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1.0 OBJECTIVES AND PLAN OF ATTACK

The purpose of this investigation was to determine the nature and degree of improvement of satellite orbit determination when precise altimeter data are used in combination with conventional tracking data.

To achieve these objectives it is desirable to perform both long-arc and short-arc solutions. A long-arc solution requires tracking data over many satellite revolutions and from one or more of the worldwide tracking networks. A short-arc solution requires intensive tracking coverage during a satellite traverse over the geographical region of interest.

The experiment plan was to develop a versatile orbit determination program that could combine the various types of tracking data that would be made available. Inherent in the software are geopotential and geoid models that can be updated easily. It was anticipated that an important ingredient to the success of the study would be the availability of a precise near-worldwide geoid determined from the altimeter data by the other principal investigators.

Exercising the orbit determination software with various combinations of data types would provide differential changes to the orbital solution. The character and magnitudes of these differences for several such intervals would provide a measure of the efficiency of the altimeter data.

2.0 DATA LIMITATIONS ON THE SCOPE OF THE EXPERIMENT

Because of limitations on the density and distribution of the tracking data that were available, it was necessary to modify the scope of the experiment. Intensive tracking data from several sites in the same geographical region together with altimeter data were not available. Consequently, it was not possible to perform the short-arc studies that had been planned. The sparsity of the altimeter and laser data increased the minimum possible meaningful data span to two days. Only long-arc solutions could be performed.

An improved geopotential model, GEM-9, was obtained during the course of the investigation. Since this model incorporated GEOS-3 data, it provided a substantial improvement to the orbit determination solution. Unfortunately, the fine-structured near-worldwide geoid model that had been anticipated from the other investigators was never obtained. It was necessary to use the GEM-9 geoid for our final studies.

3.0 COMPUTER SOFTWARE

A complex of computer programs was developed to achieve the goals of the GEOS-3 orbit determination experiment. In this section we describe the software starting with an overall system flow in Section 3.1, followed by a description of station navigation as a data editing tool in Section 3.2. A brief description of the individual modules can be found in Appendix A.

3.1 SYSTEM FLOW

Figure 1 is a system flowchart for the GEOS-3 orbit determination software. Starting with a set of initial conditions for the satellite, the ephemeris generation module produces a table of satellite positions as a function of time (the ephemeris file). Each data type has a FORMATOR/SIFTOR that performs initial data editing and data compression when desired. The sifted data are processed by separate EDITOR/PEF (Post-EDITOR Fit) modules that also access the ephemeris and station properties files. These modules perform a dual function:

1. Data editing via pass navigation (except for altimeter) and

2. Computation of orbit partials and residuals and the setup of the normal matrices and right-hand side (R.H.S.) vectors.

The SOLVOR combines the separate normal matrices and their R.H.S. vectors, applying appropriate pass weights. The combined matrix is then solved, and the state vector (initial conditions) is "corrected." The process is iterated until the corrections to the state vector fall below prescribed thresholds. The navigation results from the EDITOR/PEF processors can be used to "improve" the station positions (not shown in Fig. 1).

3.2 NAVIGATION IN THE EDITOR

Station navigation is a scheme that determines the station position and auxiliary parameters that best fit the data. The navigation is performed in two spatial dimensions: one parallel to the satellite subtrack, and the other from the station to the position of the satellite when it is at minimum range relative to the station. These two components are called the along-track error, ECA, and the slant-range error, ECR, respectively. The auxiliary parameters that are determined are:

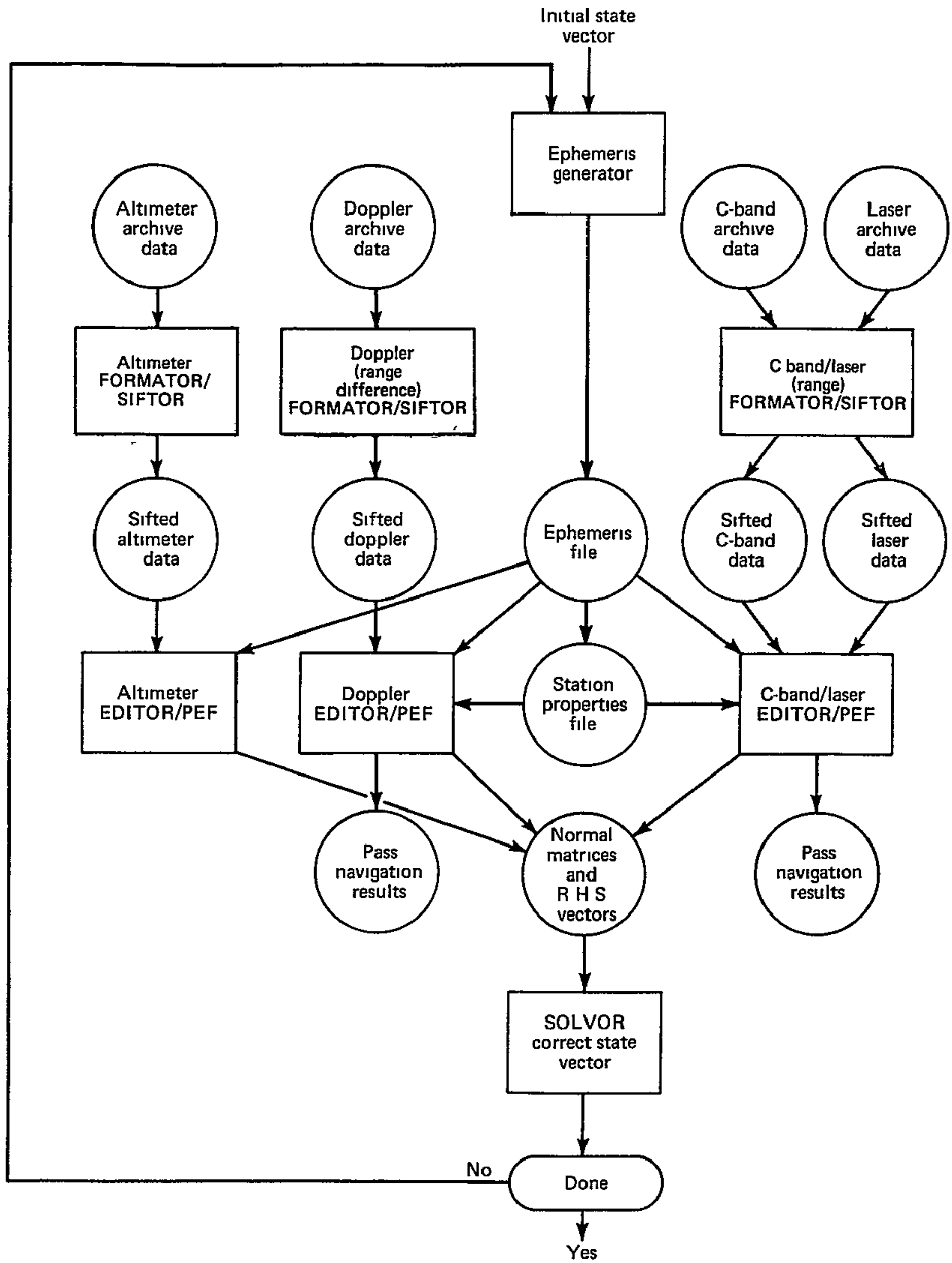

Fig 1 System Flowchart

1. For doppler data, the frequency difference between the spacecraft and station oscillator;

2. For laser data, a range bias and a range-rate bias; and

3. For C-band data, a range bias and a range-rate bias.

(The altimeter EDITOR does not perform the navigation function.)

In using the navigation method to detect "bad data," the following assumptions are made:

1. Data sets (passes) are treated independently of each other and most are unbiased;

2. Geodetic station locations are known to better than potential data biases; and

3. We have a reasonable representation of the position of the satellite (i.e., we have an ephemeris covering the data span in question).

Given the above assumptions, we proceed to determine the position of the station associated with a given pass. When we compare the navigated station position with the known station location, we discover errors that reflect (a) orbital inaccuracies, (b) bad geodetic station location, or (c) bad data. Of the three, (b) can be eliminated since we generally navigate passes whose station coordinates have been well established. We usually have at least a gross measure of the expected orbit errors, which allows us to judge a pass as "good" or "bad" by examining the resulting navigated position errors and the post-navigation measurement residuals.

Navigating in the minimum-slant-range (MSR) coordinate system starts with the determination of the time of closest approach (tca) and the establishment of an orthogonal coordinate system (MSR system) at tca (defined in Appendix B). Next the pass is navigated (i.e., its MSR coordinates are "moved") in the along-track and slant-range directions. Noisy points are detected during each navigation iteration and are excluded from the least-squares fit. Points whose elevation is below a given threshold are similarly excluded. The result of navigation is a set of station coordinate corrections to the nominal station position.

4.0 ORBIT DETERMINATION USING SYNTHETIC DATA

To check out the orbit determination software, synthetic (noise-free) data were generated using a nominal GEOS-3 ephemeris and a set of four stations. The four stations (311 Maine, 321 Minnesota, 332 California, and 340 Hawaii) were used to generate doppler (range difference) and laser (range) data (altimeter data require no earth-based station).

A second ephemeris (the "error" ephemeris) was produced with errors introduced in the initial conditions. The data were processed "against" the error ephemeris. The resulting corrections, when compared to the known errors, become a good measure of the maximum capability of each processor. For doppler and laser data we have the additional comparison of individual pass navigation results.

The following errors were introduced into the initial conditions of the error ephemeris:

Semimajor axis — $\delta a = 1 \times 10^{-7}\ R_0 (0.64\ \text{m})$,

Eccentricity — $\delta e = 1 \times 10^{-6}$,

Inclination — $\delta i = 1 \times 10^{-6}$ rad,

Node — $\delta \Omega = 1 \times 10^{-6}$ rad,

Perigee — $\delta \omega = 1 \times 10^{-6}$ rad, and

Mean anomaly — $\delta M = 1 \times 10^{-6}$ rad.

