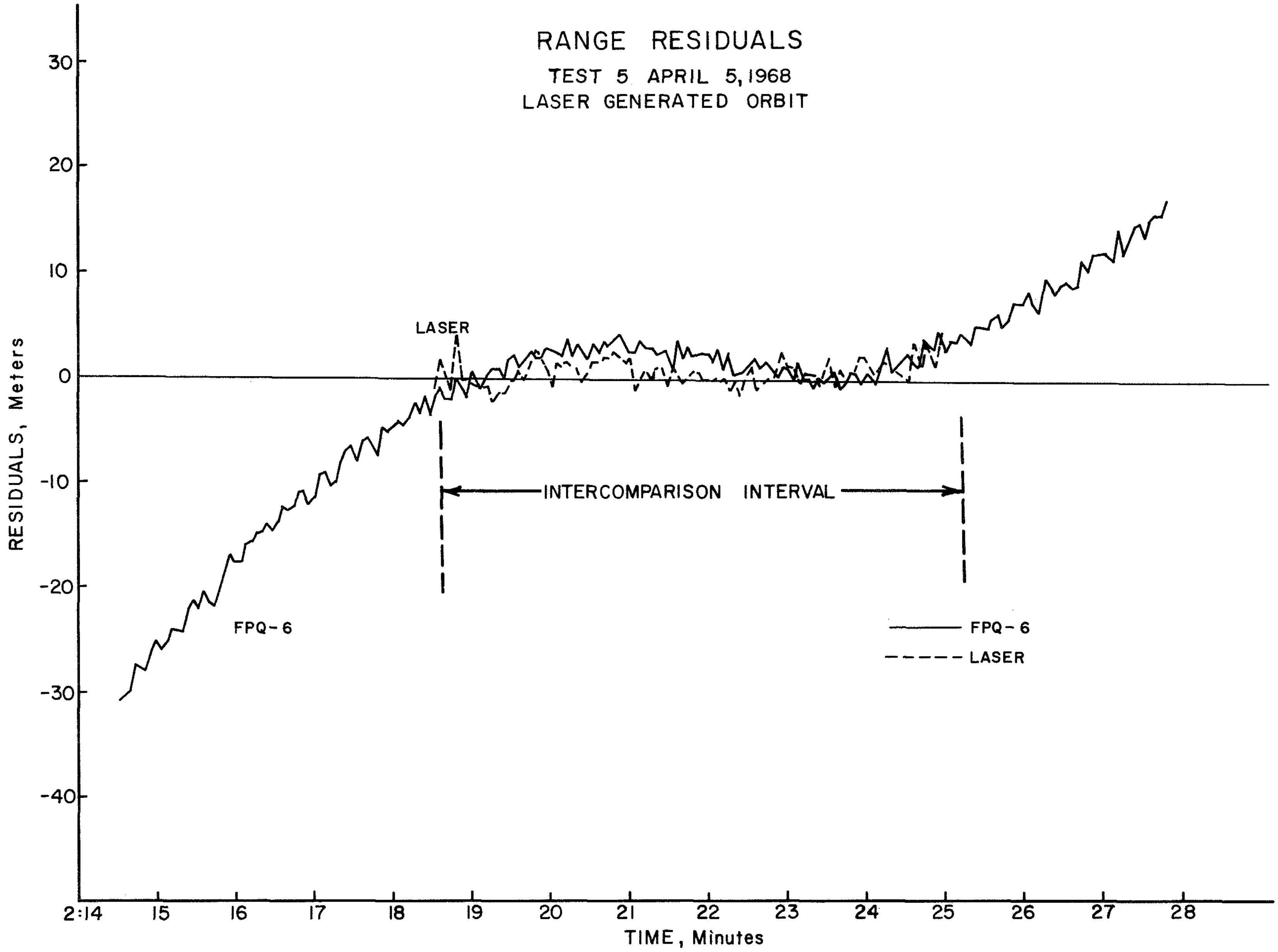

RANGE RESIDUALS
TEST 5 APRIL 5, 1968
LASER GENERATED ORBIT
LASER
INTERCOMPARISON INTERVAL
FPQ-6
FPQ-6
LASER
RESIDUALS, Meters
30
20
10
0
-10
-20
-30
-40
2:14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
TIME, Minutes

Figure 15

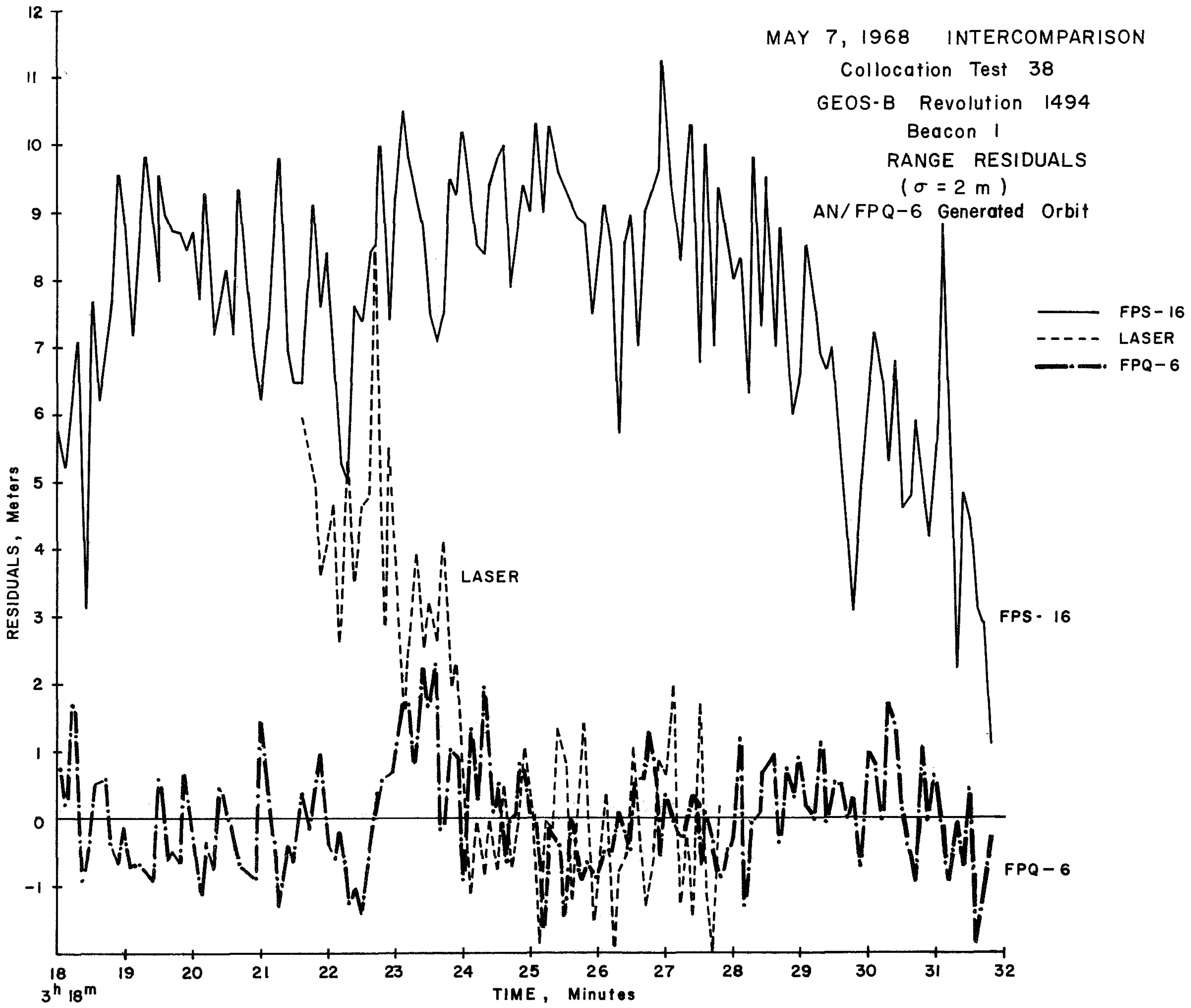

MAY 7, 1968 INTERCOMPARISON
Collocation Test 38
GEOS-B Revolution 1494
Beacon I
RANGE RESIDUALS
(σ = 2 m)
AN/FPQ-6 Generated Orbit
FPS-16
LASER
FPQ-6
LASER
FPS-16
FPQ-6
RESIDUALS, Meters
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
18
3h 18m
19
20
21
22
23
24
25
26
27
28
29
30
31
32
TIME, Minutes

Figure 16

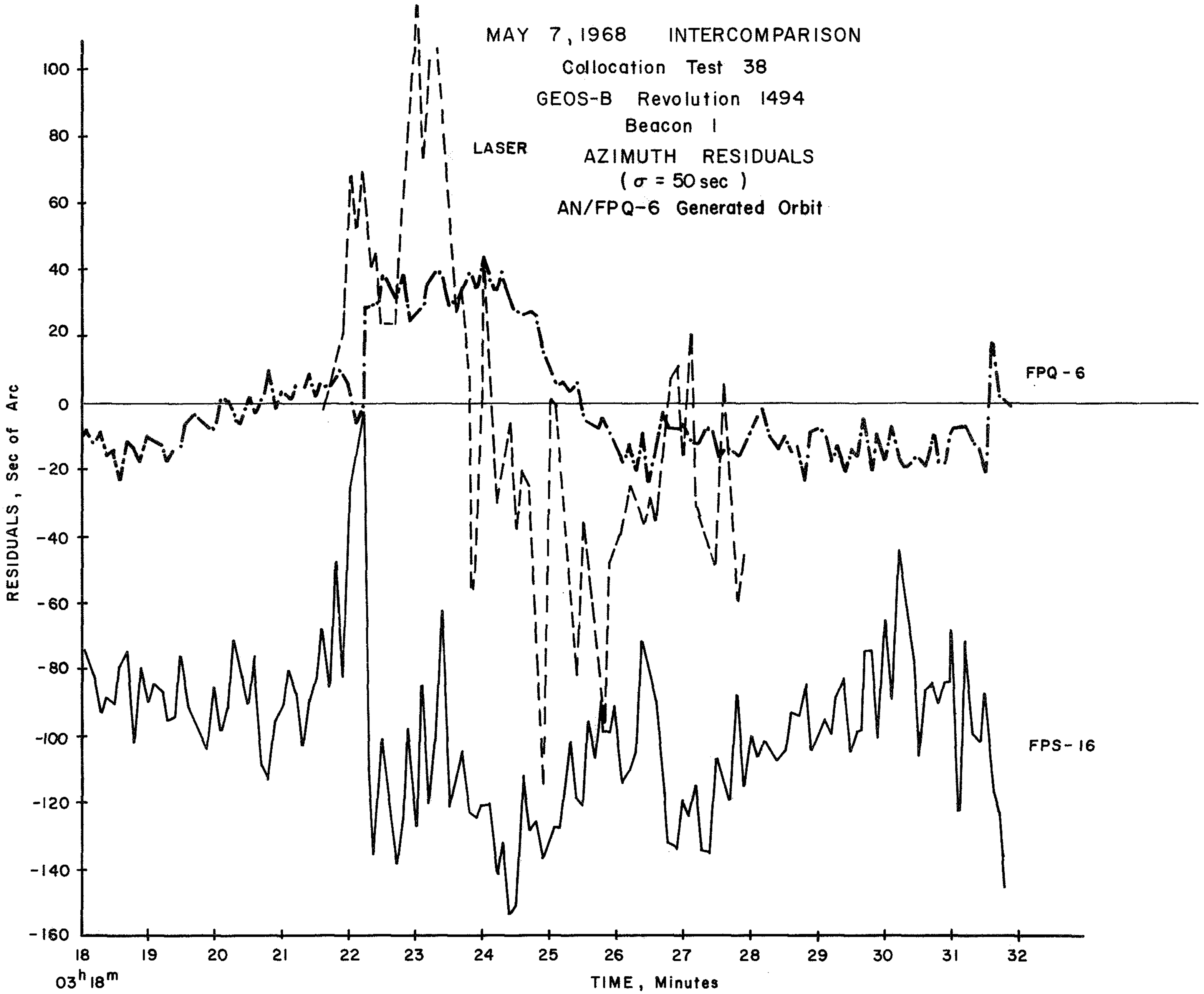

MAY 7, 1968 INTERCOMPARISON
Collocation Test 38
GEOS-B Revolution 1494
Beacon I
AZIMUTH RESIDUALS
(σ = 50 sec)
AN/FPQ-6 Generated Orbit
LASER
FPQ - 6
FPS- 16
RESIDUALS, Sec of Arc
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
03h 18m
TIME, Minutes