Table 1 compares the navigation results for doppler and laser data. The differences are about 10 cm, which seems quite reasonable. Table 2 summarizes the results of using the various data types in orbit determination. Note that the doppler and laser corrections would remove 99% of the total error in a single iteration. The second laser case where the data were corrected for range bias and range-rate bias (using the fitted results out of the navigation process) did not do well. A second iteration reduced the errors further but still left 40% in e, 11% in i, 13% in Ω, and 20% in $M + \omega$. Clearly, it is difficult to separate ephemeris errors from legitimate range and range-rate biases. We did not use this mode with the real C-band and laser data and chose instead to use large fitted biases as indicators of possibly bad data. Such passes were excluded from the orbit determination process. We did, in fact, find what looked like legitimate biases in two C-band sites (see Table 8). The altimeter case fully recovered the semimajor axis (δa)

Table 1
Navigation Results

Pass				Doppler			Laser			
Station	Rise Time			ECA(m)*	ECR(m)*	ECF(Hz/MHz)*	ECA(m)*	ECR(m)*	Bias(m)	Drift (m/ks)
	year	day	h min							
332	74	1	1 50	13 45	-6 66	$-0\ 68 \times 10^{-5}$	13 18	-6 62	2 58	-1 05
321	74	1	1 52	16 49	-8 11	$-0\ 65 \times 10^{5}$	16 38	-8 01	4 20	-1 67
340	74	1	5 16	0 81	-8 96	$-0\ 55 \times 10^{-5}$	0 56	-9 13	2 42	-0 67
311	74	1	12 50	-16.27	9 85	$-0\ 38 \times 10^{-5}$	-16 14	9 90	-1 48	-1 53
311	74	1	14 34	-19 20	-0 16	$-0\ 57 \times 10^{-5}$	-19 00	-0 30	-3 53	-2 26
321	74	1	14 36	-21 10	9 31	$-0\ 37 \times 10^{-5}$	-20 96	9 35	-1 49	-1 54
332	74	1	14·42	-23 89	15 40	$-0\ 40 \times 10^{-5}$	-23 80	15 29	-4 36	-1 41
332	74	1	16 24	-27 94	6 43	$-0\ 16 \times 10^{-5}$	-27 65	6 53	-2 80	-1 44
340	74	1	16 34	-32 11	16 31	$-0\ 30 \times 10^{-5}$	-32 09	16 26	-6 73	-0 96
311	74	1	21 16	-39 33	-7 25	$-0\ 65 \times 10^{-5}$	-39 50	-7 20	2 15	-1 43
311	74	1	22 58	-43 49	-5 41	$-0\ 70 \times 10^{-5}$	-43 75	-5 45	2 57	-1 17
321	74	1	23 02	-44 41	-7 24	$-0\ 53 \times 10^{-5}$	-44 58	-7 17	2 01	-1 04
321	74	2	0 44	-48 25	-5 20	$-0\ 59 \times 10^{-5}$	-48 54	-5 17	2 73	-0 76
332	74	2	2 26	-56 10	-7 29	$-0\ 61 \times 10^{-5}$	-56 36	-7 41	2 37	-0 81
340	74	2	4 10	-62 99	-8 86	$-0\ 43 \times 10^{-5}$	-63 18	-8 73	4 19	-0 81
340	74	2	5 54	-68 26	-8 51	$-0\ 83 \times 10^{-6}$	-68 61	-8 34	3 60	0 93
16 passes Mean $\pm\sigma$				$-29\ 5 \pm 25\ 1$	$-1\ 0 \pm 9\ 2$	$-0\ 53 \times 10^{-6}$ $\pm 0\ 17 \times 10^{-6}$	$-29\ 6 \pm 25\ 2$	$-1\ 0 \pm 9\ 2$	$0\ 5 \pm 3\ 4$	$-1\ 1 \pm 0\ 7$

*ECA - error along orbit
ECR - error in slant range
ECF - frequency bias

Table 2
Orbit Determination Using Synthetic Data

	Ephemeris Initial Condition Errors	Fitted Corrections (first iteration)				
		Doppler	Laser	Laser*	Altimeter	Combined DOP+LSR+ALT
δa (m)	0 638	0 638	0 637	0 660	0 612	0 631
$R_0 \delta e$ (m)	6 38	6 40	6 32	10.53	6 33	6 29
$R_0 \delta i$ (m)	6 38	6 38	6 36	6 51	1 29	6 60
$R_0 \delta \Omega$ (m)	6 38	6 36	6 42	7 65	1 49	5 77
R_0 $(\delta\omega + \delta M)$ (m)	12 76	12 80	12 74	8 63	4 36	12 34
R_0 = 6378 166 km						

* Data corrected for bias and drift computed by the navigation process

and eccentricity (δe) errors but only 20% of the inclination (δi), 23% of the node ($\delta\Omega$), and 34% of the along-track ($\delta\omega + \delta M$) errors. Finally, the combined solution (doppler + laser + altimeter) fully recovered the ephemeris errors in a single iteration. The altimeter case confirmed our intuition that orbit determination with real (noisy) altimeter data is not likely to be well-conditioned and that some other data (doppler or laser) would be necessary to determine the node, inclination, and perigee.

5.0 PRELIMINARY ORBIT DETERMINATION RESULTS

5.1 INTRODUCTION

In support of the long-arc orbit determination objectives, two preliminary studies were undertaken soon after the altimeter data became available. The purpose of these investigations was primarily to evaluate the integrity of the software that had been developed and to obtain experience in processing the altimetry data. Two intervals, each of a two-day duration, were selected on the basis of providing the maximum amount of tracking data. Because of our long experience in determining satellite ephemerides with doppler data, only doppler and altimeter data were processed for the first interval. Over the second interval, doppler, C-band, laser, and altimeter data were processed. Each of these studies will be discussed in turn.

5.2 ORBIT DETERMINATION, 1975 DAYS 113 to 114

When the first effort was undertaken only a limited amount of altimeter data was available. During day numbers 113 and 114 in 1975, there were four segments of altimeter data available. This is the interval with the second highest density of altimeter data. The interval with the highest density was reserved for the study discussed next. Because of our intimate acquaintance with the characteristics of doppler data in orbit determination, the first experiment was limited to studying the properties of combining doppler and altimeter data. In addition, this made it possible to use station coordinates that had been determined here previously and that are consistent with the in-house geopotential and geoid models used in the orbit determination procedure. Since dense doppler data were available consistently, their distribution posed no constraints on selecting the tracking intervals.

A total of 66 passes of doppler data were used from 10 tracking sites. From these data, a "base" ephemeris was determined for the two-day interval. The rms of the navigation solutions* for the 57 doppler passes that survived the editing processor is 25.9 m in the along-track direction and 14.7 m in the slant-range direction. These combine to give an rms total error of 29.8 m. The navigation solution residuals are given as a function of time in Fig. 2 and are listed in Table C-1 in Appendix C. The initial conditions for the orbit are given in Table C-2.

The navigation solution residuals are about a factor of two larger than what was anticipated and are correlated with time.

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* The navigation solution philosophy is discussed in Section 3.0.

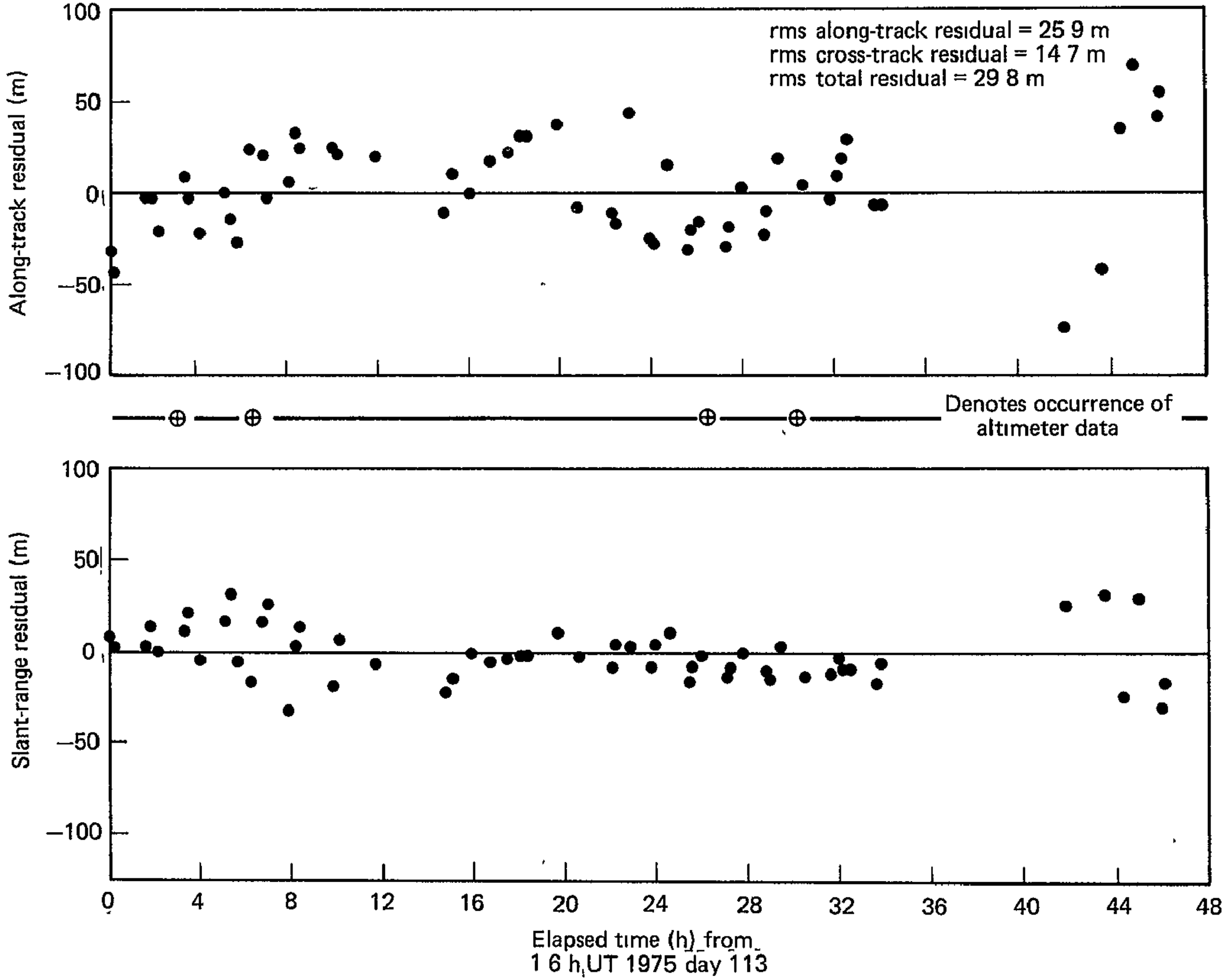


Fig. 2 GEOS-3 Pass Navigation Residuals, Doppler Data, 1975 Days 113 and 114

This appeared to be most likely due to the resonance of the GEOS-3 orbit with the 14th-order harmonic geopotential. To explore the possibility, adjustments were made to the coefficients of the (2,1), (3,1), (15,14), and (15,15) harmonics. By this means, it was possible to reduce the navigation solution residuals to 18 m in the along-track direction and 13 m in the slant-range direction, which combine to a total rms error of 22.2 m. This demonstrated the need for improved geopotential and geoid models for the subsequent studies.

The temporal distribution of the four segments of altimeter data is shown in Fig. 2 with the spatial distribution shown in Fig. C-1.

In using the altimeter data for orbit determination, the doppler-determined ephemeris was used as the base or "true" ephemeris. A comparison was made of the altimeter-measured geoidal heights, and those geoidal heights were determined from the base ephemeris. The rms for all the altimeter data was 20.17 m. The geoid used in the computation was determined from the in-house geopotential model used in obtaining the ephemeris to establish overall consistency.

Next, altimeter data alone were used to compute changes to the doppler-determined ephemeris. Because of the limited geographical extent of the altimeter data, only changes to the semimajor axis, the eccentricity, and an altimeter bias were determined. The other Kepler parameters were constrained to the doppler solution. The results of the orbit determination solution are given in Table 3 where a conversion to distance has been made for each orbit element to allow for easier comparison. Even with the limited amount of altimeter data, it was possible to recover reasonable values for the solved parameters.

To study the procedure of combining altimeter and doppler data, five combined solutions were obtained with different relative weights for the altimeter and doppler data. The results are given in Table 3. The combined solutions are close to the doppler solution principally because the doppler consists of 57 passes of data while the altimeter provided only 4 passes of data.

Table 3
Orbit Determination Solutions, 1977 Days 113 and 114

	Changes to Kepler Initial Conditions from Entry in Table C 2						
Data Type	Relative Weight* $\frac{\sigma^{-2}_{altimeter}}{\sigma^{-2}_{doppler}}$	δa (m)	$R_0 \delta e$ (m)	$R_0 \delta i$ (m)	$R_0 \delta \Omega$ (m)	$R_0 (\delta \omega + \delta M)$ (m)	Altimeter Bias (m)
Altimeter	0	6.12	-27.2	---	---	---	-1 2
Altimeter and Doppler	1 1	-0 02	1.12	-0.08	-3.19	-0.25	16.8
	0.8	-0.01	1.21	-0.21	-2 90	2 31	16 4
	0 6	-0.01	-3.86	-0.344	-2 63	4.82	15 4
	0.4	-0 01	-7.48	-0.63	-2.45	7 06	12 9
	0.3	-0 02	-10.29	-1 26	-2.51	7 62	9.7

* These relative weights are on a per pass basis.

5.3 ORBIT DETERMINATION, 1975 DAYS 115 to 116

During the two-day interval of days 115 and 116, 56 passes of doppler data, 21 passes of C-band ranging data, 5 passes of laser ranging data, and 8 passes of altimeter height data were available.

To obtain a base ephemeris, the doppler data were processed first. The doppler passes that were used originated at 12 tracking sites (see Fig. C-2 for the distribution of these sites). Of the 56 passes, 47 survived the process of orbit determination. Seven passes were deweighted because of excessive noise or low-elevation angles (i.e., maximum elevation is below 5°) and two were deleted because of unusually large navigation residuals (see Table C-3 for individual station navigation results). A time history of the navigation residuals for the 47 good passes is given in Fig. 3 where the rms is 12.5 m along track and 7.6 m slant range. That these residuals are a factor of two less than for the comparable doppler-determined ephemeris discussed in Section 5.2 for days 113 and 114 is due to the use of the GEM-8 geopotential model that had become available (Ref. 1). Since this model was based partially on tracking data from GEOS-3, it was judged to be the best available. Station coordinates for the doppler sites were not readjusted at this time.

The 21 passes of C-band ranging data were from seven sites and the five passes of laser data from three sites (see Fig. C-3 for the geographical distribution of these sites).

To obtain a measure of quality of the C-band and laser data, each pass of data was navigated using the doppler-determined ephemeris. The navigation solution for the ranging data consisted of determining a station position error in the along-track and slant-range directions together with a range bias and range-rate bias. The station positions used were those supplied with the data. These navigation results are given in Table 4. The large range and range-rate biases for some of the C-band data were unexpected. Figure 4 shows the range residuals before and after navigation for a pass of C-band data for which the range and range-rate biases were large. Even after navigation, the residuals remain correlated. Figure 5 shows analogous results for a pass of C-band data for which the range and range-rate biases were small. No evidence of correlation in the measurement residuals over the data span is seen. By deleting six of the 21 C-band passes that had large range and/or range-rate biases, it was possible to reduce the navigation residuals significantly as shown in Fig. 6.

Ref. 1. J. Marsh, private communication, 1976.

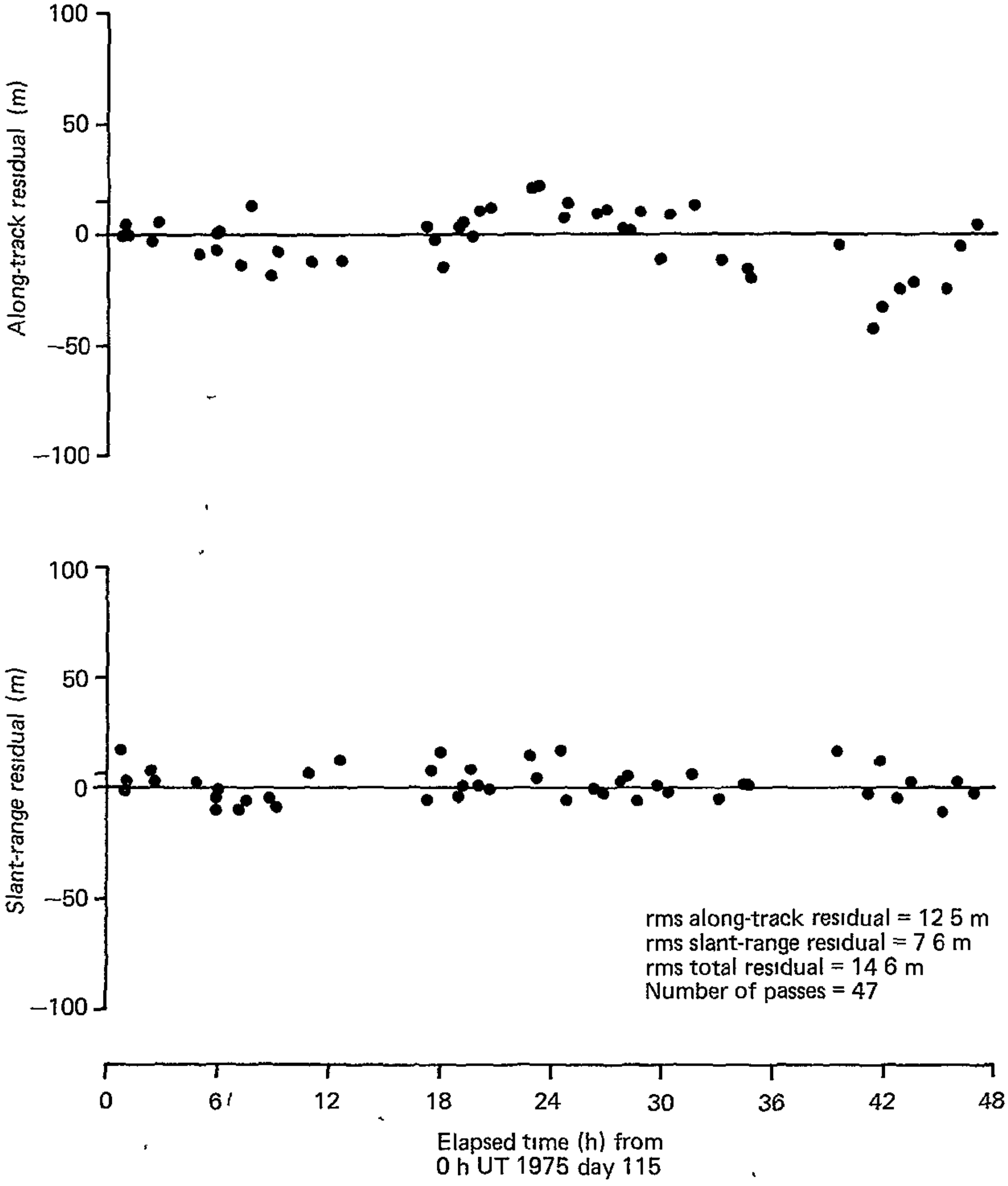


Fig 3 GEOS-3 Doppler Navigation Residuals, 1975 Days 115 and 116

Table 4
GEOS-3 C-Band and Laser Navigation Residuals for Doppler Orbit, 1975 Days 115 and 116

Pass I D				Navigation Results					
Yr	Day	Rise H Min	Sta	Along Track(m)	Slant Range(m)	Range Bias(m)	Range-Rate Bias (m/ks)	Residual(m)	Data Type CBD = C-Band Range LSR = Laser Range
75	115	01 12	4610	- 1 95	- 8 72	4 56	- 5 06	0 807	CBD
75	115	03 08	4281	6 50	-41 21	427 14	-181 92	2.701	CBD*
75	115	07 29	4760	10 78	- 8 02	2 46	2 01	0 862	CBD
75	115	07 33	4840	12 88	-10 86	2 83	5.11	1 341	CBD
75	115	09 12	4840	2 31	2 47	4 71	- 5 6	1 413	CBD
75	115	09 12	7068	2 75	6.62	3 66	0 93	0 074	LSR
75	115	09 18	7063	- 7 13	3 67	0.34	30 52	0.102	LSR
75	115	12 36	4260	12 80	21 96	-0 13	26 62	1 480	CBD*
75	115	21 36	4840	- 7 90	- 6 99	-3 13	16 5	2.268	CBD*
75	115	21 35	4760	8 41	- 3 15	-0 37	- 1.66	0 800	CBD
75	115	21 43	7068	4 10	6 57	0 87	0.07	0 051	LSR
75	115	23 15	4760	34 15	10 63	0 31	0 52	0 964	CBD
75	115	23 14	4840	25 18	12 16	-2.58	1 50	1 343	CBD
75	116	00 58	4610	7 36	-16 63	2.26	- 3 14	0.869	CBD
75	116	02 54	4281	17 73	-57.51	36 86	11 04	1 917	CBD*
75	116	04 24	4282	140 04	- 6 98	42 57	18 50	2 795	CBD*
75	116	04 32	4281	3 31	- 8.46	25 94	16 87	2 194	CBD*
75	116	07 16	4760	11 41	- 5 14	-0 71	1 19	0 940	CBD
75	116	07 19	4860	12 83	- 5 10	-1 99	2 44	0 950	CBD
75	116	08 54	4760	- 6 64	14 51	5 75	0 88	0.787	CBD
75	116	08 58	4860	- 5 19	7 48	1 08	5 28	0 872	CBD
75	116	08 59	7068	- 1 78	11 09	0 71	10 95	0.065	LSR
75	116	23 00	4760	15 53	5 05	1 27	- 4 63	0 997	CBD
75	116	23 00	4860	6 63	1 03	1 05	- 2 90	0 818	CBD
75	116	23 04	7063	7 33	- 5 02	1 80	- 4 58	0 246	LSR

* Passes deleted in subsequent orbit determination

Station Catalog

C-Band	Laser
4260 Pillar Point	7063 Greenbelt, MD
4281 Canton Island	7068 Grand Turk, BWI
4282 Kaena Pt, HA	
4610 Ely, NV	
4760 Bermuda	
4840 Wallops Island, VA	
4860 Wallops Island, VA	