Figure 17

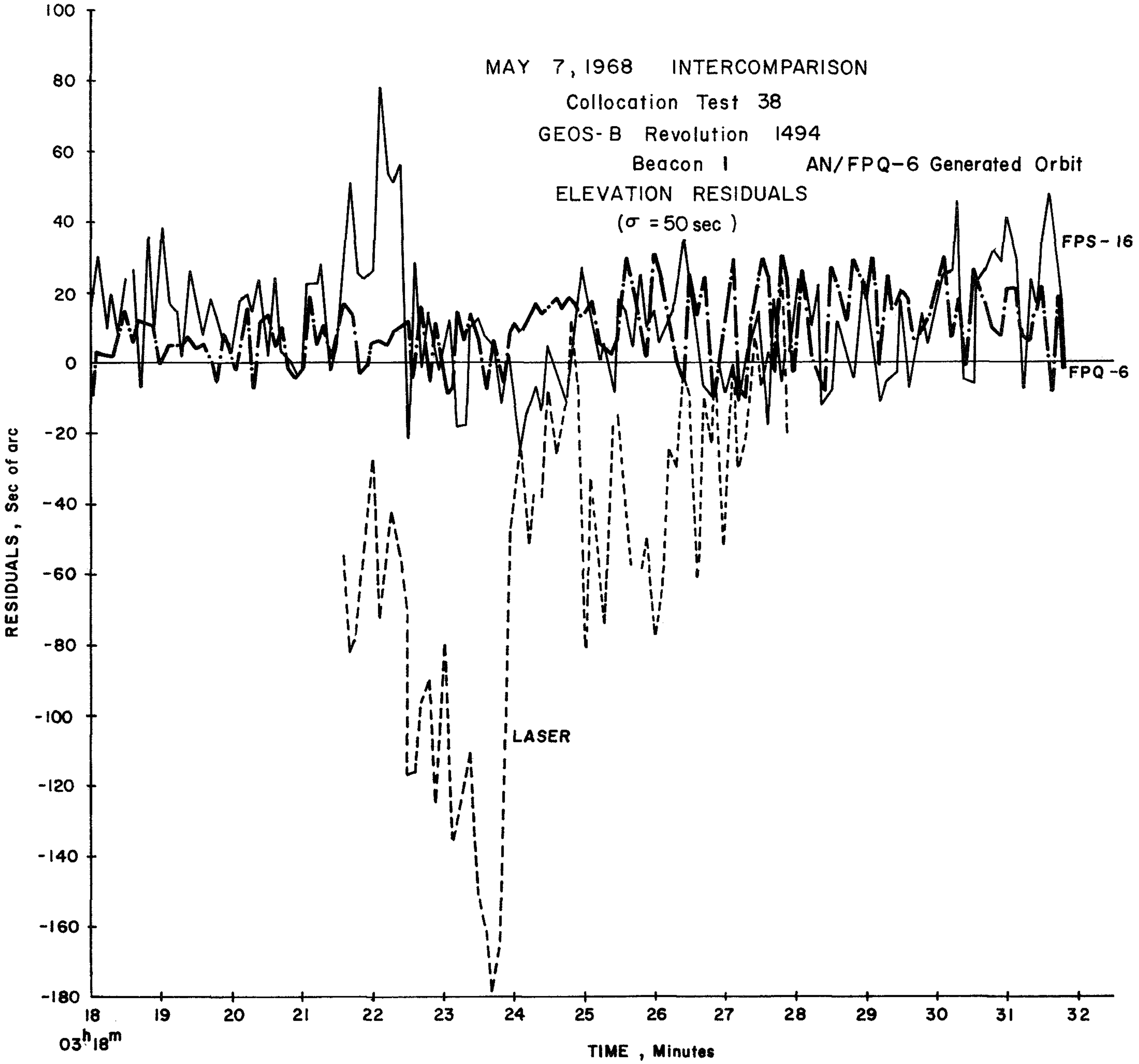

MAY 7, 1968 INTERCOMPARISON
Collocation Test 38
GEOS-B Revolution 1494
Beacon 1 AN/FPQ-6 Generated Orbit
ELEVATION RESIDUALS
(σ = 50 sec)
FPS-16
FPQ-6
LASER
RESIDUALS, Sec of arc
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
03h18m
TIME, Minutes

Figure 18

Figures 19 through 24 show results from passes on 21 May 1968 and 24 May 1968, respectively. Again these represent solutions determined using AN/FPQ-6 data but include the LASER and/or AN/FPS-16 residuals from this solution. The maximum elevation angles in these passes are 40.9° and 84.3° respectively. Of particular interest in both cases is the agreement among the measured ranges.

We find this agreement very encouraging and we feel that the sources of the biases can be identified. Investigation of the pulse returned by the spacecraft beacon has uncovered a deviation in width from the 0.5 microseconds previously assumed. Since the range error is determined from the time interval between the centroid of the transmitted pulse and the centroid of the received pulse a bias proportional to one half the difference in these pulsewidths will occur. In beacon mode we have determined that this is of the order of six meters. This is an example of a systematic error being identified which is uncorrectable in the hardware. We, consequently, can account for it in postflight processing or calibration. This bias, which is not taken into account in the results, is present in Figures 19-24 and is in part the cause of the systematic difference between the AN/FPQ-6 and the other instruments.

Another systematic error source was discovered from the analysis of the AN/FPS-16 range residuals on test 47, Figure 19. The AN/FPS-16 range residuals show a sudden dip at approximately $02^h21^m30^s$; they remain at this lower level until $02^h25^m30^s$ where they rise to this original level again. Investigation of the data revealed that an elevation bit drop-out in the AN/FPS-16 data occurred

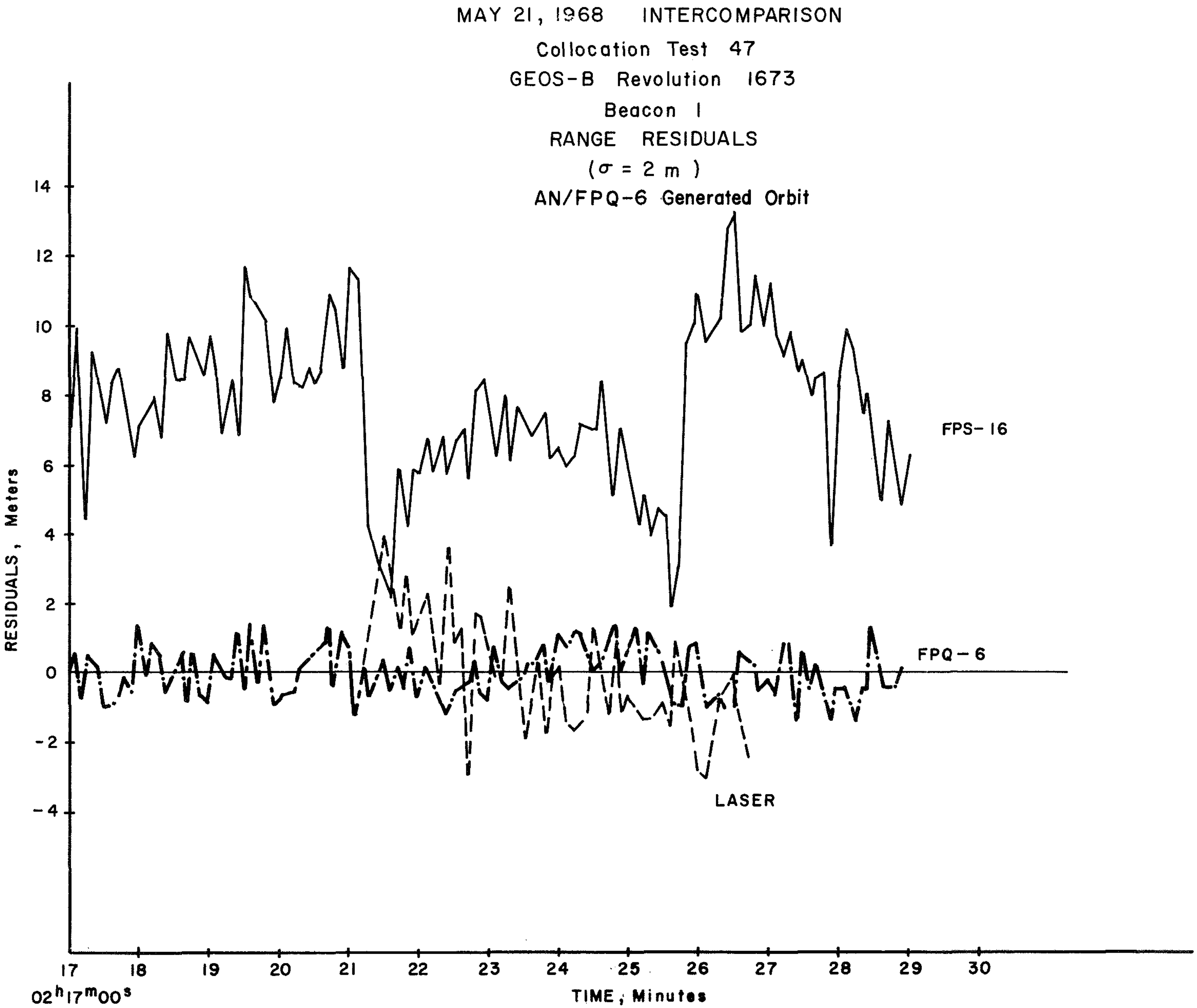
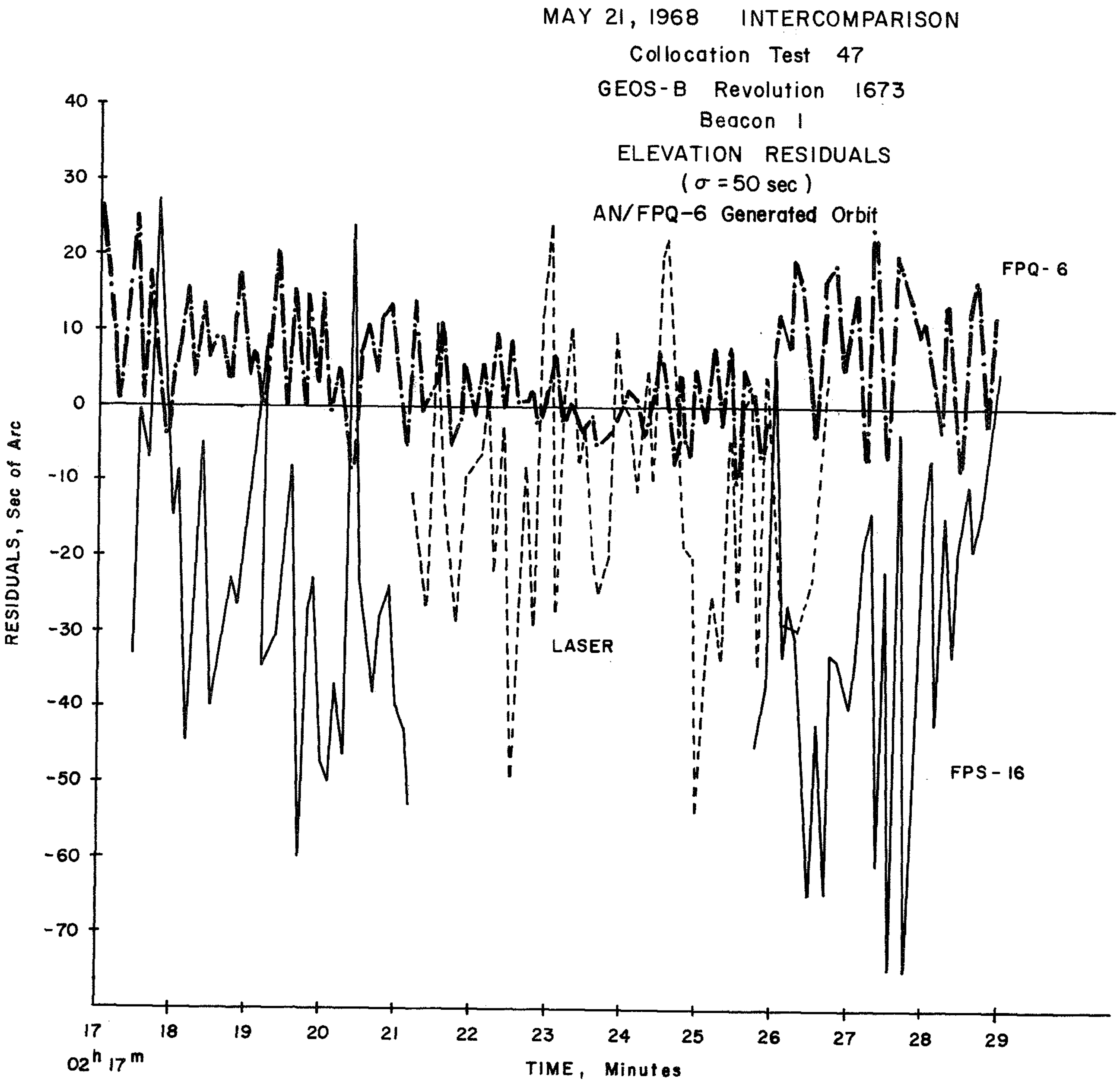

MAY 21, 1968 INTERCOMPARISON
Collocation Test 47
GEOS-B Revolution 1673
Beacon 1
RANGE RESIDUALS
(σ = 2 m)
AN/FPQ-6 Generated Orbit
RESIDUALS, Meters
14
12
10
8
6
4
2
0
-2
-4
FPS-16
FPQ-6
LASER
17
18
19
20
21
22
23
24
25
26
27
28
29
30
02h17m00s
TIME, Minutes

Figure 19



MAY 21, 1968 INTERCOMPARISON
Collocation Test 47
GEOS-B Revolution 1673
Beacon I
ELEVATION RESIDUALS
(σ = 50 sec)
AN/FPQ-6 Generated Orbit

Figure 20

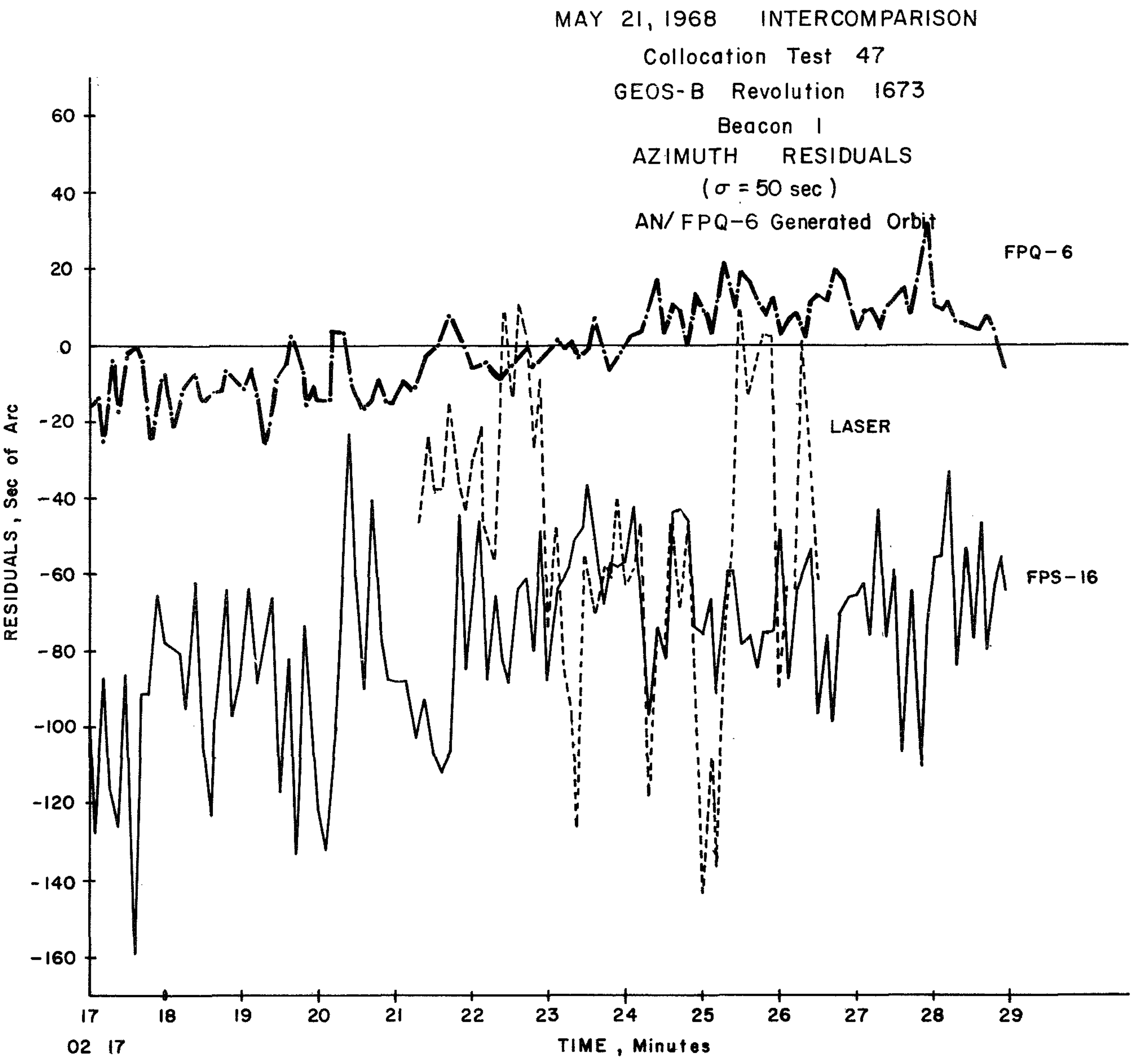

MAY 21, 1968 INTERCOMPARISON
Collocation Test 47
GEOS-B Revolution 1673
Beacon I
AZIMUTH RESIDUALS
(σ = 50 sec)
AN/FPQ-6 Generated Orbit
FPQ-6
LASER
FPS-16
RESIDUALS, Sec of Arc
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
17
18
19
20
21
22
23
24
25
26
27
28
29
02 17
TIME, Minutes