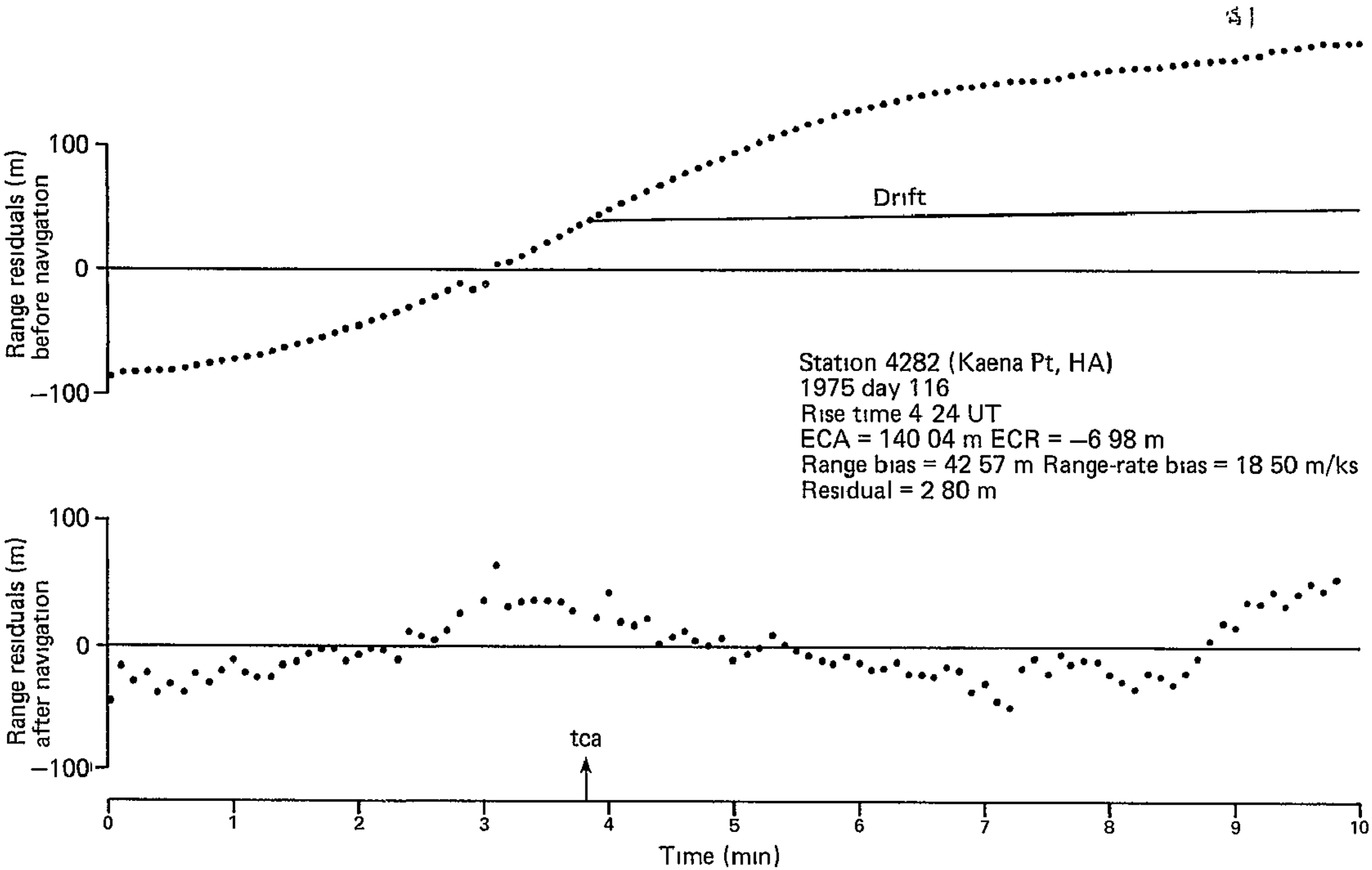


Fig 4 GEOS-3 C-Band Range Residuals, Large Bias and Drift, Station 4282

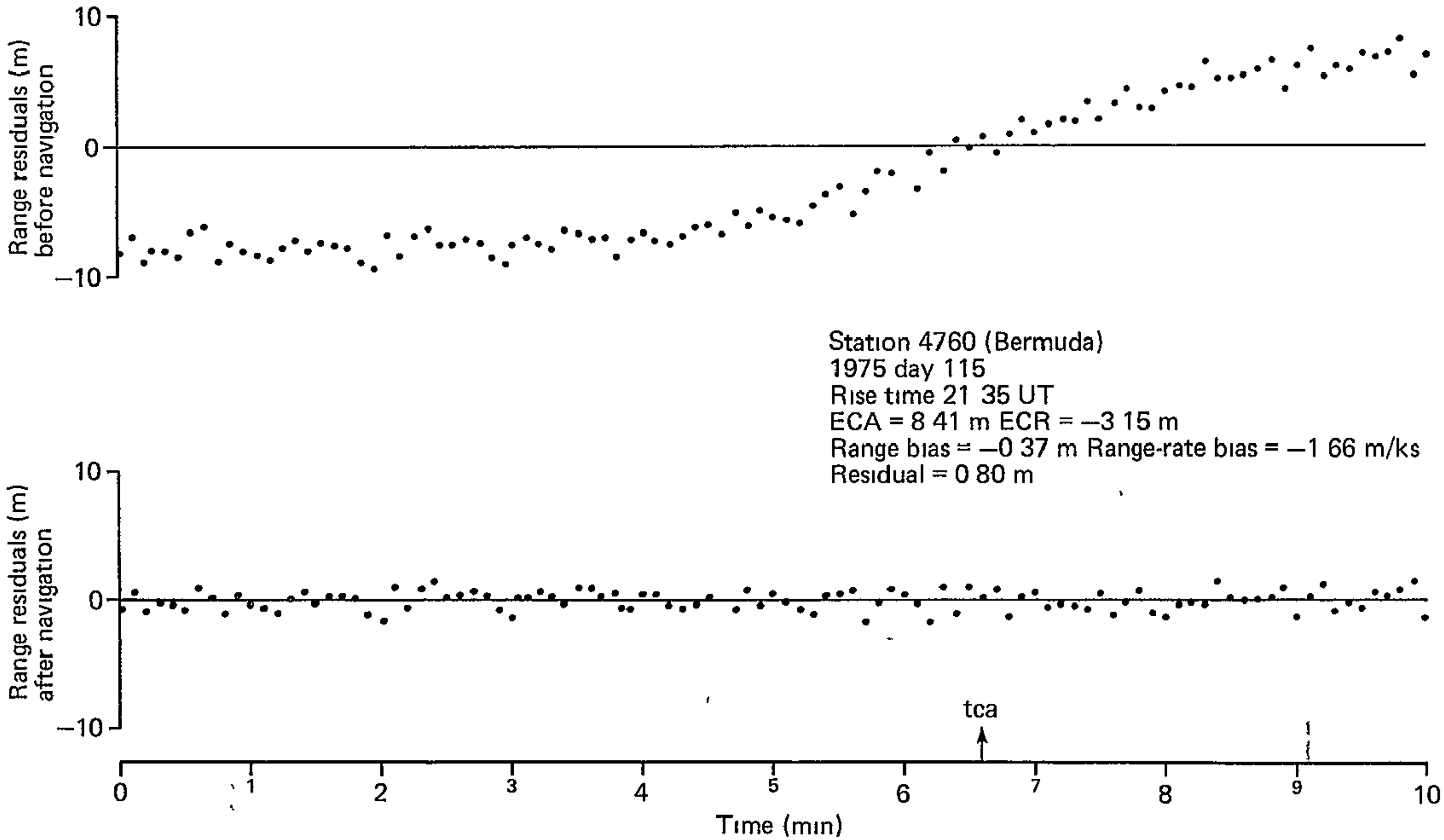
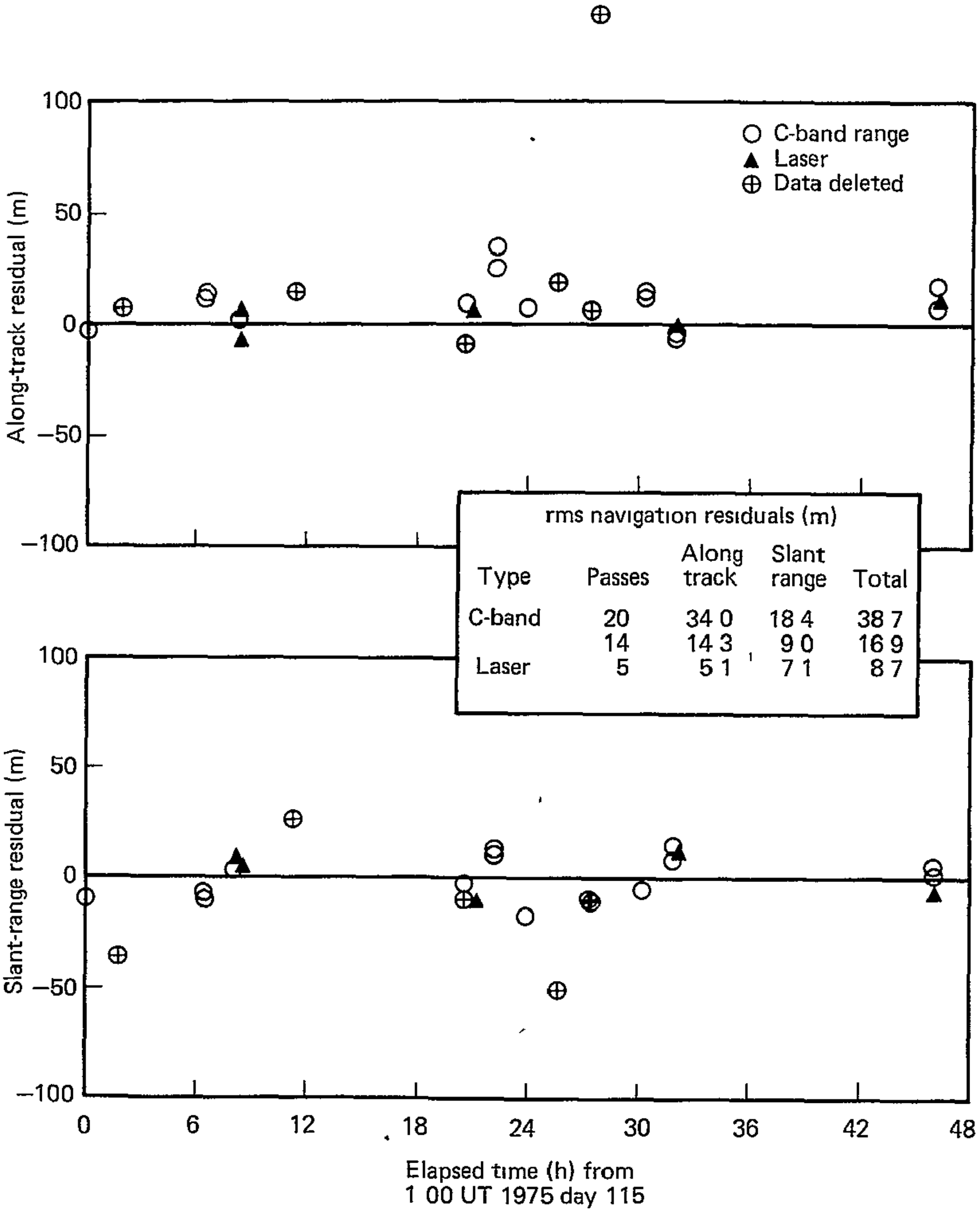


Fig 5 GEOS-3 C-Band Range Residuals, Small Bias and Drift, Station 4760



Type	Passes	Along track	Slant range	Total
C-band	20	34 0	18 4	38 7
	14	14 3	9 0	16 9
Laser	5	5 1	7 1	8 7

Fıg 6 GEOS-3 C-Band and Laser Navıgatıon Resıduals for Doppler Orbıt, 1975 Days 114 and 115

The five passes of laser ranging data that were available are from the three sites (see Fig. C-3 for the geographical distribution of these sites). Pass navigation solutions based on the doppler-determined ephemeris are given in Table 4. None of the laser data showed the large range and range-rate biases determined for some of the C-band ranging data. The mean along-track and slant-range residuals are 5.1 m and 7.1 m, respectively. The navigation solutions as a function of time are given in Fig. 6.

The altimetry height data for this span represent a significant improvement in both the amount and distribution of data over what were available for the study discussed in Section 5.2 (see Fig. C-4). Smoothing of the data to a data point every 20 s was used to reduce the required processing time. To examine the quality of the altimeter data, the differences between the smoothed observations and calculated height based on the doppler ephemeris and the GEM-8 geopotential model were determined. These residuals and the geoidal heights for each pass are given in Fig. 7. The character of the residuals over each pass as anticipated is structured. A negative bias of about 6 m is present with an rms of 7 m.

Now that the qualities and characteristics of the C-band, laser, and altimeter data had been studied, the next objective was to use the different types of data in determining ephemerides over the span of interest. Corrections to the doppler-determined ephemeris for the various data types are given in Table 5 where the changes to the Kepler elements have been transformed to distances for ease of comparison.

The laser data, although totaling only five passes, produced an ephemeris comparable to the doppler ephemeris. This is expected since our past experience has shown that, for satellites with orbital altitudes comparable to GEOS-3, data from as few as one doppler site can be used to provide an ephemeris that differs by only a few meters from one determined for data from tens of sites.

The differences obtained with the C-band data were as anticipated, i.e., at the approximately two-per-meter level, except for the orbit node. The reason for this is that there is a bias in the average longitude of the C-band stations relative to the doppler sites. This is seen in the mean station position corrections obtained from the navigation solutions using the doppler-determined ephemeris (see Table 6). The mean longitude bias for the four C-band sites weighed by the number of passes was -17.5 m; this is close to the -17.3-m change in the longitude of the ascending node given in Table 5. This demonstrated that a consistent set of station coordinates should be determined for the final studies.

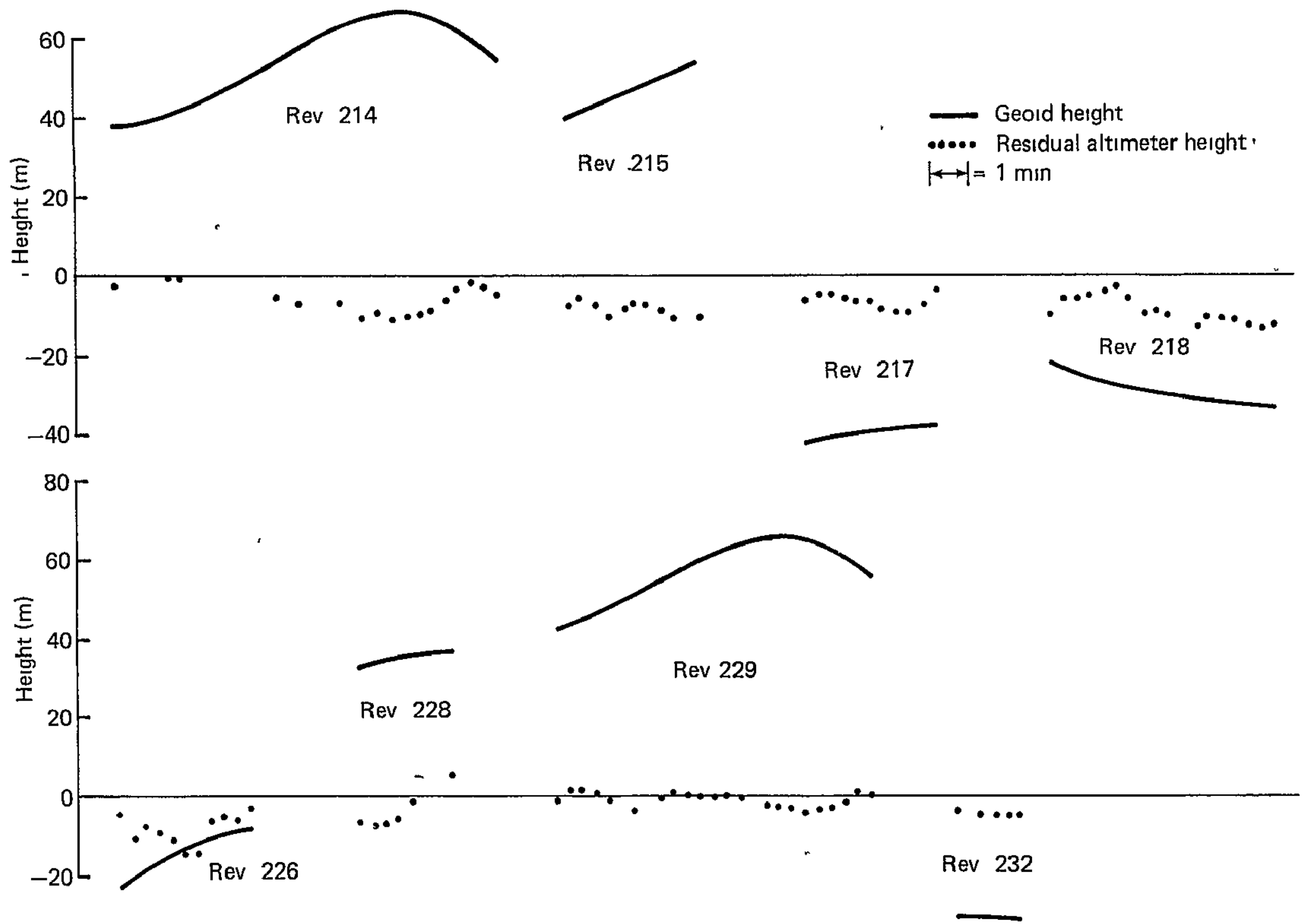


Fig. 7 GEOS-3 Altimeter Height Residuals for Doppler Orbit, 1975 Days 115 and 116

Table 5

GEOS-3 Orbit Corrections to Doppler Ephemeris, 1975 Days 115 and 116

Data Type	Laser Range	C-Band Range	Doppler and Altimeter*	Altimeter
δa (m)	0.0658	-0.0041	0.0328	-10.5
$R_0 \delta e$ (m)	-5.7594	3.2911	-1.4861	-4.1075
$R_0 \delta i$ (m)	5 8306	-4.0455	0.2681	$1\ 52 \times 10^3$
$R_0 \delta \Omega$ (m)	-3.7315	-17.2832**	0.3039	65.6×10^3
$R_0(\delta\omega + \delta M)$ (m)	1 2721	-3.280	2.5670	-1.6×10^3
Δf (Hz/MHz)	—	—	-0.013694	—
A priori Residual (m)	8.7	16.9	15 (doppler), 7 (alt.)	7
Altitude Bias (m)	—	—	7.731	—
Number of Passes of Data	5	14	56 + 8	8

$R_0 \equiv 6.378166 \times 10^6$ m

* Altimeter fit constrained to a, e, and bias

** Due to bias in longitude of C-band network

Table 6

Station Location Corrections Based on Pass Navigation Solutions Using Doppler Ephemeris, 1975 Days 115 and 116

Station	Number of Passes	Delta Latitude(m)	Delta Longitude(m)	Delta Radius(m)	Noise (m)	Data Type*
4610	2	+9.3	-13.8	-6.8	—	
4760	6	-6.9	-20 9	-0.4	0.9	CBD
4840	3	-4.7	-20 1	-1.1	1 4	CBD
4860	3	-2.6	-10.6	1.3	0.9	CBD
All C-Band	14	-3.2	-17.5	-1.1	—	CBD
7068	3	-3.2	- 9.8	1.3	0.06	LSR

* CBD - C-band range
LSR - laser range

An attempt was made to determine an ephemeris based solely on altimeter data. Simulation studies had shown that the semimajor axis, eccentricity, and altimeter bias were the better-conditioned parameters for an orbit with the characteristics of GEOS-3. Nevertheless, to judge the efficacy of using altimeter data alone, all six orbital parameters for an altimeter height bias were determined solely from the eight passes of altimeter data. Seven of the eight passes are over the same portion of the orbit and are all from the same geographic region (see Fig. C-4). Both of the characteristics suggest that conditioning of the solution should be a problem.

As anticipated, the semimajor axis and eccentricity agree to about the 10-m level with the solutions based on the other data types. The position of the spacecraft along track is specified to about 1.6 km, and the inclination error is about the same. As expected, the right ascension of the ascending node is the poorest determined quantity with an error of about 65.6 km.

6.0 ORBIT DETERMINATION WITH GEM-9 GEODESY USING 1976 DATA

In the last of the sets of orbit determination experiments, we used a four-day span in 1976 (days 62 to 65). The criterion for choosing these particular days was to maximize the available altimeter and laser data, particularly the former. The other two data types (doppler and C band) were plentiful and provided good worldwide coverage (see Table D-1 in Appendix D for station locations).

The experimental objectives were threefold:

1. To establish a set of two reference or base ephemerides,

2. To assess the effects of progressively reducing non-altimeter data-type coverage on the ephemerides accuracy, and

3. To assess the value of altimeter data in orbit determination starting with altimeter only and progressively adding nonaltimeter data to improve the resulting ephemerides.

In general, we will assume that the base or reference ephemerides most accurately reproduce the true position of the satellite during the four days in question. Deviation from the true position can therefore be considered to be a "worse" or less accurate reproduction of the true orbital path of the satellite.

6.1 THE BASE OR REFERENCE EPHEMERIDES

Days 62 to 65 were divided into two spans of two days each. For Span 1 (days 62 to 63), we started with 86 doppler passes, 64 C-band passes, 11 laser passes, and 15 altimeter passes. For Span 2 (days 64 to 65), we started with 75 doppler passes, 73 C-band passes, 12 laser passes, and 21 altimeter passes. Using GEM-9 geodesy (Ref. 2) (GM = 398600.640 km^3/s^2) and nominal (not GEM-9) station coordinates, we proceeded in an iterative fashion to obtain two ephemerides and a new set of station coordinates that best fit the data. The best initial conditions can be found in Table D-2. The summary of the navigation results is presented in the first and sixth line entries of Table 7. Note that several

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Ref. 2. F. J. Lerch, S. M. Klosko, R. E. Laubscher, and C. A. Wagner, "Gravity Model Improvement Using GEOS-3 (GEM 9 and 10)," GSFC X-921-77-246, September 1977.

Table 7

GEOS-3 Orbit Determination Tracking Results, 1976 Days 62 to 65

Line No	Span	Navigation Results (m)												Ephemeris Deviation from Reference Ephemeris (m)				Data Description
		Doppler (DOP)				C-band (CBD)				Laser (LSR)								
		No Passes	ECR	ECR	ECT	No Passes	ECA	ECR	ECT	No Passes	ECA	ECR	ECT	H	L	C	D	
1		66	-0 3±4 6	-0 4±3 2	5 7	43	-0 5±3 7	0±2 8	4 7	9	0 4±2 6	-1 4±1 4	3 3					(DOP, CBD, LSR, ALT)
2	62	66	-0 3±4 6	-0 4±3 2	5 7	43	-0 5±3 7	0±2 8	4 7	9	0 4±2 6	-1 4±1 4	3 3	0	0	0	0	(DOP CBD LSR)
3	63					5	-0 5±2 9	0 5±1 5	3 3					0±0 9	3 0±1 9	0±2 5	4 4	Sta 4150 (CBD) Same results obtained with or without ALT
4	1976					2	2 4±0 3	-0 2±0 9						0 2±14 4	-57 8±39 3	1 9±456 8	462 4	Sta 4150 (CBD) 2 south passes
5						2	0 1±0 1	0 7±1 2						0±1 3	5 4±3 8	0±6 3	9 2	Sta 4150 (CBD) 2 south passes and ALT data
6		64	0 3±6 2	0 4±4 1	7 5	60	0 9±5 9	-0 3±4 5	7 5	11	-0 9±2 8	0 2±2 5	3 9					(DOP + CBD + LSR + ALT)
7	64													0	0	0	0	(DOP + CBD + LSR)
8	65					6	0 4±2 0	1 2±2 2	3 2					0±0 5	-0 7±2 6	-0 1±3 2	4 2	Sta 4150 (CBD) Same results obtained with or without ALT
9	1976					2	1 2±2 4	2 4±2 0						2 2±22 6	64 2±128 6	-10 6±674 7	690 3	Sta 4150 (CBD) 2 south passes
10						2	1 7±3 2	0 9±2 5						0±1 6	4 6±3 2	-0 2±9 7	11 4	Sta 4150 (CBD) 2 south passes and ALT data

ECA - along-track error
ECR - slant-range error
ECT - total navigation error
H - radial error
L - along-track error
C - cross-track error
D - total error

input passes were deleted in arriving at the final solution. For Span 1, there were 66 doppler, 43 C-band, 9 laser, and 15 altimeter surviving passes. For Span 2, there were 64 doppler, 60 C-band, 11 laser, and 21 altimeter surviving passes. The large casualty rate is a result of the rigorous data editing. The resulting navigation residuals were 6 to 8 m for doppler, 5 to 8 m for C band, and 4 m for laser. The altimeter residuals were 6 to 7 m, which include a large altimeter bias (discussed later). Removing the bias (5.4 m) reduces the altimeter residuals to 2 to 3 m (see Table 8). The fitted GEM-9 station coordinates can be found in Table D-1. Figures 8 and 9 are plots of navigation residuals for the three data types combined for Spans 1 and 2, respectively. Additional figures and tables of individual pass residuals are in Appendix D. Altimeter data results are dealt with separately in another section of this report.