Figure 21

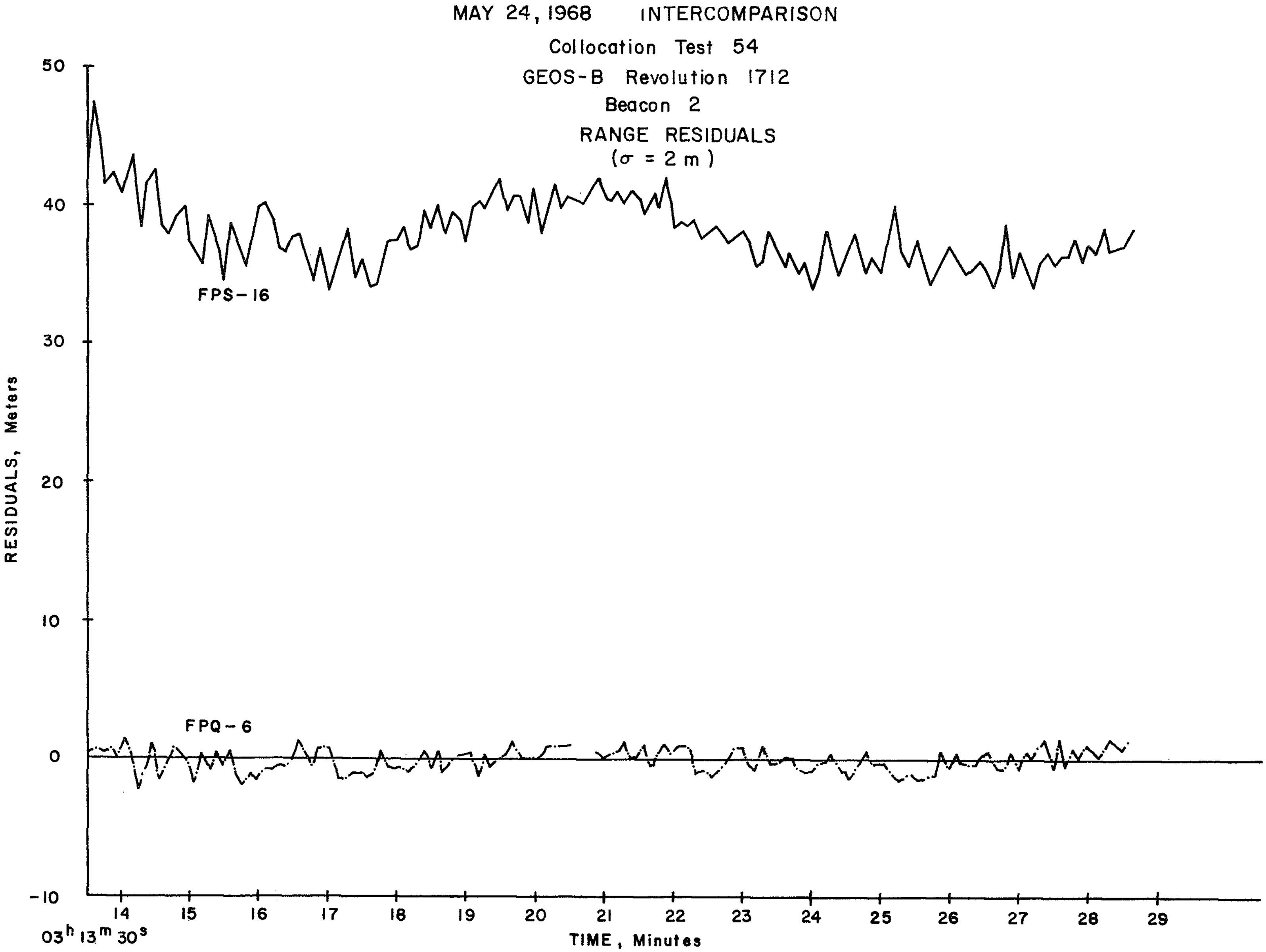

MAY 24, 1968 INTERCOMPARISON
Collocation Test 54
GEOS-B Revolution 1712
Beacon 2
RANGE RESIDUALS
(σ = 2 m)
RESIDUALS, Meters
50
40
30
20
10
0
-10
FPS-16
FPQ-6
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
03h 13m 30s
TIME, Minutes

Figure 22

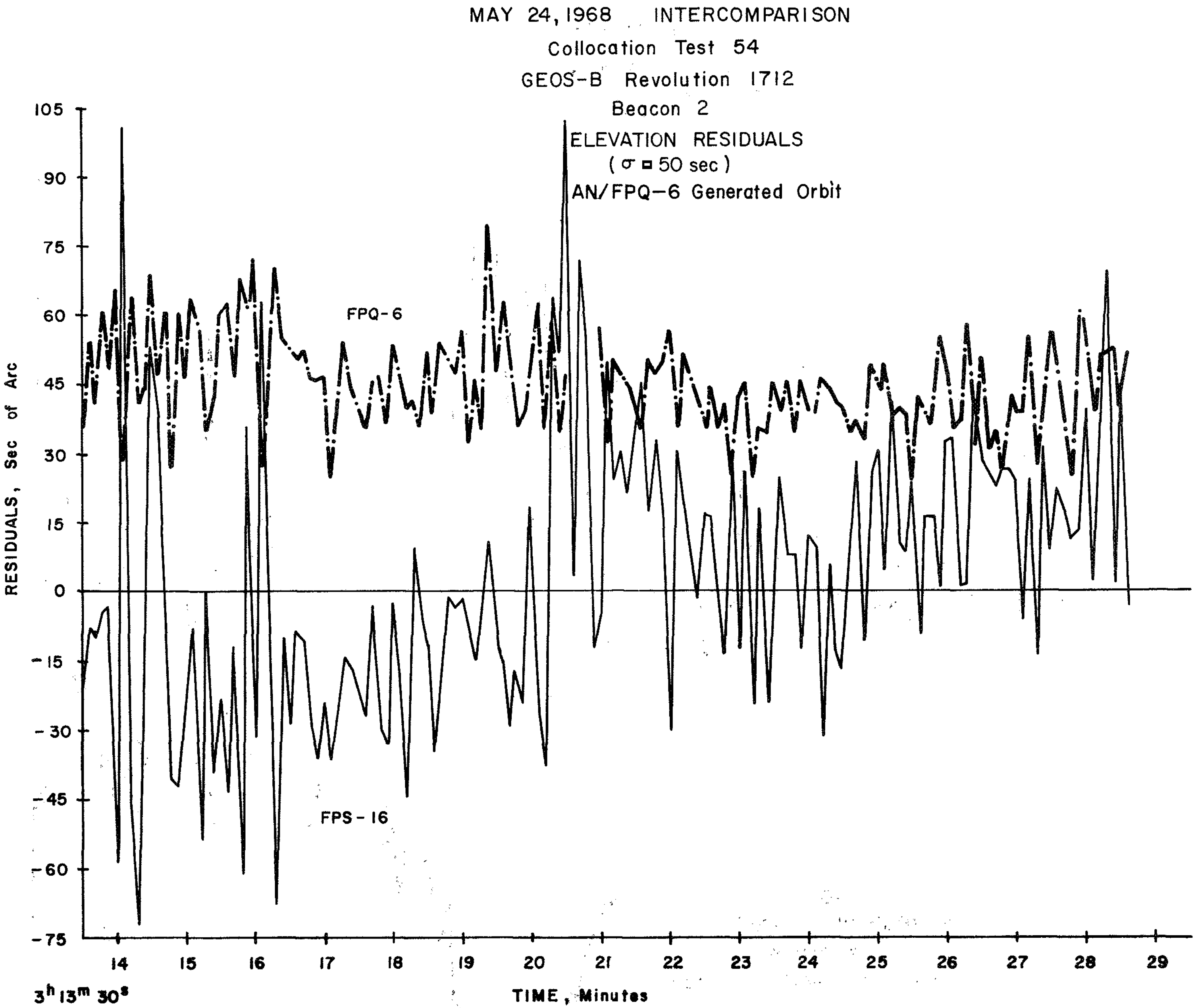

MAY 24, 1968 INTERCOMPARISON
Collocation Test 54
GEOS-B Revolution 1712
Beacon 2
ELEVATION RESIDUALS
(σ = 50 sec)
AN/FPQ-6 Generated Orbit
FPQ-6
FPS-16
RESIDUALS, Sec of Arc
105
90
75
60
45
30
15
0
-15
-30
-45
-60
-75
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
$3^h 13^m 30^s$
TIME, Minutes

Figure 23

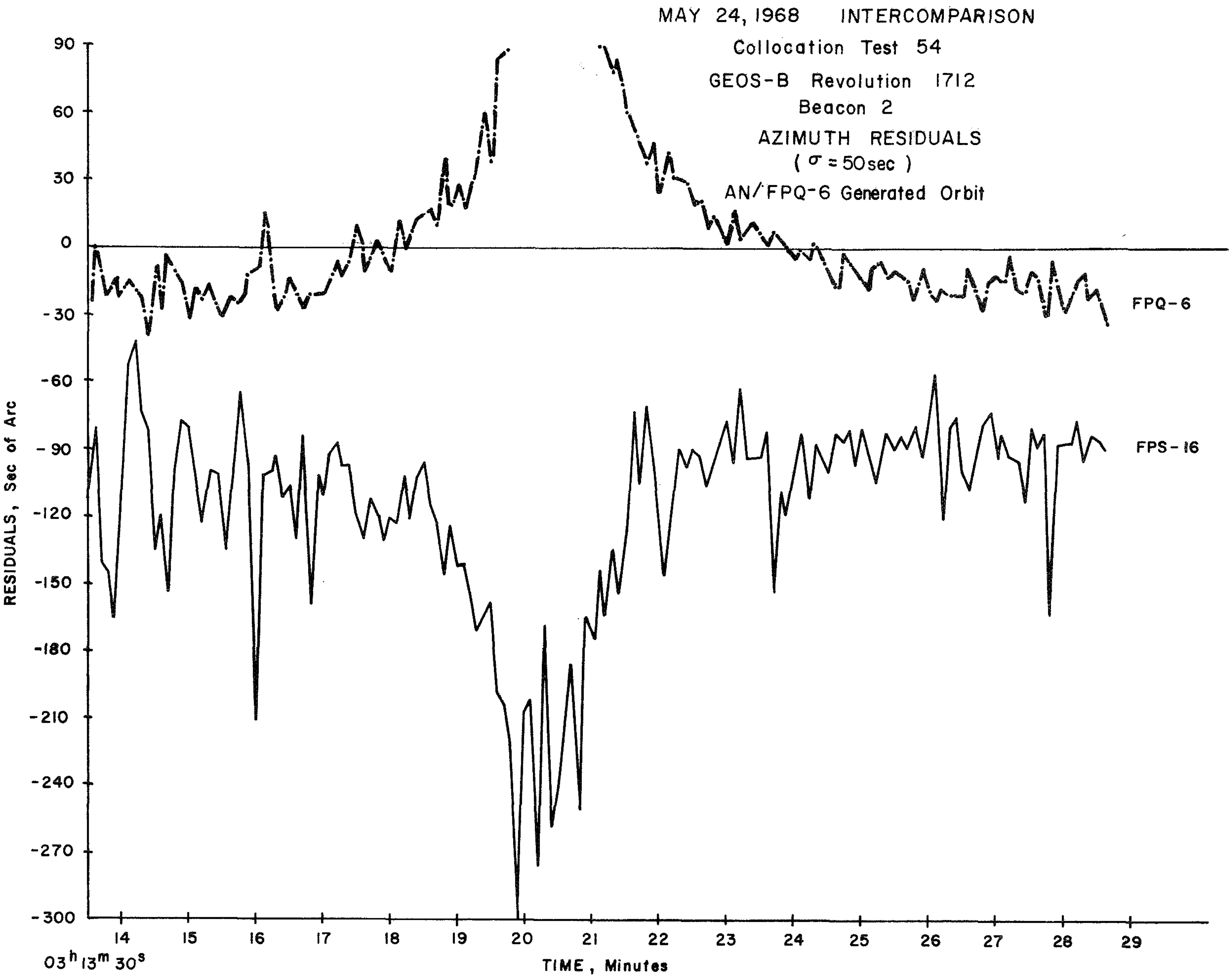

MAY 24, 1968 INTERCOMPARISON
Collocation Test 54
GEOS-B Revolution 1712
Beacon 2
AZIMUTH RESIDUALS
(σ = 50sec)
AN/FPQ-6 Generated Orbit
RESIDUALS, Sec of Arc
90
60
30
0
-30
-60
-90
-120
-150
-180
-210
-240
-270
-300
FPQ-6
FPS-16
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
$03^h 13^m 30^s$
TIME, Minutes

Figure 24

during this period, causing the elevation angle to be in error by 22.5 degrees. Thus, since range is refraction corrected as a function of elevation angle, the range refraction corrections during this period were in error.

The short arc intercomparisons pointed up some procedural difficulties in data taken during beacon/skin missions. Figures 25 and 26 show results obtained from beacon/skin missions of 16 April and 24 May 1968, (tests 14 and 54) where only the An/FPQ-6 data was used to determine the short arc. As can be seen from Figure 25, the AN/FPS-16, the LASER and skin track portion of the AN/FPQ-6 data agree extremely well, but appear to be biased by approximately 30 meters with respect to the AN/FPQ-6 beacon data, entirely consistent with our explanation in Section 5.5 (b). This pulsewidth bias, discovered from the intercomparison, can be removed either in calibration or postflight processing.