Table 8 summarizes the C-band and laser results by station. We note a number of interesting features in this table:

1. The post-navigation (range) residuals (σ) of the laser sites are about 4 to 7 cm compared to 1 to 2.5 m for the C-band sites; and

2. There are large range biases and drifts for C-band stations 4958 and 4959, as well as non-negligible biases for many of the other stations.

Range bias, drift, and post-navigation residuals were used in the orbit determination process as a measure of data (pass) quality for C-band and laser data. For doppler data, maximum pass elevation above the horizon and post-navigation residuals were used as a measure of data (pass) quality. All the passes from station 4958 and 4959 were excluded from the orbit determination process, and many doppler passes were excluded as a result of the low-elevation criteria (see Tables D-3 to D-8).

6.1.1 Orbit Extrapolation from Reference Runs

In the previous section we discussed the reference runs in terms of how close the resulting ephemerides agree with the collected experimental data. In this section we will assess the quality of the extrapolated or predicted ephemerides. Theoretically, if we were able to precisely model all the forces acting on a satellite as a function of time, then once we establish a set of initial conditions using all the available data we should be able to extrapolate the resulting reference ephemeris into either future (update) or past (backdate). However, in reality the force models are only an approximation of the real forces, and so one expects

Table 8

Range Bias, Drift, and Noise Summary by Station, 1976 Days 62 to 65

Station	Type	No. of Passes	Summary Results ⟨Bias⟩ (m)	⟨Drift⟩ (km/day)	⟨σ⟩ (m)
4013	C band	1	22.98	1.56	1.86
4150		13	- 0.50 ± 2.00	0.14 ± 0.73	2.00 ± 0.33
4198		10	- 4.35 ± 1.52	0.06 ± 0.47	1.31 ± 0.19
4280		5	2.57 ± 2.70	- 0.30 ± 1.44	1.14 ± 0.07
4446		7	- 1.49 ± 2.80	0.47 ± 0.77	1.61 ± 0.57
4860		11	- 7.69 ± 2.76	- 0.15 ± 0.55	1.64 ± 0.29
4610		11	- 1.48 ± 1.23	- 0.28 ± 1.55	1.03 ± 0.20
4742		10	- 6.07 ± 3.45	- 0.01 ± 0.31	0.94 ± 0.44
4760		15	- 2.89 ± 1.35	0.02 ± 0.32	0.90 ± 0.09
4840		8	- 3.63 ± 1.25	0.94 ± 0.46	1.63 ± 0.06
4860		6	- 12.36 ± 6.50	- 4.43 ± 4.42	2.48 ± 0.89
4958		6	-377.50 ±12.91	13.95 ± 2.04	2.16 ± 0.32
4959		7	392.58 ±10.66	14.23 ± 1.74	2.47 ± 0.51
4960		26	3.40 ± 4.56	- 0.13 ± 1.47	1.73 ± 0.40
7067	Laser	9	- 2.44 ± 3.83	- 0.97 ± 4.24	0.05 ± 0.006
7068		5	- 0.09 ± 2.07	0.94 ± 2.53	0.04 ± 0.003
7069		8	- 1.08 ± 0.68	0.09 ± 0.20	0.07 ± 0.006

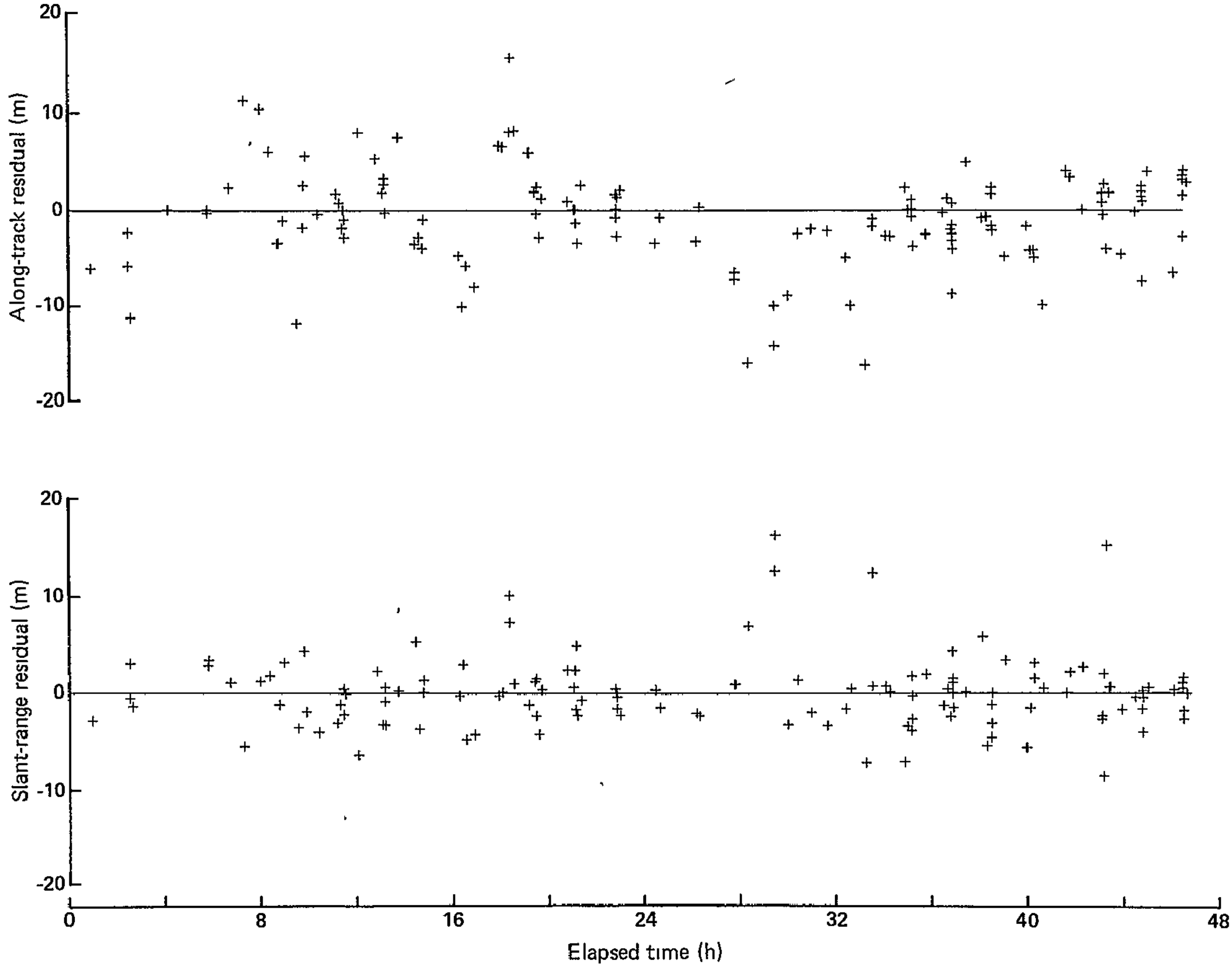


Fig 8 GEOS-3 Combined Navigation Residuals-Reference Track, 1976 Days 62 to 63

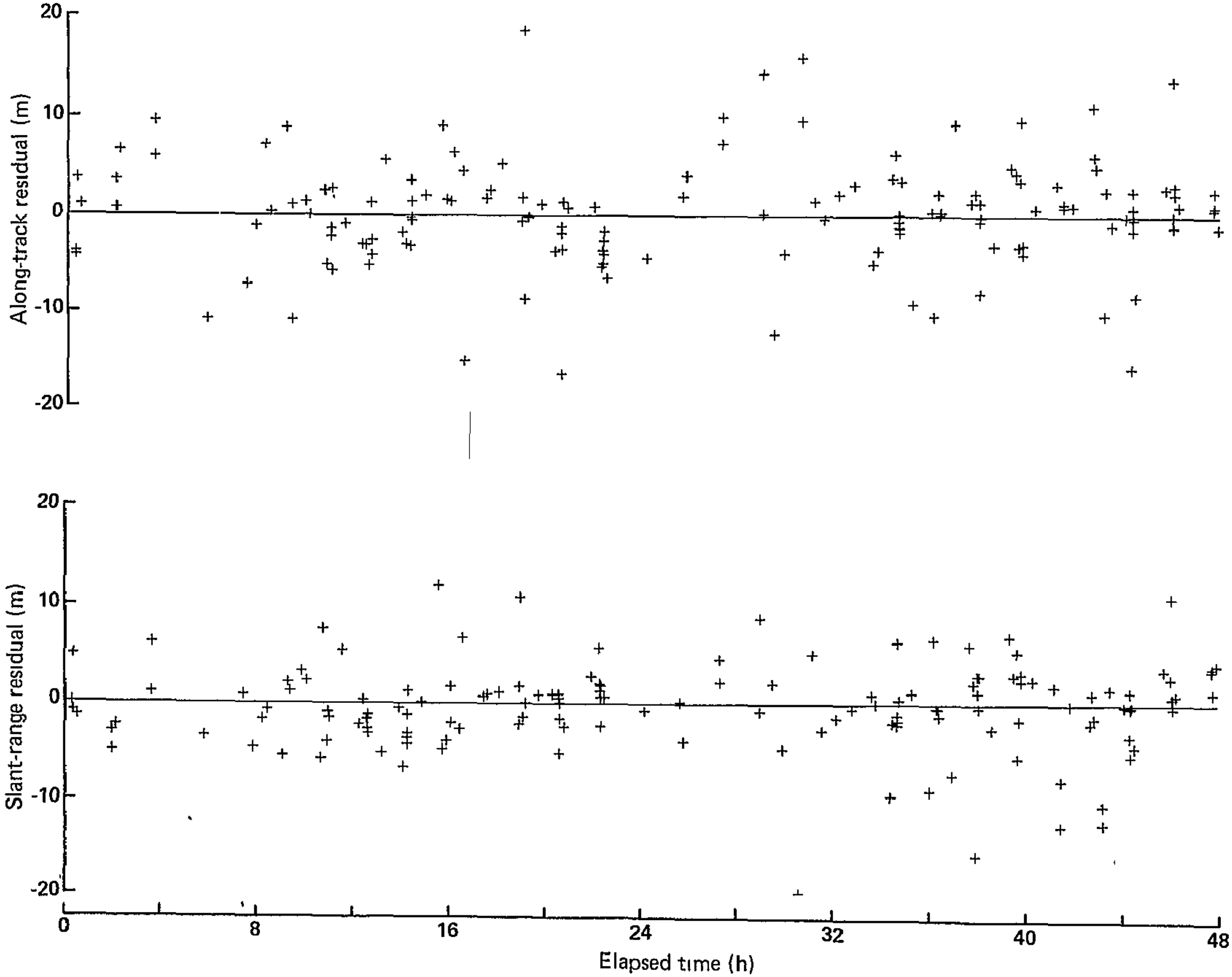


Fig. 9 GEOS-3 Combined Navigation Residuals Reference Track, 1976 Days 64 to 65

a degradation in the precisions of extrapolated ephemerides. Even if the models were perfect (which they are not), we still have to contend with noisy data. One would expect, under such conditions, that it would be advantageous to have as much data as possible, well distributed in time and space. This, in fact, has been our criterion for establishing the GEOS-3 reference ephemerides. By using four independent data types and as much data as were available, we achieved the desired goal of good data coverage in both space and time. As it turns out, it is not noisy data but rather the imperfect force models that limit our ability to extrapolate far into the future (or past).

Each of our two reference ephemerides were extrapolated, and each extrapolated ephemeris was compared with its tracked counterpart as follows:

1. Span 1 (days 62 to 63) was extrapolated into the future (updated) to cover days 64 to 65, and

2. Span 2 (days 64 to 65) was extrapolated into the past (backdated) to cover days 62 to 63.

Before confusion sets in, let us define the four ephemerides in question:

1. Reference 1: 1976 days 62 to 63 (tracked),

2. Reference 2: 1976 days 64 to 65 (tracked),

3. Update: 1976 days 64 to 65 (extrapolated from Reference 1), and

4. Backdate: 1976 days 62 to 63 (extrapolated from Reference 2).

The comparison for Span 1 is therefore between Reference 1 and backdate and for Span 2 between Reference 2 and update. Table 9, lines 1 and 6, presents the results of this comparison. Two sets of results are presented:

1. Direct differencing of the ephemerides in question (H,L,C,D), and

2. Navigation of real (doppler) data against the extrapolated ephemeris.

In the latter case, the results (ECA, ECR, ECT) are a measure of how much the stations had to be moved in order to compensate for the satellite errors. Comparing Tables 9 and 7 (tracked versus

Table 9
GEOS-3 Orbit Determination, Update and Backdate, 1976 Days 62 to 65

Span	Navigation Results (m) (DOP) No. of Passes	ECA	ECR	ECT	Ephemeris Deviation from Reference (m) H	L	C	D	Description
Backdate 62→63 1976	66	-0 6±6 3	-0.9±4.1	7.6	0±2.1	-1.2±4.6	0±0.5	5.2	DOP + CBD + LSR + ALT
	66	-0 6±6 3	-0.9±4.1	7.6	0±2.1	-1.2±4.6	0±0.5	5.2	DOP + CBD + LSR
	66	7.0±6.9	-1 6±4.3	10.8	-0 1±1.7	-10.1±5.4	-2.2±3.2	12 0	Sta 4150 (CBD) Same results with or without ALT
	66	-347 7±182.1	-218.4±403 5	603 8					Sta 4150 (CBD) 2 south passes
	66	-3.5±6.7	-3.9±7.9	11 6	0±2.4	3 8±5 1	-0.1±10.3	12 4	Sta 4150 (CBD + ALT) 2 south passes of CBD
Update 64→65 1976	64	6.9±8 1	0 8±4.9	11.7	0±2.1	-6 3±5.0	0±0.4	8.3	DOP + CBD + LSR + ALT
	64	6.9±8.1	0 8±4.9	11.7	0±2.1	-6.3±5.0	0±0.4	8.3	DOP + CBD + LSR
	64	3.6±8.9	-0 1±5.4	11.1	0±2.7	-2.0±5.7	0±2.5	7.1	Sta 4150 (CBD) Same results with or without ALT
	64	108.8±88.1	163.5±255.3	339.9					Sta 4150 (CBD) 2 south passes
	64	11.5±9.3	-1.3±6.2	16.1	0 1±2.0	-10 7±6.7	0±6.1	14.2	Sta 4150 (CBD + ALT) 2 south passes of CBD

ECA - along-track error
ECR - slant-range error
ECT - total navigation error
H - radial error
L - along-track error
C - cross-track error
D - total error

extrapolated) we find a degradation of 2 m in the rms of Span 1 (5.7 to 7.6 m) and a degradation of 4 m for Span 2 (7.5 to 11.7 m). We will return to these two tables in other sections of this report.

Figures 10 and 11 present the doppler navigation results (backdate and update). Plots of the actual ephemeris differences (H,L,C backdate and update) can be found in Figs. D-7 and D-8.

6 2 ORBIT DETERMINATION WITHOUT ALTIMETER DATA

Having established the two reference ephemerides, we now look at the effects of reducing data coverage. In this section we will deal with nonaltimeter data. We will introduce altimeter data in the next section of the report.

It is of no surprise to anyone that using a great deal of data from many tracking sites in conjunction with good force models results in high-precision ephemerides. We have demonstrated this in the previous section. The questions we would like to discuss here are: What happens when we have only limited data (possibly from a single tracking site)? How closely will the resulting ephemeris approximate the true (reference) satellite ephemeris? We will answer these questions by progressively reducing the data coverage for GEOS-3 from maximum (all) down to two passes from a single site as follows:

A. All data (doppler, C band, laser) (ALL).

B. All data from a single C-band site (SCB).

C. All data from a single doppler site (SDP).

D. Two passes from a single C-band site (2CB).

E. Two passes from a single laser site (2LR).

The five cases are summarized in Table 10, which presents the computed "corrections" to the initial conditions of the reference orbits. The larger the correction to the reference Kepler elements, the greater the expected deviation of the resulting ephemerides from their reference counterparts. We will also refer to Table 7 for the tracking results and Table 8 for the extrapolated results.

A. <u>All Data (doppler, C band, laser) (ALL)</u>

Removing altimeter data from the reference runs does not affect the solution at all. Lines 2 and 7 in Tables 7 and 9 confirm that the resulting tracked and extrapolated ephemerides are identical.

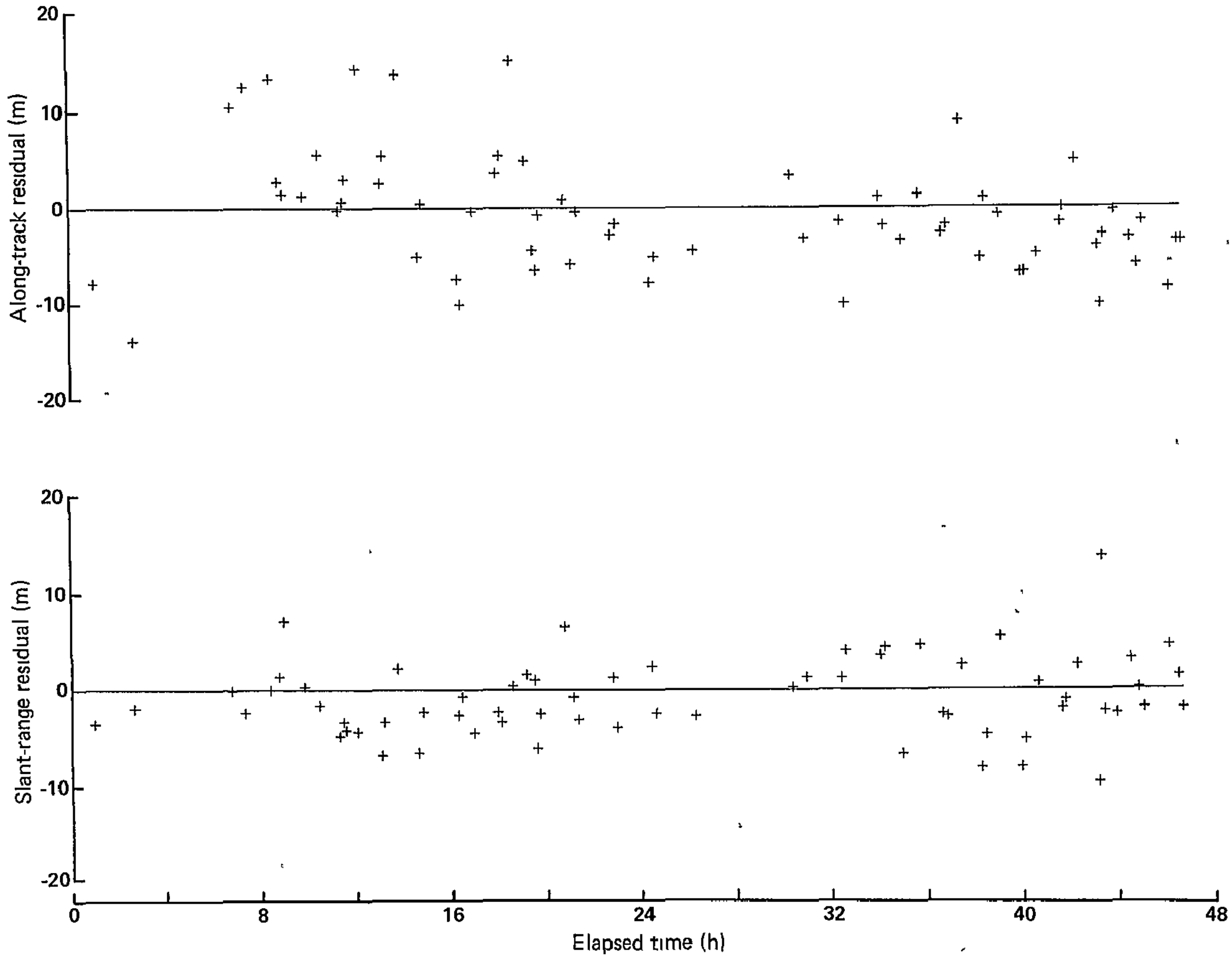


Fig 10 GEOS-3 Doppler Residuals (backdate from reference track), 1976 Days 62 to 63