The same type of residual pattern is evident in Figure 26 (Test 54). This test was originally scheduled as an AN/FPQ-6 beacon/skin mission, but the skin track attempt was unsuccessful (note the break in AN/FPQ-6 track at approximately $3^h20^m30^s$). A pulsewidth problem, described in Section 5.5 (b), is evidenced by comparing the AN/FPS-16 and AN/FPQ-6 range residuals.

The intercomparison results to date indicate good agreement between the AN/FPQ-6, LASER and AN/FPS-16 systems. There do remain biases of a few meters between these instruments which we are continuing to investigate. A number of error sources have been identified and are being evaluated for their stability and magnitude.

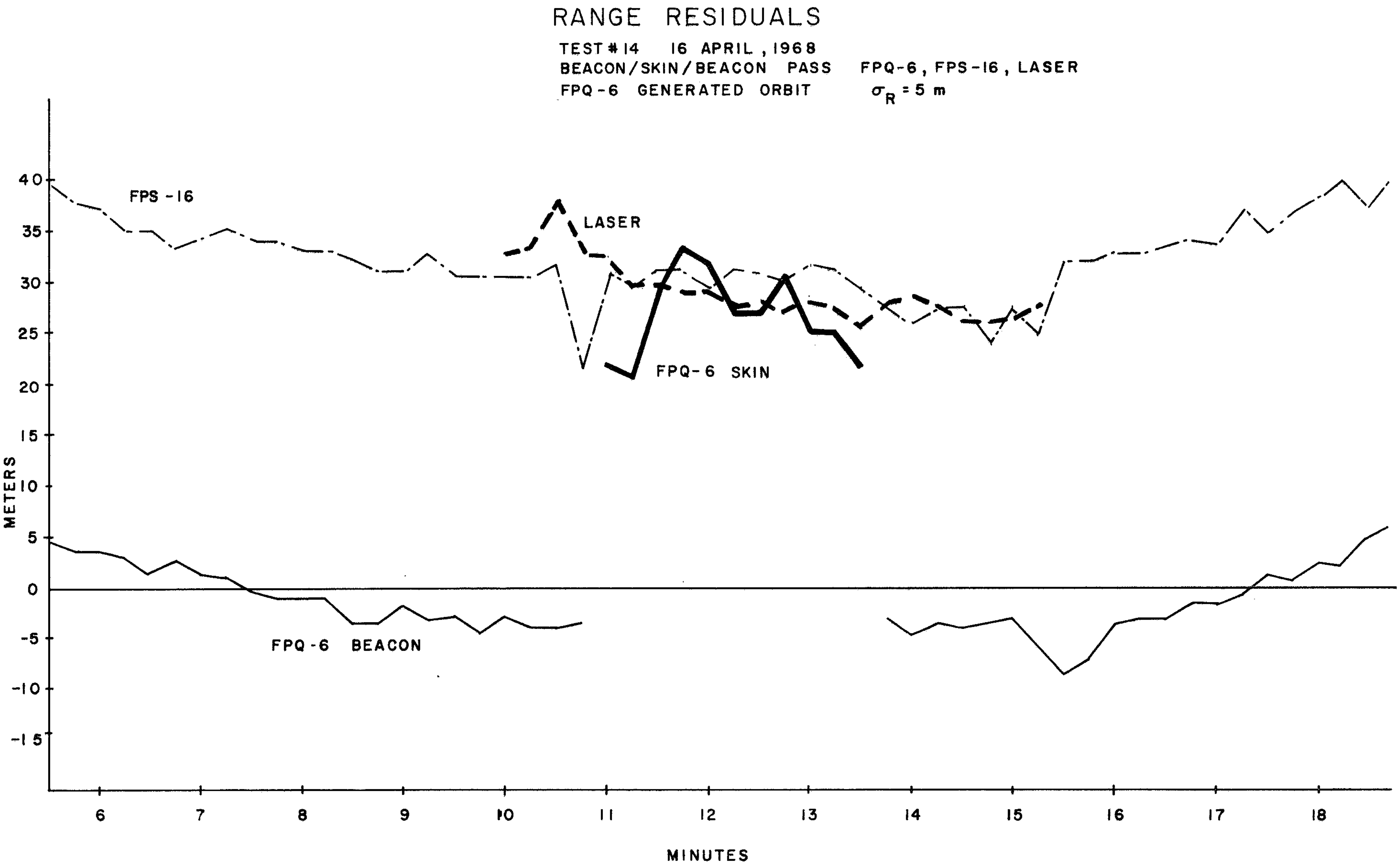

RANGE RESIDUALS
TEST # 14 16 APRIL, 1968
BEACON/SKIN/BEACON PASS FPQ-6, FPS-16, LASER
FPQ-6 GENERATED ORBIT $\sigma_R = 5$ m
FPS-16
LASER
FPQ-6 SKIN
FPQ-6 BEACON
METERS
40
35
30
25
20
15
10
5
0
-5
-10
-15
MINUTES
6
7
8
9
10
11
12
13
14
15
16
17
18

Figure 25

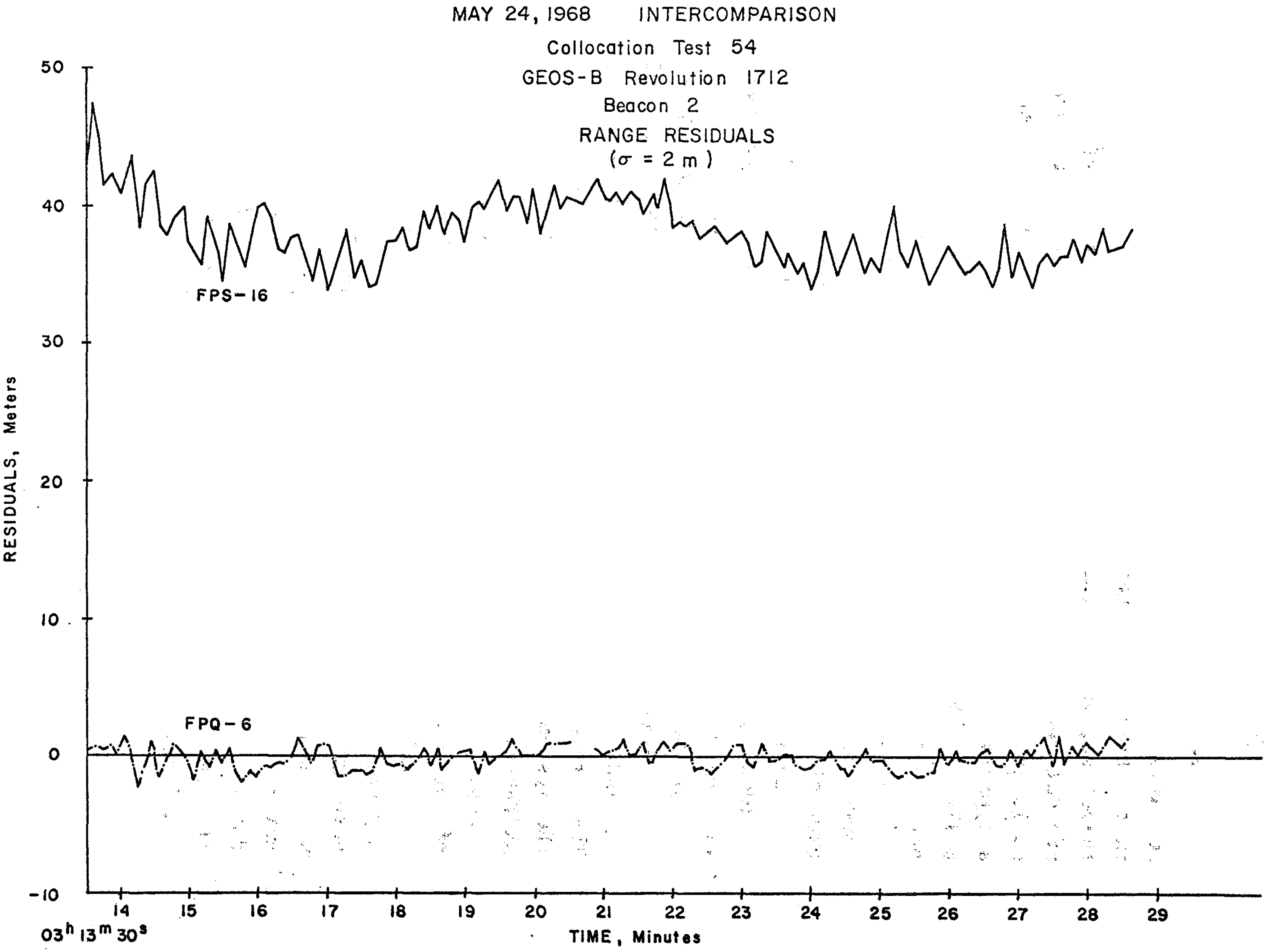

MAY 24, 1968 INTERCOMPARISON
Collocation Test 54
GEOS-B Revolution 1712
Beacon 2
RANGE RESIDUALS
(σ = 2 m)
RESIDUALS, Meters
50
40
30
20
10
0
-10
FPS-16
FPQ-6
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
03h 13m 30s
TIME, Minutes

Figure 26

5.3 Long Arc Intercomparison

In any short arc reduction, the orbit itself can act as a filter and absorb some of the systematic errors in the tracking system. A complete calibration procedure, therefore, must include the reduction and analysis of long arc data where the effects of major systematic errors can no longer be masked. Figure 27 shows the residuals from a typical long arc of AN/FPQ-6 GEOS-II track taken at Wallops. The arc covers a period of approximately 26 hours and consists of two consecutive revolutions on 22 May 1968 and two consecutive revolutions on 23 May 1968. Figures 28 to 31 show the R, A & E residuals for each of these passes reduced individually (short arc). One can readily see that the short arc results, while yielding good noise estimates, do not give a clear indication of the presence and nature of systematic errors in any of the channels. The long arc results, however, indicate a probable 35 sec of arc bias in the Az and El channels and indicate systematic trending of the range residuals. These results should not be interpreted as meaning that the systematic errors are necessarily caused by the AN/FPQ-6. The trending of the range residuals, for example, could be caused by the uncertainty in the model of the geopotential or by other modelling uncertainties. As a further indication that the range residual trends may not be caused by AN/FPQ-6 system problems, LASER observations were taken on test 49 and test 52, and they were included in the reduction with "zero" weight so as not to affect the solution. A plot of these LASER residuals in Figure 27 shows that they are trended in exactly the same manner as the AN/FPQ-6 residuals and agree to ± 2-3 meters with the AN/FPQ-6.

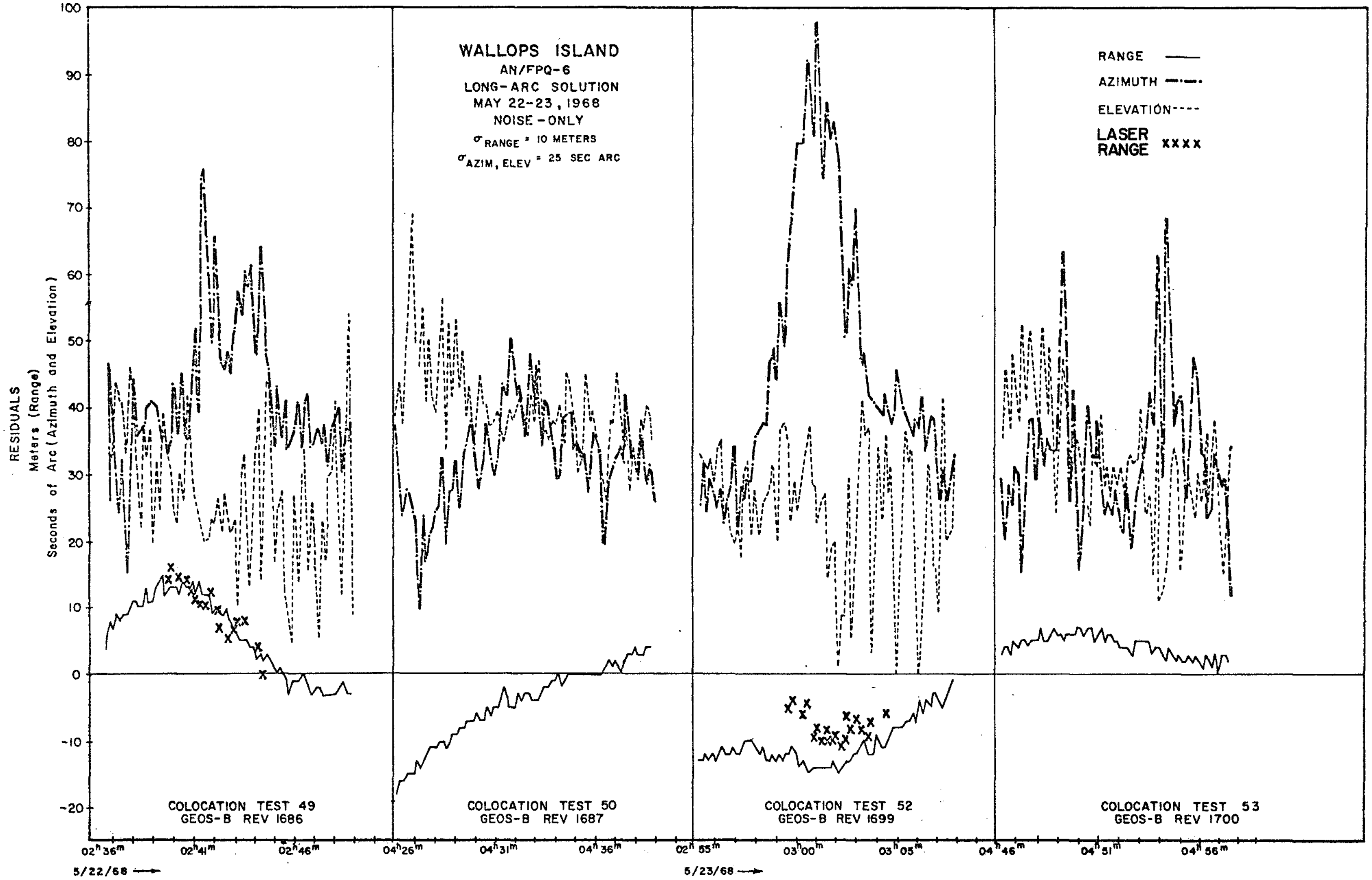

WALLOPS ISLAND
AN/FPQ-6
LONG-ARC SOLUTION
MAY 22-23, 1968
NOISE-ONLY
σ RANGE = 10 METERS
σ AZIM, ELEV = 25 SEC ARC
RANGE
AZIMUTH
ELEVATION
LASER RANGE xxxx
RESIDUALS
Meters (Range)
Seconds of Arc (Azimuth and Elevation)
100
90
80
70
60
50
40
30
20
10
0
-10
-20
COLOCATION TEST 49
GEOS-B REV 1686
COLOCATION TEST 50
GEOS-B REV 1687
COLOCATION TEST 52
GEOS-B REV 1699
COLOCATION TEST 53
GEOS-B REV 1700
02h 36m
02h 41m
02h 46m
04h 26m
04h 31m
04h 36m
02h 55m
03h 00m
03h 05m
04h 46m
04h 51m
04h 56m
5/22/68 →
5/23/68 →

Figure 27

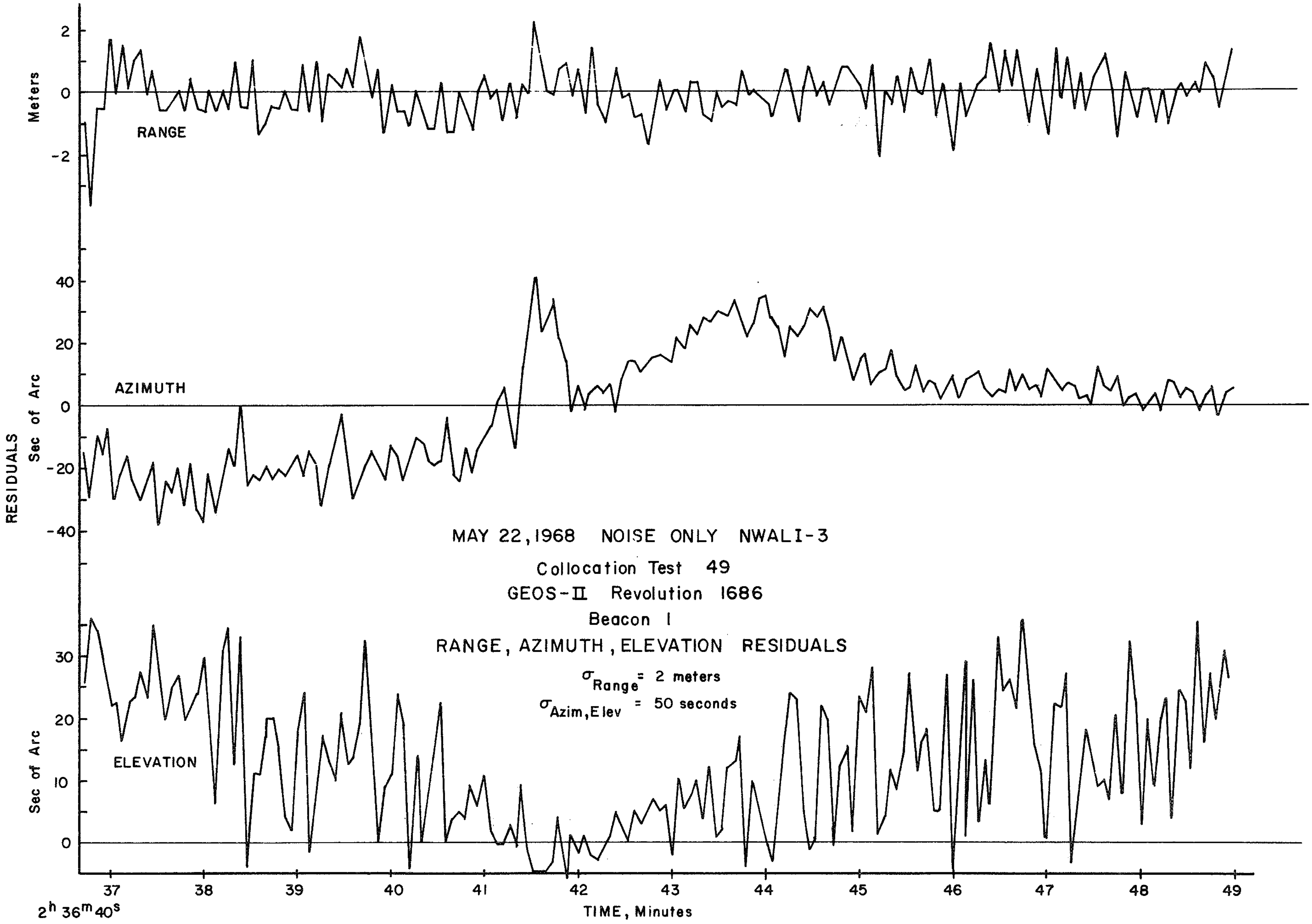
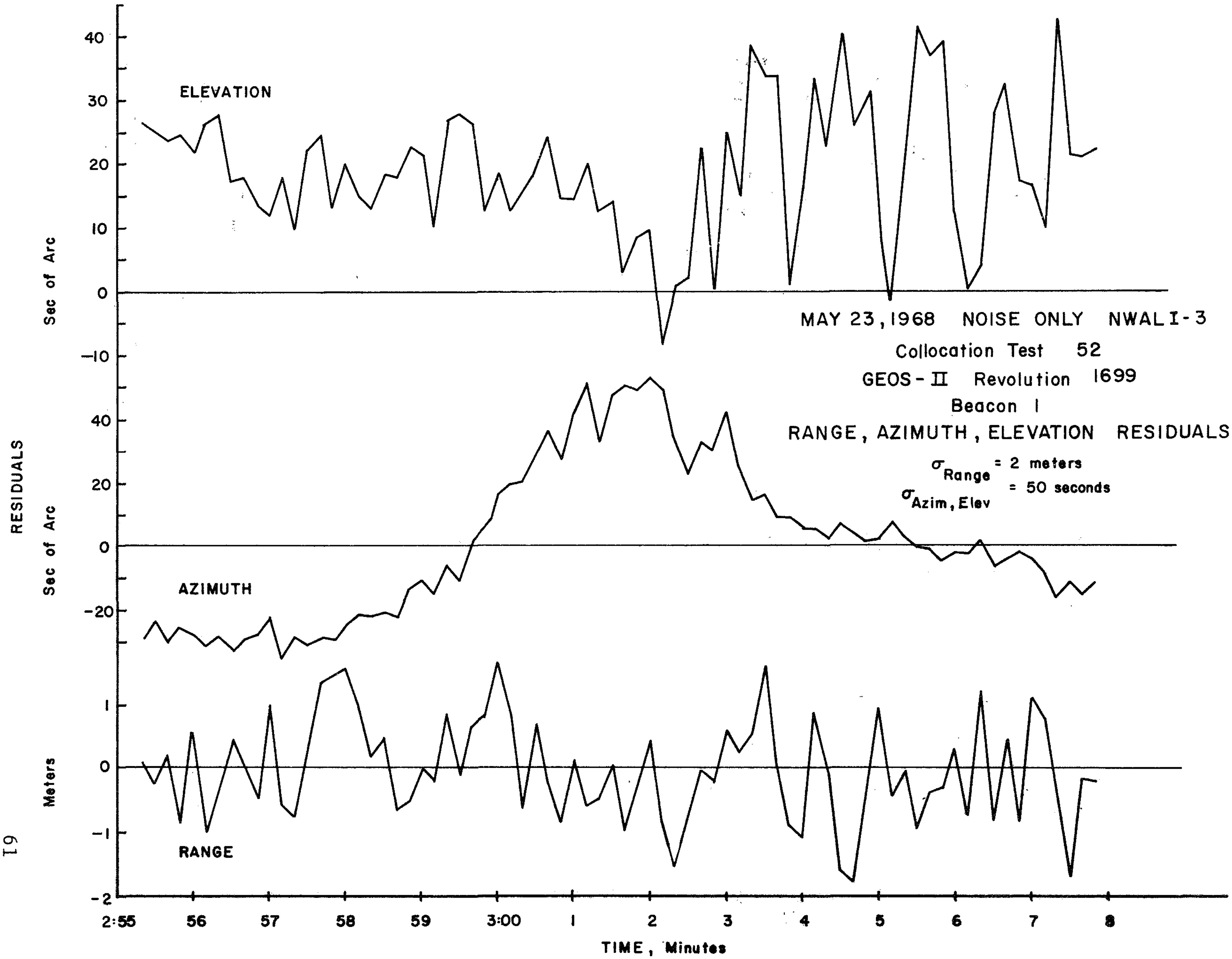

MAY 22, 1968 NOISE ONLY NWALI-3
Collocation Test 49
GEOS-II Revolution 1686
Beacon I
RANGE, AZIMUTH, ELEVATION RESIDUALS
σ_{Range} = 2 meters
$\sigma_{Azim, Elev}$ = 50 seconds
RESIDUALS
RANGE
Meters
2
0
-2
AZIMUTH
Sec of Arc
40
20
0
-20
-40
ELEVATION
Sec of Arc
30
20
10
0
37
38
39
40
41
42
43
44
45
46
47
48
49
$2^h 36^m 40^s$
TIME, Minutes

Figure 28



MAY 23, 1968 NOISE ONLY NWAL I-3
Collocation Test 52
GEOS - II Revolution 1699
Beacon 1
RANGE, AZIMUTH, ELEVATION RESIDUALS
σ_{Range} = 2 meters
$\sigma_{Azim, Elev}$ = 50 seconds
RESIDUALS
ELEVATION
Sec of Arc
40
30
20
10
0
-10
AZIMUTH
Sec of Arc
40
20
0
-20
RANGE
Meters
1
0
-1
-2
2:55
56
57
58
59
3:00
1
2
3
4
5
6
7
8
TIME, Minutes

Figure 29

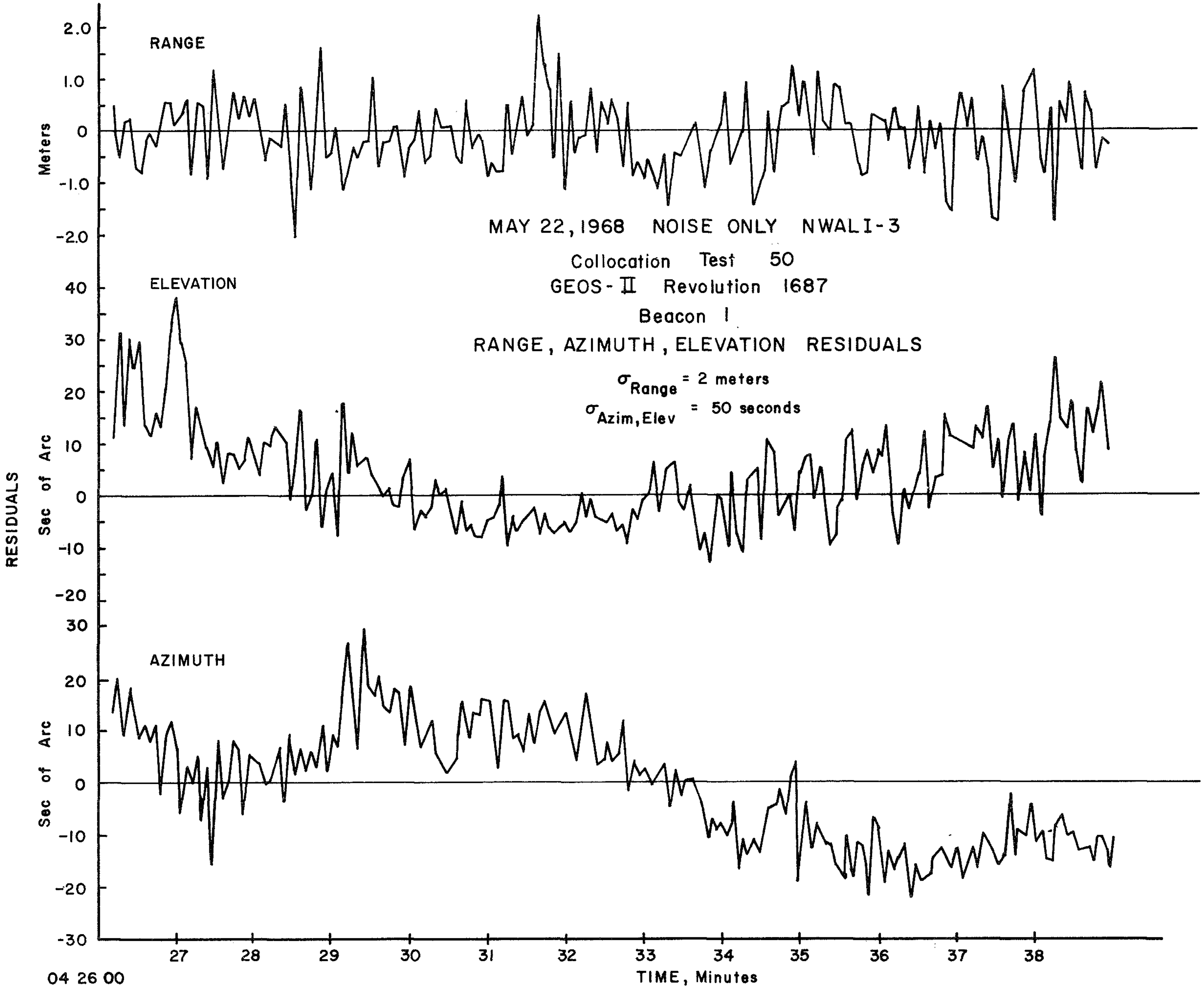

MAY 22, 1968 NOISE ONLY NWALI-3
Collocation Test 50
GEOS-II Revolution 1687
Beacon I
RANGE, AZIMUTH, ELEVATION RESIDUALS
σ_{Range} = 2 meters
$\sigma_{Azim,Elev}$ = 50 seconds
RANGE
Meters
2.0
1.0
0
-1.0
-2.0
ELEVATION
40
30
20
10
0
-10
-20
AZIMUTH
30
20
10
0
-10
-20
-30
RESIDUALS
Sec of Arc
Sec of Arc
27
28
29
30
31
32
33
34
35
36
37
38
04 26 00
TIME, Minutes

Figure 30

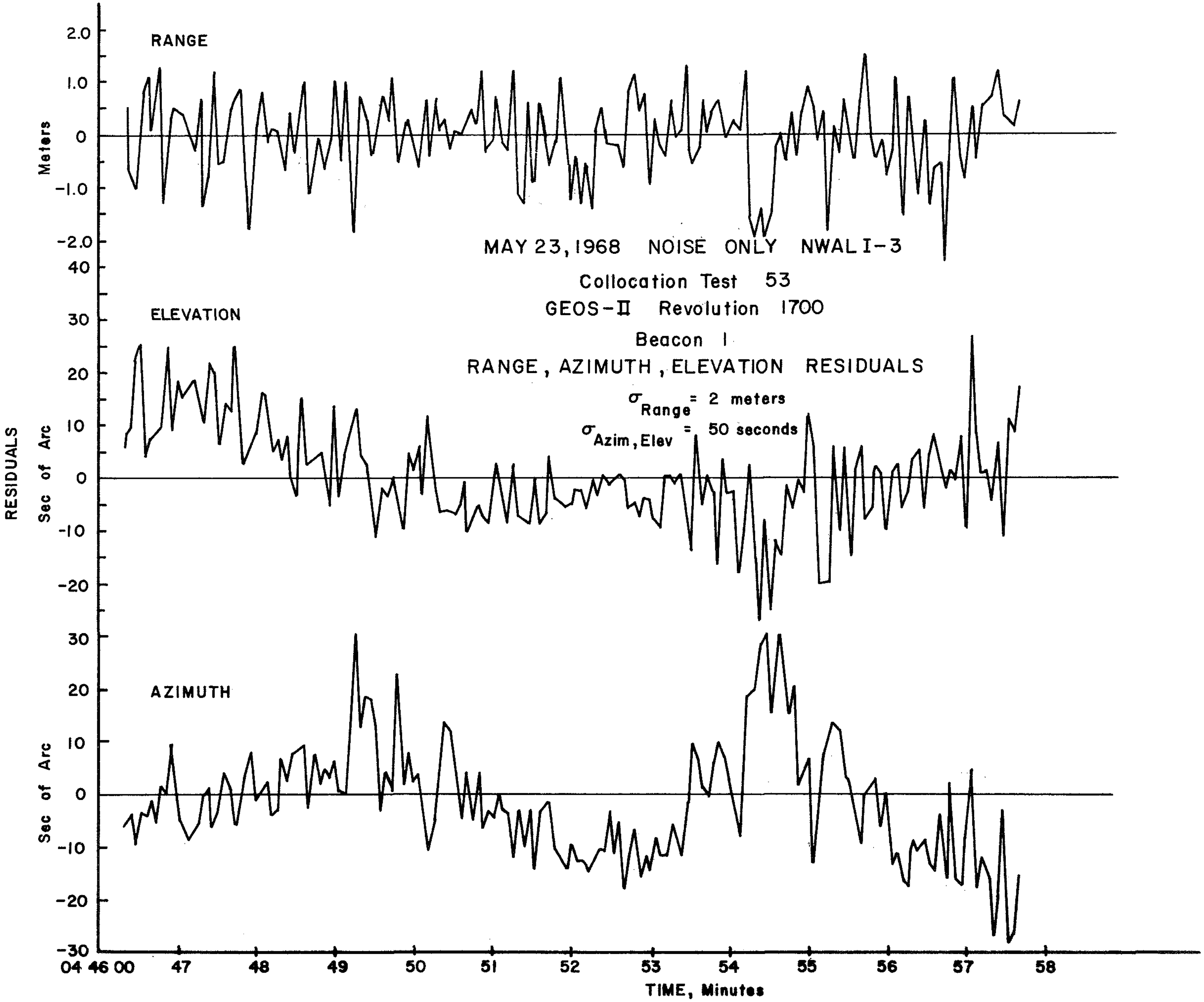

MAY 23, 1968 NOISE ONLY NWAL I-3
Collocation Test 53
GEOS-II Revolution 1700
Beacon I
RANGE, AZIMUTH, ELEVATION RESIDUALS
σ_{Range} = 2 meters
$\sigma_{Azim, Elev}$ = 50 seconds
RANGE
Meters
2.0
1.0
0
-1.0
-2.0
ELEVATION
40
30
20
10
0
-10
-20
AZIMUTH
30
20
10
0
-10
-20
-30
RESIDUALS
Sec of Arc
Sec of Arc
04 46 00
47
48
49
50
51
52
53
54
55
56
57
58
TIME, Minutes

Figure 31

The results of this and other long arc reductions are an indication that there are no gross systematic errors in the AN/FPQ-6. We are continuing our investigation into the possible sources of the existing systematic errors, and we intend to further investigate the contribution of geopotential model uncertainties, survey error, etc., on the R, A, and E measurements.

5.4 Long Arc Prediction Capability

One of the most sensitive means of determining the validity of an orbital solution is to compare the positions of the satellite predicted by this solution with those determined by actual measurement. Ideally, one would like to have satellite observations taken from a network well distributed geographically so that the quality of the solution over a complete orbit can be judged. At this writing, however, world wide observations from GEOS-II are not available. Therefore, we turn our attention to a more restricted but pertinent study, the single station long arc prediction.

The interest in this special case is two-fold:

a. to show that some systematic errors can be identified in near real-time without actually reducing the data in an orbital solution, and

b. to show that the AN/FPQ-6 is capable of providing acquisition data of sufficient accuracy to allow the GSFC LASER to track without manual aid.

Unaided LASER tracking is of interest because it would lift the present restrictions requiring the LASER station to be in darkness and satellite to be illuminated by the sun and even suggests the possibility of daylight tracking. Furthermore, although it has been demonstrated [4] that the LASER itself has the capability of providing its acquisition data to operate in the mode, there are likely to be periods of several days where weather will make LASER tracking impossible. The AN/FPQ-6 is, of course, not limited in this respect and therefore would be able to obtain the daily data necessary to update the orbits.

We are able to demonstrate these capabilities using the experiment discussed in Section 5.3, Long Arc Intercomparison. The long arc solution fit to AN/FPQ-6 data covering a twenty-six hour period in Tests 49, 50, 52 and 53 was used to predict the range measurements expected from Test 54, approximately 24 hours after test 52 or 50 hours from the long arc solution epoch. These computed range measurements were then compared with those obtained from the AN/FPQ-6 and the AN/FPS-16 radar which tracked during Test 54. Figure 32 shows the differences between the radar measured ranges and those predicted from the long arc. We see that the AN/FPS-16 residuals are always less than 20 meters and have an RMS of fit of 7 meters. The AN/FPQ-6 residuals display the same trend as the AN/FPS-16 data but are significantly larger in magnitude reaching as much as 55 meters. Investigation into the radar set-up leads us to discover that a one microsecond pulsewidth rather than the prescribed 0.5 microsecond width has been used. As mentioned previously this causes a bias in range. Figure 33 shows the same residual plots but with the pulsewidth bias removed from the AN/FPQ-6. The agreement between the instruments is now excellent.

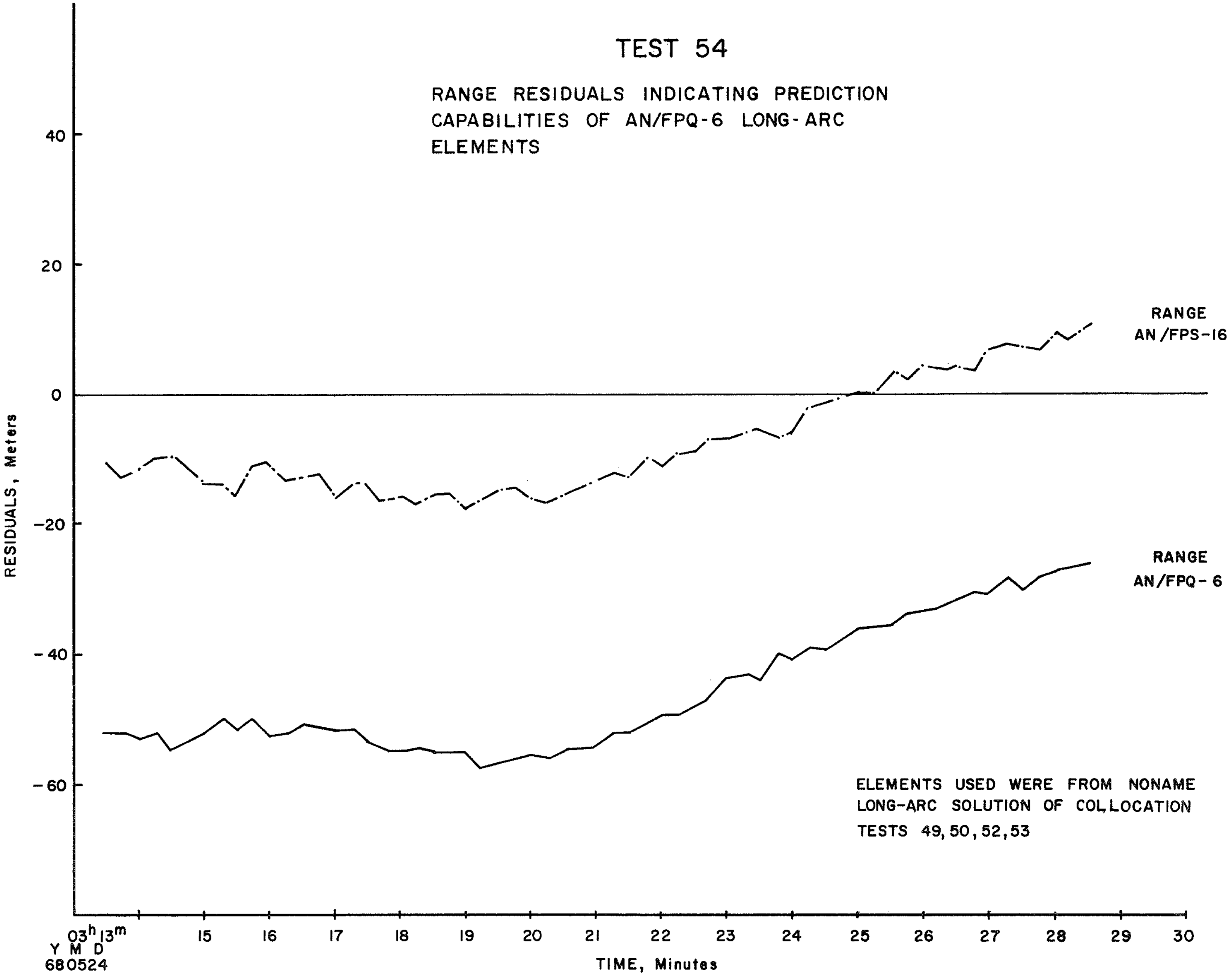
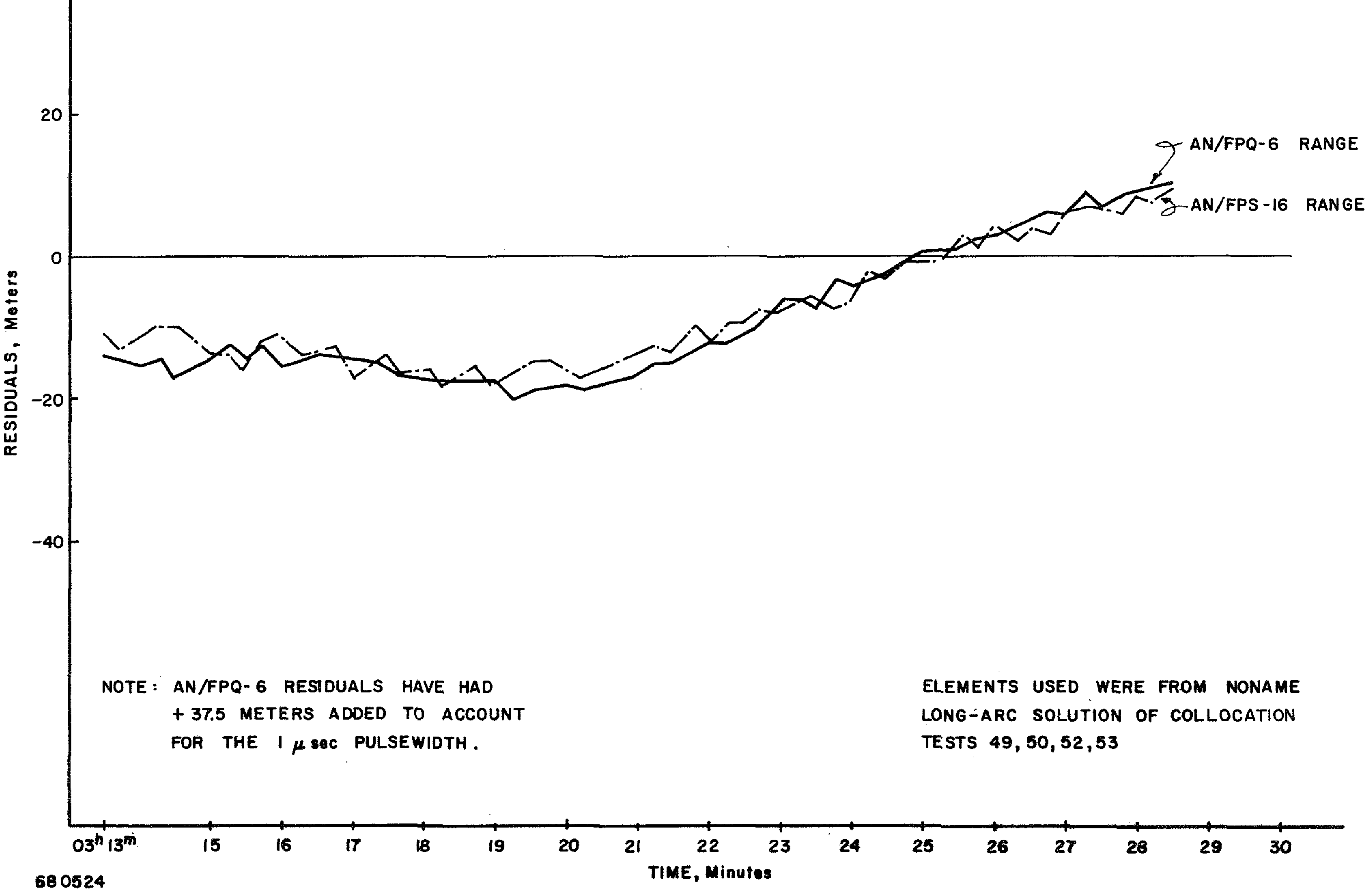

TEST 54
RANGE RESIDUALS INDICATING PREDICTION CAPABILITIES OF AN/FPQ-6 LONG-ARC ELEMENTS
RESIDUALS, Meters
40
20
0
-20
-40
-60
RANGE AN/FPS-16
RANGE AN/FPQ-6
ELEMENTS USED WERE FROM NONAME LONG-ARC SOLUTION OF COLLOCATION TESTS 49, 50, 52, 53
03h 13m
Y M D
680524
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
TIME, Minutes

Figure 32

TEST 54

RANGE RESIDUALS INDICATING PREDICTION CAPABILITIES OF AN/FPQ-6 LONG-ARC ELEMENTS



NOTE: AN/FPQ-6 RESIDUALS HAVE HAD + 37.5 METERS ADDED TO ACCOUNT FOR THE 1 μsec PULSEWIDTH.

ELEMENTS USED WERE FROM NONAME LONG-ARC SOLUTION OF COLLOCATION TESTS 49, 50, 52, 53

Figure 33

These results demonstrate both the capability for bias identification and adequacy of the data to provide accurate acquisition information.

5.5 Hardware Evaluation Experiments

Since an important aspect of the calibration mission is the identification of sources of systematic errors, we are performing a series of radar experiments designed to assist us in determining the magnitude and sign of systematic errors in the range data. The results of these experiments are described below, and a tabulation of the errors defined to date is given in Table IV. It should be noted that this tabulation is by no means comprehensive or general in nature. It defines errors which we have discovered and measured at Wallops. Some of the errors are inherent in the procedures used to gather and process the data. We are continuing the experiments to further define additional sources and expect to update our tabulation as the results of these experiments become available and are analyzed.

a. Range Oscillator Drift

The AN/FPQ-6 range reference oscillator is designed to provide 2000 International yards per cycle. In order to ascertain the actual frequency of the oscillators in the AN/FPQ-6 and AN/FPS-16, they were compared to the Wallops cesium beam standard. These measurements indicate

TABLE IV

SUMMARY OF RANGE ERROR CORRECTIONS --- - COLLOCATION TESTS 1-109

(Dependent on Wallops Calibration Methods)

TEST DESCRIPTION		AN/FPQ-6 RADAR						AN/FPS-16 RADAR		REMARKS
		SKIN TRACK		BEACON TRACK		BEACON PORTION of Beacon/Skin Track		BEACON TRACK		
		Bias	Variation	Bias	Variation	Bias	Variation	Bias	Variation	
1. RANGE OSCILLATOR DRIFT			± 1 yd		± 1 yd		± 1 yd		± 1 yd	(a) oscillator frequency measured (b) effect on Range calculated
2. CALIBRATION PULSEWIDTH versus TRACK PULSEWIDTH				- 8.2 yds	± 2 yds	+ 31.1 yds	± 2 yds			(a) Range Bias calculated from pulsewidths measured
3. REFRACTION CORRECTION for Calibration (Range Target)		+ 3 yds	± 0.5 yd	+ 3 yds	± 0.5 yd	+ 3 yds	± 0.5 yd			(a) calculated error from normal weather conditions
4. RANGE DRIFT (Warmup)			± 1 yd		± 1 yd		± 1 yd			(a) measured on Range Target
5. Difference between: TRANSPONDER DELAY vs. INTERROGATION SIGNAL STRENGTH -and- DELAY VALUES used in Data Reduction	Serial No.5 (Short Delay)			+ 0.8 yd	± 1 yd	+ 0.8 yd	± 1 yd			(a) Interrogation Signal Strength computed from measured radar received signal strength (b) Delay picked from preflight measured delay curves
	Serial No.6 (Long Delay)			+ 0.3 yd	± 1 yd	+ 0.3 yd	± 1 yd			
6. UNCERTAINTY in Delay Curve Orgin					± 2 yds		± 2 yds			(a) value obtained from preflight transponder test data
7. P R F CHANGE 160 (for Calibration) versus 640 (for Track)		+ 4.5 yds	± 1 yd							(a) measured on Range Target
8. LOCAL OSCILLATOR CHANGE Continuous (for Calibration) versus Off (for Track)						+ 0.5 yd	± 0.1 yd			(a) measured on Range Target
9. TIMING			± 1 yd		± 1 yd		± 1 yd			(a) Timing Bias measured (b) effect on Range calculated
10. RECEIVER BANDWIDTH (Mismatch)							± 1 yd			(a) measured on Range Target
TOTAL CORRECTIONS:										
SKIN TRACK		+ 7.5 yds	± 2.1 yds							
SHORT DELAY TRANSPONDER				- 4.4 yds	± 3.5 yds	+ 35.4 yds	± 3.7 yds			
LONG DELAY TRANSPONDER				- 4.9 yds	± 3.5 yds	+ 34.9 yds	± 3.7 yds			

that the AN/FPQ-6 oscillator rate is 81,964.2$\overline{8}$* cps and that of the AN/FPS-16 is 81,964.2$\overline{9}$ cps. These measurements are limited by the resolution of the time interval counter available at Wallops. We hope to make additional measurements in the future using a more precise counting technique. Since the design frequency (based on the speed of light in vacuo = 327,857,0$\overline{64}$ ± 4$\overline{37}$ yds/sec [6]) is 81, 964.2$\overline{66}$ cps, an error approximately 1 yard in 1000 nautical miles is possible with the knowledge of the oscillator frequency. This range is typical for GEOS-II passes.

The error in range is represented by:

$$\varepsilon_R = \left[2000 \text{ yds} - \frac{C}{2fr}\right] \times \frac{\text{Target Range (yds)}}{2000 \text{ yds}}$$

where C = velocity of light in vacuo (yds/sec)

fr = Range Reference Oscillator Frequency (cps).

The AN/FPS-16 oscillator is more stable than that of the AN/FPQ-6, and we therefore adjust the AN/FPQ-6 oscillator prior to each mission until the range rate between the AN/FPQ-6 and AN/FPS-16 is under 20 yards/sec. At 1000 nautical miles (12,202μsec) range, the range error between the two radars is less than 0.25 yds.

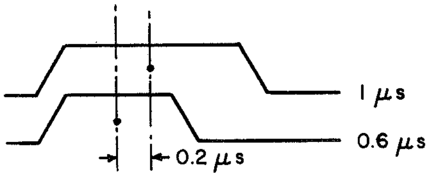
---

* The bar over the final digit(s) indicates that this is a non-significant number carried in the calibration to prevent rounding errors.

Since this error is systematic and proportional to range, it could be further reduced if we were able to precisely measure the oscillator frequencies prior to, during, or after track. This is not possible with our present test equipment. Until better equipment is available for these measurements, the radars will be maintained to within 20 yds/sec of each other and the absolute oscillator frequencies assumed to be more precise than our capability to measure them.

b. Pulse Width Matching

Since the AN/FPQ-6 and AN/FPS-16 radars are centroid trackers, any difference in the pulsewidth used for calibration and the pulsewidth experienced in tracking will result in a range bias error. For example, for GEOS-II beacon/skin missions, the AN/FPQ-6 was calibrated using a 1µsec pulsewidth; the beacon portion of the mission was tracked using 1µsec pulsewidth while the actual transponder reply was 0.6µsec. As shown below, the difference between the two centroids is 0.2µsec when the same leading edge is referenced.



The radar range system does reference the leading edge when establishing zero range with the transmitter trigger. The 0.2µsec difference thus results in a range bias which, at the radar propagation velocity of 163.9 yards/µsec, represents 32.8 yards of range error which must be added to the data to maintain calibration.

When supporting pure beacon missions, the AN/FPQ-6 was calibrated using a 0.5μsec pulsewidth, which when compared to the transponder return of 0.6μsec, results in a range bias of -8.2 yards. A further error of the same nature could develop if the actual radar pulsewidth were different from that indicated. For example, the actual pulsewidth could be 0.98μsec when the mode selector indicates 1 μsec. This possible source is currently being investigated.

c. Refraction

The survey distance to the range target is 26,880 ft. at an elevation of .3°. At this range and elevation the distance to the range target should measure approximately 3 meters ± .5 meters longer than survey because of the effect of atmospheric refraction. This 3 meter error was not removed from any of the 39 noise-only short arc data reduction runs.

The refraction corrections to range and elevation were made using nominal values to calculate the refractive index. No attempt was made to use any meteorological data to correct for refraction errors.

d. Range Drift

We have compiled the pre- and post-mission range target calibration data for 109 AN/FPQ-6 tracks taken during the course of the collocation experiments at Wallops Station. Investigation of this data reveals that the pre-mission range calibrations average approximately 2 yards longer than the post-mission calibrations.

We assumed that this variation was attributable to "warm up" of the circuitry in the range system. In order to verify this assumption, an experiment was performed whereby apparent target range versus time was monitored for a period of 19 hours on 16 July 1968. The data from this experiment is plotted in Figure 34. We did not use the data obtained during the first two hours of the experiment since the radar is always warmed up for at least two hours prior to any tracking mission.

The significance of this plot is the magnitude of the drift which can occur during the time interval (approximately 1 hour) between pre- and post-calibrations and not the total diurnal variation. From the curve we can see that in the worst case, a 3 yard change could occur. Since we are currently averaging pre- and post-mission calibration data, the peak error will be approximately 1.5 yards.

A refined technique for weighting the pre- and post-mission calibration data as a function of their proximity to the track time should reduce this error to less than ± 0.5 yds.

e. Transponder Delay vs Interrogation Signal Strength

The C-Band transponders aboard GEOS-II have delays which vary as a function of the strength of the interrogation signal. The nominal delay vs signal strength curves for each transponder are shown in Figure 35. In the preprocessing of the radar data for the collocation experiment, sufficient information was not available to predict this signal strength due to the AN/FPQ-6 or AN/FPS-16 systems. We therefore chose nominal values from the curves to serve as first approximations to the true delay value.

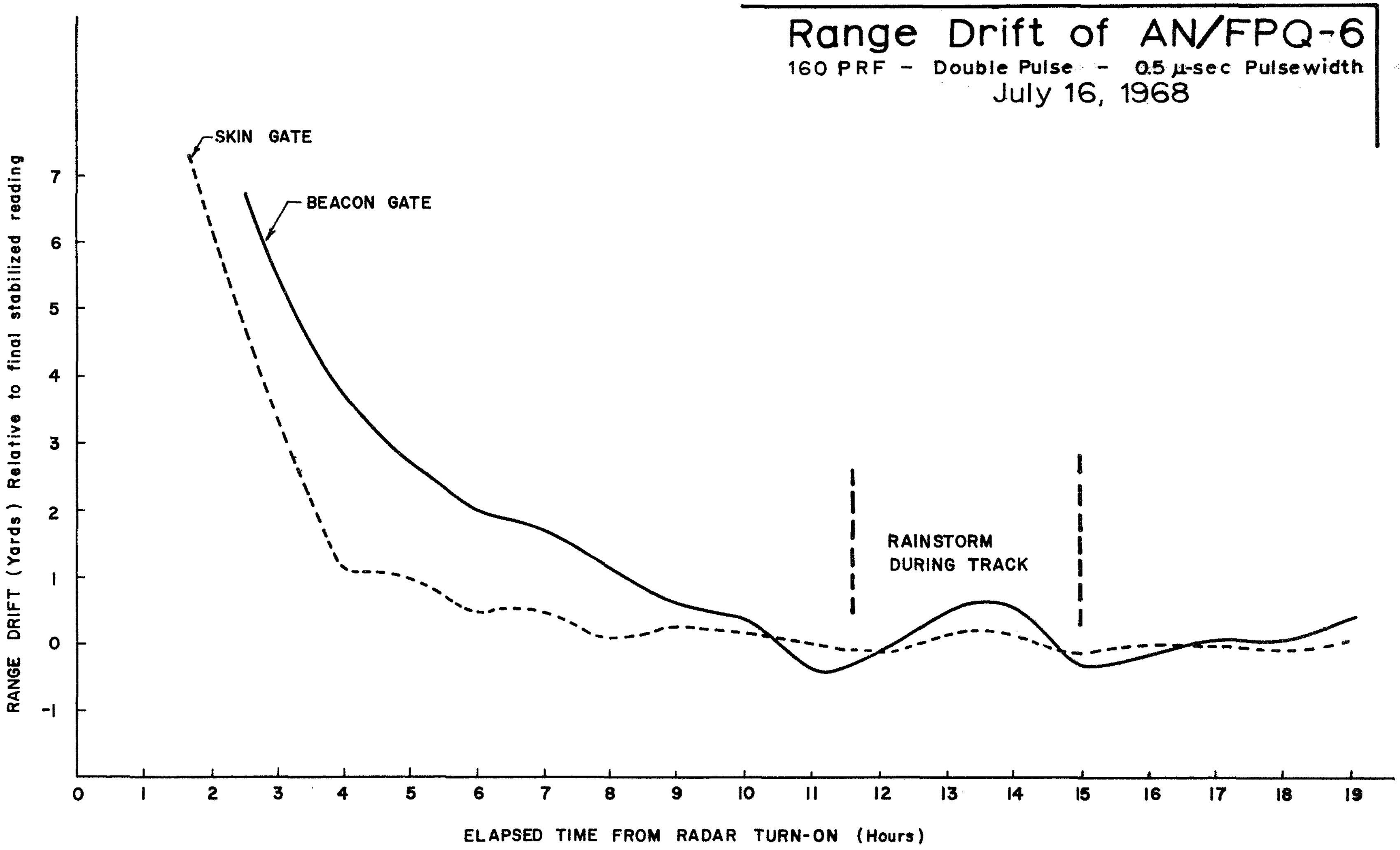
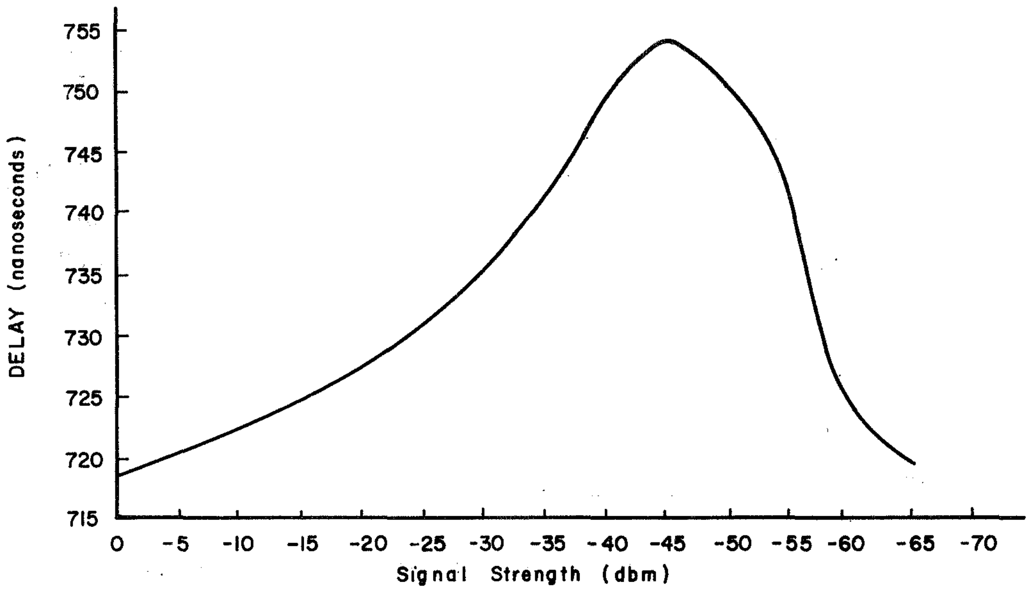
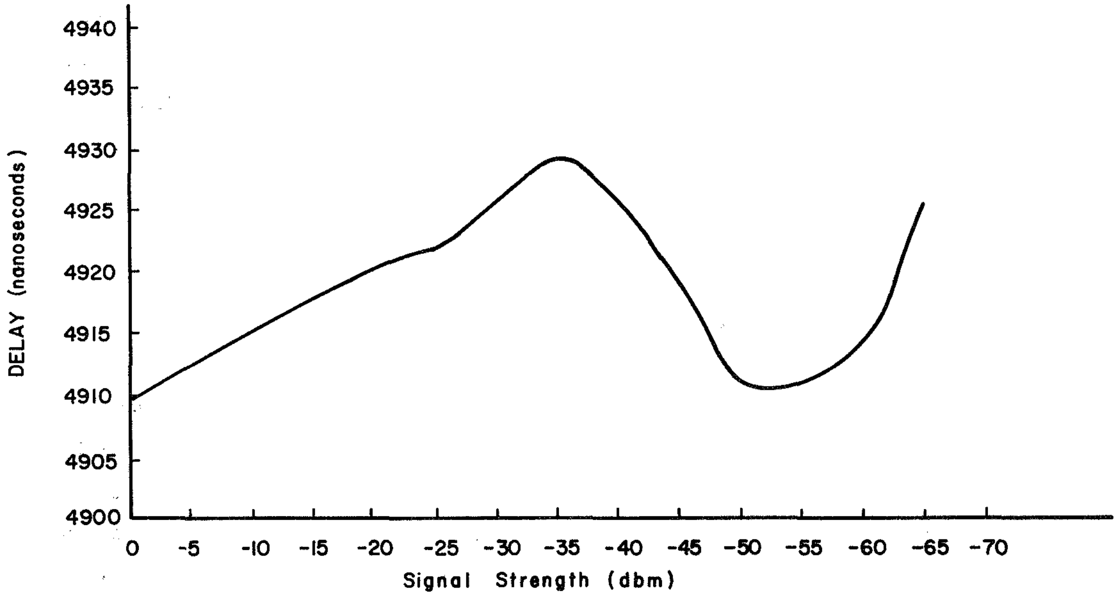

Range Drift of AN/FPQ-6
160 PRF – Double Pulse – 0.5 μ-sec Pulsewidth
July 16, 1968
SKIN GATE
BEACON GATE
RAINSTORM
DURING TRACK
RANGE DRIFT (Yards) Relative to final stabilized reading
7
6
5
4
3
2
1
0
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
ELAPSED TIME FROM RADAR TURN-ON (Hours)

Figure 34

TRANSPONDER DELAY CURVES



SHORT DELAY TRANSPONDER SN #5 (Beacon 1)



LONG DELAY TRANSPONDER SN # 6 (Beacon 2)

Figure 35

The same delays were used for both the AN/FPQ-6 and AN/FPS-16, and they correspond to range corrections of 123 yds for the short delay transponder and 809 yds for the long delay transponder. Since the same transponder antenna, radar antenna, and atmospheric losses occur in both the transmission and receiving paths of the radar track, a better estimate of the interrogation signal strength can be obtained by studying the radar received signal strength. We have performed this study, and the corrections indicated on line 5 of Table IV are the differences between the original delay estimates and the newly determined delays.

f. Uncertainty in Delay Curve Origin

Although the shape of the delay curves is well defined (± 1 yd), the total delay with respect to the leading edge of the interrogation pulse was not well defined. Data taken during the flight qualification of the transponders indicates an uncertainty of ± 2 yds in the 0dbm delay point. It has not been determined whether this is a transponder problem or a limitation in the test equipment used to measure the transponder characteristics. We hope to reduce this error through the reduction and analysis of a sufficient number of AN/FPQ-6 beacon/skin AN/FPQ-6/LASER tracks.

g. PRF Dependent Error

A consistent -4.5 yd difference in range between skin and beacon tracking is attributable to the fact that we calibrate at a Pulse Repetition Frequency (PRF) of 160 cps and track at 640 cps during skin missions. This dependence on PRF is probably caused by frequency sensitivity of the radar circuitry.

h. Local Oscillator Mode Dependent Error

The radar has two independent local oscillators (LO) and range tracking gates which can be either simultaneously or independently used for skin and beacon tracking. During the pre and post mission calibrations it is desirable to make measurements in both skin and beacon; therefore the "continuous" (both LO on) condition is used. During the tracking mission only one mode is required; therefore, the "off" (one LO on) condition is selected. In this condition, the selection of the track mode chooses the appropriate local oscillator. Measurements taken on the range target indicate that this procedure produces, under certain circumstances, a range error. The cause and stability of this error have not been determined but are under study at this time.

i. Timing Errors

There is a small, variable error in the time tag of the radar data which has not been accounted for in our reductions thus far. This error is due to the fact that we do not correct for diurnal variations in the "time-of-day-generator" (TODG) oscillator at the master timing site.

The TODG uses an ultra-stable ($1:10^{-11}$) quartz crystal oscillator to generate coded time pulses which are transmitted by wire to the various instrumentation sites. The TODG is synchronized to UTC by comparing it daily with a cesium beam standard which in turn is compared quarterly with the U.S. Naval Observatory Standard.

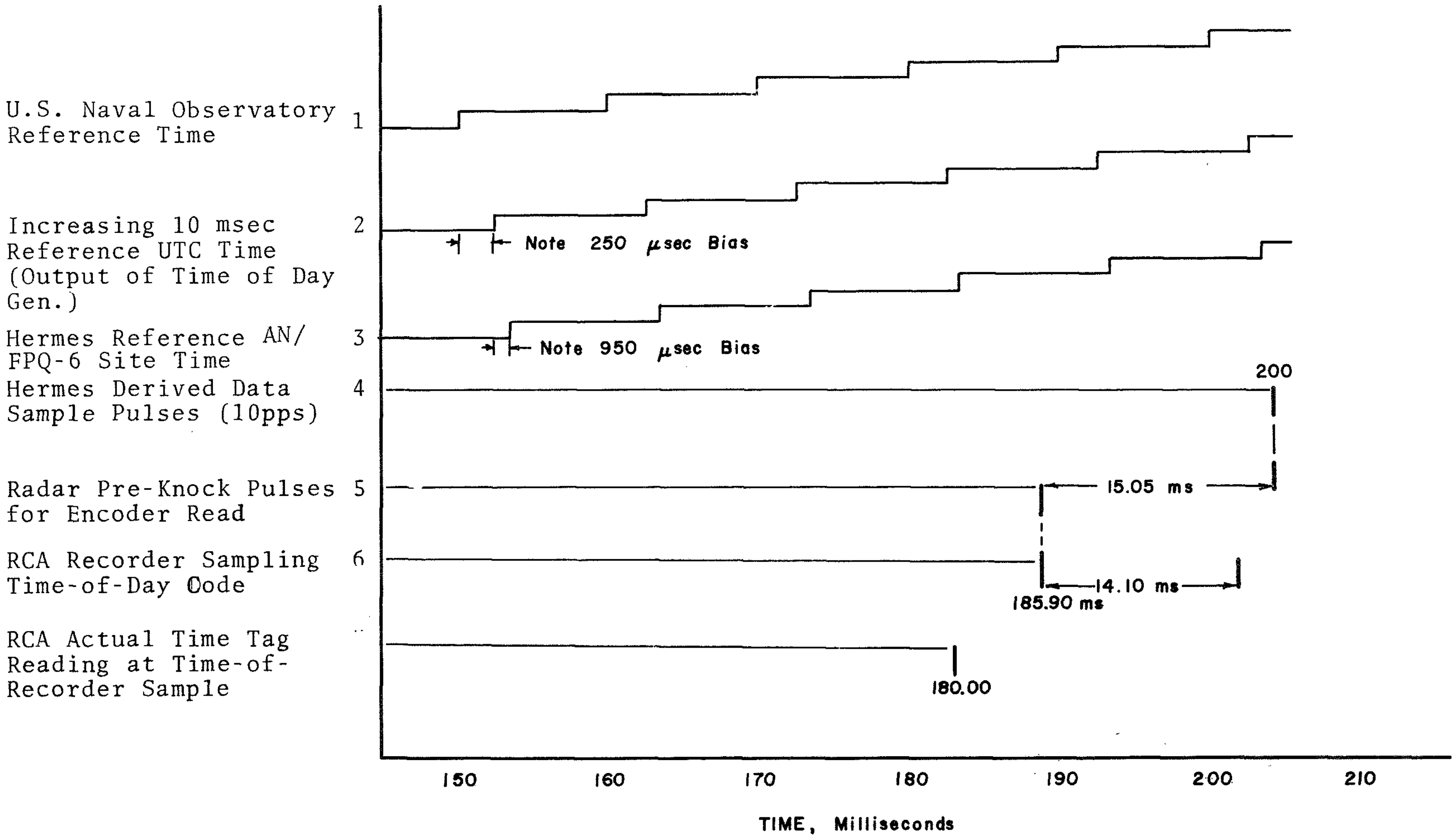
The received TODG pulse is used by the AN/FPQ-6 4101 Hermes system to time tag the R, A, E data at the site. The procedures and circuitry used in tagging the data bias the time tag by -5msec ± 5μsec (see AN/FPQ-6 Timing Diagram, Figure 36). The time is further biased by -0.9msec, the transmission delay between the TODG and the AN/FPQ-6 site. These two biases have been accurately determined and are properly accounted for in the PASS-1 program.

The uncorrected error is due to short period variations of the TODG oscillator. These variations are measured and recorded daily at the master site by direct comparison of the TODG oscillator and the cesium beam standard. The log indicates that this variation can range from 43 to 300μsec (measurement accuracy ± 2-3μsec). At GEOS-II satellite ranges, this time tag error could cause up to ≈1 yd error in range. Since a log of these variations has been kept, we can apply the proper correction to the time tag at some future date.

j. Receiver Bandwidth Mismatch

The receiver bandwidth was found to be mismatched in the beacon portion of beacon/skin missions. The error caused by this mismatch has been investigated. This mismatch contributes less than 1 yd error to the beacon portion of the mission.

We have tabulated in Table IV all of the errors investigated to date along with their sign and probable uncertainty. We must emphasize that this tabulation is not yet complete. We are continuing investigations into other probable sources of error, and we will continue to



FPQ-6 TIMING DIAGRAM

Figure 36

NOTE:

1. Since all encoders are read at pre-knock time all recorded time should be corrected to the UT-C Time-of-pre-knock, i.e.:
   RCA True Time = RCA Recorded Time + 5.9 msec.
   Milgo True Time = Milgo Recorded Time - 14.1 msec.
2. Under rare conditions where 4101 Computer corrections are not desired data may be recorded without pre-knock.

update the table as our investigations indicate. From time-to-time we will evaluate the validity of the total correction by applying it to data which has already been processed and analyzed to see whether in fact the application of these corrections does improve the fit of the data over short and long arc passes.

6.0 CONCLUSIONS

The results of the investigations carried out thus far attest to the quality of the AN/FPQ-6 radar as a satellite tracking system. The reliability, precision and overall accuracy of the radar have proven to be remarkably consistent. At this point in the calibration effort there are very strong indications that the AN/FPQ-6 radar in particular, and C-Band Systems in general have the potential for providing significant contributions to the scientific objectives of the National Geodetic Satellites Program.

6.1 Reliability

The AN/FPQ-6 and AN/FPS-16 radars have both proven to be extremely reliable systems. During the period covered by this report, not one track was missed due to equipment malfunction, weather or acquisition problems. The only GEOS-II missions scheduled but not tracked were cancelled due to conflicting schedule requirements or at the request of the project coordinator for project requirement purposes such as weather problems for other tracking systems preventing simultaneous tracking. Not only were the vast majority of scheduled missions tracked, but also the data obtained from the tracks were consistently of high quality.

The reduction and analysis of over 35 passes of short arc data have proven that the precision of the AN/FPQ-6 range measurements is 1.5 yds or less, and that of the angle measurements is approximately 15 arc seconds. These precision figures are very close to the radar design specifications. In fact, the range noise level estimates approach the lower bounds for noise levels as determined by the granularity (quantizing error) of the range system.

6.2 Accuracy

The reduction and analysis of short and long arc intercomparison passes of AN/FPQ-6, AN/FPS-16, and LASER tracking provide strong evidence that the systematic error in the AN/FPQ-6 range measurements is less than 10 meters. This is further reinforced by the results obtained from an AN/FPQ-6 prediction reduction. In all passes reduced and analyzed, the agreement among AN/FPQ-6, AN/FPS-16, and LASER range measurements has been less than 10 meters. In the cases where apparent discrepancies of more than 10 meters were indicated, the reason for the discrepancy can be accounted for in the hardware, radar set-up, or data handling procedure.

We are continuing investigations into possible sources of the systematic errors in range and have preliminary indications that the errors can be reduced even further.

6.3 Consistency

The systematic errors in range, azimuth and elevation angle have exhibited consistent behavioral characteristics. For example, a dependency of azimuth residual behavior upon pass geometry is clearly evident from the results of our analyses. We are currently investigating lag error correction procedures, boresighting procedures, and pedestal mislevel correction procedures as probable sources for these behavorial patterns. The fact that the systematic errors are stable and exhibit consistent patterns is encouraging since this is an indication that the source of these systematic errors can be determined and corrected without resort to extensive data reduction error modeling.

6.4 Summary

Although the results presented in this report are preliminary, they provide strong evidence that the AN/FPQ-6 radar, properly calibrated and operated, is a highly precise and accurate tracking system. Further work is in progress to determine the form and function of angular systematic errors, and we shall soon start investigating the AN/FPQ-6 range rate capability. We are also planning to use optical data and optically determined reference orbits to further evaluate the AN/FPQ-6 system. The results of these investigations will be the subject of a future report.

We believe that the results obtained at Wallops can be extrapolated to other C-Band Systems. The methods and procedures used for calibrating the AN/FPQ-6 are being used to evaluate the AN/FPS-16 at Wallops and preliminary results are encouraging. We are planning experiments for the near future where a network of C-Band radars with a good geographic distribution will regularly track GEOS-II using our methods and procedures. We will reduce this data, and attempt calibration and geodetic missions using multiple station, multiple revolution solutions to further qualify the C-Band systems as geodetic instrumentation systems.

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