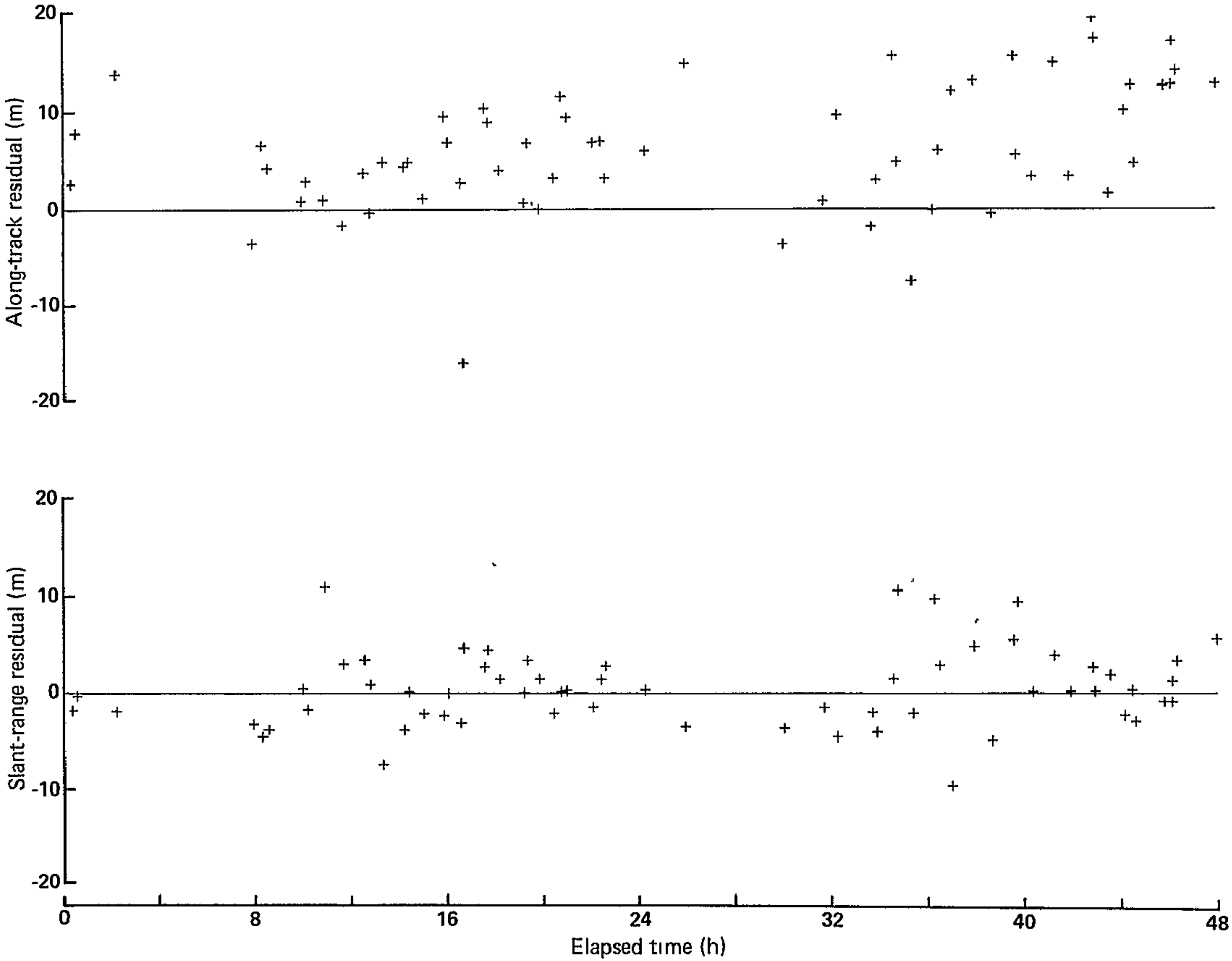


Fig. 11 GEOS-3 Doppler Residuals (update from reference track), 1976 Days 64 to 65

Table 10

GEOS-3 Orbit Determination without Altimeter Data, 1976 Days 62 to 65 (deviations from reference orbit)

	SCB		SDP		2CB		2LR	
	S1	S2	S1	S2	S1	S2	S1	S2
δa (m)	0	0	0	0	-1.3	2.8	-0.4	-0 1
$R_0 \delta e$ (m)	-0.6	-0.6	0.6	2.6	-17.2	19.8	-3.2	-1.9
$R_0 \delta i$ (m)	2.7	3.9	3.5	-0.7	-416.1	667.9	-90.6	-40.4
$R_0 \delta \Omega$ (m)	-2.0	-0.8	1.2	-0.8	472.9	-633.4	108.7	-78.6
R_0 $(\delta\omega + \delta M)$ (m)	1.1	-4.5	-4.8	-1.8	189.8	-33.3	84.5	-0.9
Altimeter Bias (m)								
Altimeter Drift (m/day)								

SCB - all passes from a single C-band site (station 4150)
SDP - all passes from a single doppler site (station 111)
2CB - two C-band south-going passes (one/day station 4150)
2LR - two laser south-going passes (one/day station 7067)
S1 - 1976 days 62 to 63
S2 - 1976 days 64 to 65
R_0 - 6378.166 km

B. All Data from a Single C-Band Site (SCB)

This is a drastic change from the previous case. We selected a single site (station 4150, Green River, UT) and used all data (two north, three south for Span 1; three north, three south for Span 2*) for the site to determine the orbit of the satellite.

We note first that the largest deviation from the reference ephemeris is 4.5 m in along track ($\delta\omega + \delta M$) and 4 m in inclination (column headed SCB in Table 10). The resulting ephemerides are only 4 m (rms) different from their reference counterparts, and the resulting extrapolations are worse for the backdate (12 versus 5 m) and slightly better for the update (7 versus 8 m). These results can be found in lines 3 and 8 of Tables 7 and 9.

C. All Data from a Single Doppler Site (SDP)

We selected a doppler site (station 111, Howard County, MD) and used all available data (three north, three south for Span 1; four north, two south for Span 2*) to determine the satellite orbit. As with the single C-band site, the maximum deviation from the reference Keplers is under 5 m (column headed SDP in Table 10).

We can conclude from SCB and SDP above that a single tracking site, well maintained and operating three shifts a day, is all that one needs to generate high-precision orbits for satellites in orbits as high as GEOS-3 (830 km).

D. Two Passes from a Single C-Band Site (2CB)

Can we reduce coverage further? For example, would it suffice to have a station operating a regular 8-h shift? In such an operation, the most likely data obtained would be a single daily pass with the same heading.

We selected such a case by reducing the number of passes from station 4150 to two for each of the two spans. Each pair of passes was separated by 24 h (one pass/day). Each pair was chosen to have the same heading (south), and consequently the orbit is determined with data sampled from only a small part of the satellite orbit. Had we picked one north- and one south-going pass, we would have doubled the portion of the orbit sampled by the data. The resulting corrections to the reference Kepler elements are shown in the column headed 2CB in Table 10. The inclination, node, and along-track positions ($\delta i, \delta\Omega, \delta\omega + \delta M$) are off by hundreds of

* Surviving good passes.

meters from the reference Keplers. The resulting ephemerides deviate from their reference counterparts by hundreds of meters (Table 7, lines 4 and 9). Likewise, the extrapolated ephemerides are hundreds of meters off from their reference counterparts (Table 9, lines 4 and 9). Figures 12 and 13 are plots of the ephemeris differences. Note that most of the errors are in the out-of-plane components (cross track). It is this case that we hoped would be helped by the introduction of altimeter data (to be dealt with in the next section).

E. Two Passes from a Single Laser Site (2LR)

We selected two passes for each of the two spans for laser site 7067 (Bermuda). The selected passes were south-going for Span 1 and north-going for Span 2, and each pair was separated by 24 h. The results were somewhat surprising. The corrections to the laser-generated Keplers were much smaller (under 100 m) than for the parallel C-band case (Table 10, column headed 2LR). It is possible that the reason the laser does so much better under these unfavorable conditions is its higher quality (less noise) when compared to C-band. The mean of the post-navigation residuals for the laser site in question was 5 ± 0.6 cm compared to the C-band site's 200 ± 33 cm (Table 8).

6.3 ORBIT DETERMINATION WITH ALTIMETER DATA

In this section we assess the value of altimeter data in orbit determination. We start with the reference runs where we noted that earlier altimeter data added nothing to the solution other than giving a good estimate of the altimeter range bias and drift parameters. We will begin with the reference case as it relates to the altimeter results and work down to the case of altimeter data alone as follows:

A. Altimeter + All Other Data (doppler, C-band, laser)

B. Altimeter + All Data from a Single C-Band Site (SCB),

C. Altimeter + All Data from a Single Doppler Site (SDP),

D. Altimeter + Two Passes from a Single C-Band Site (2CB),

E. Altimeter + Two Passes from a Single Laser Site (2LR), and

F. Altimeter Only.

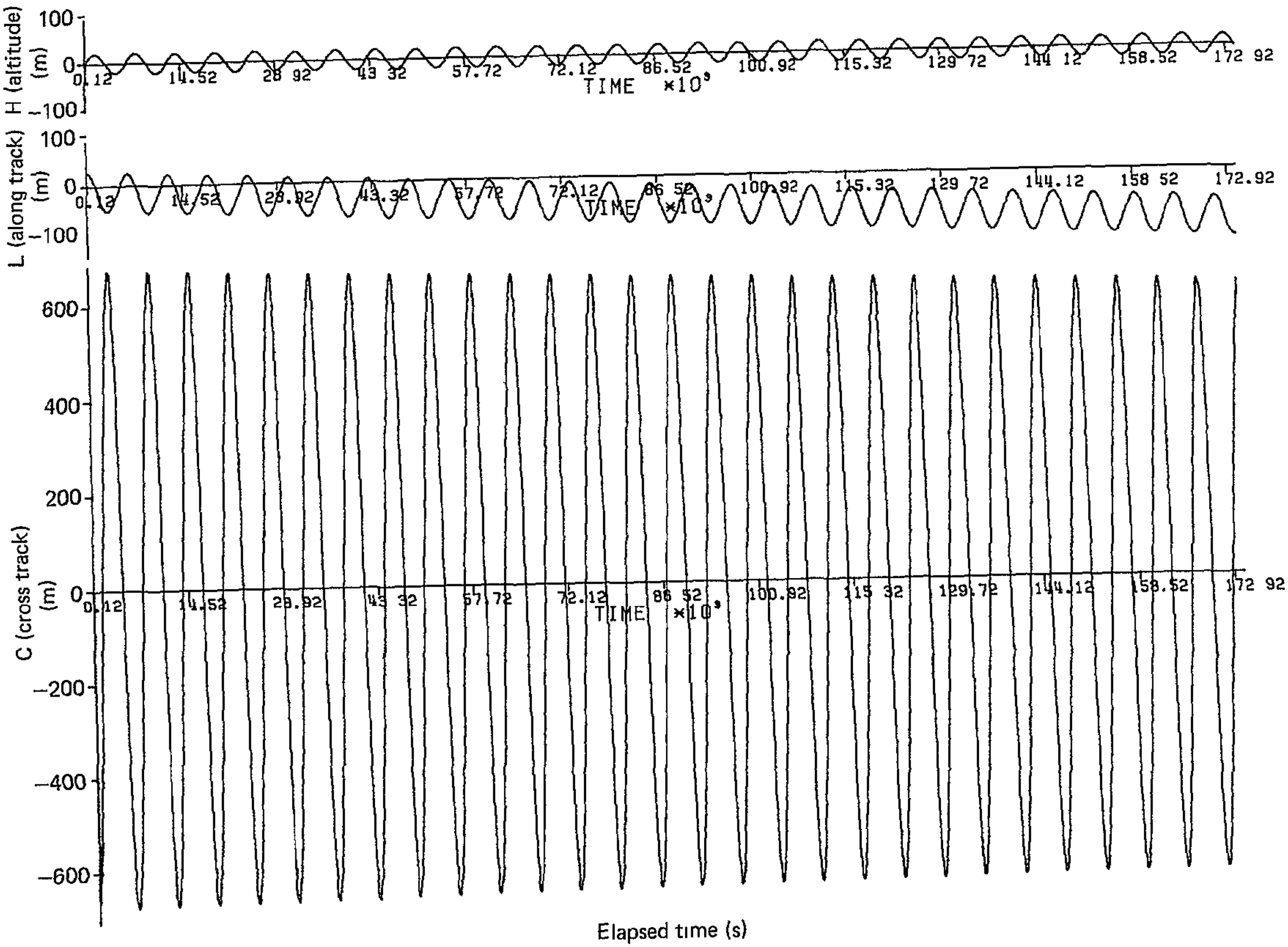


Fig. 12 GEOS-3 Ephemeris Differences, Two Passes, Station 4150 (no altimeter) Track, Reference Ephemeris, *1976 Days 62 to 63*

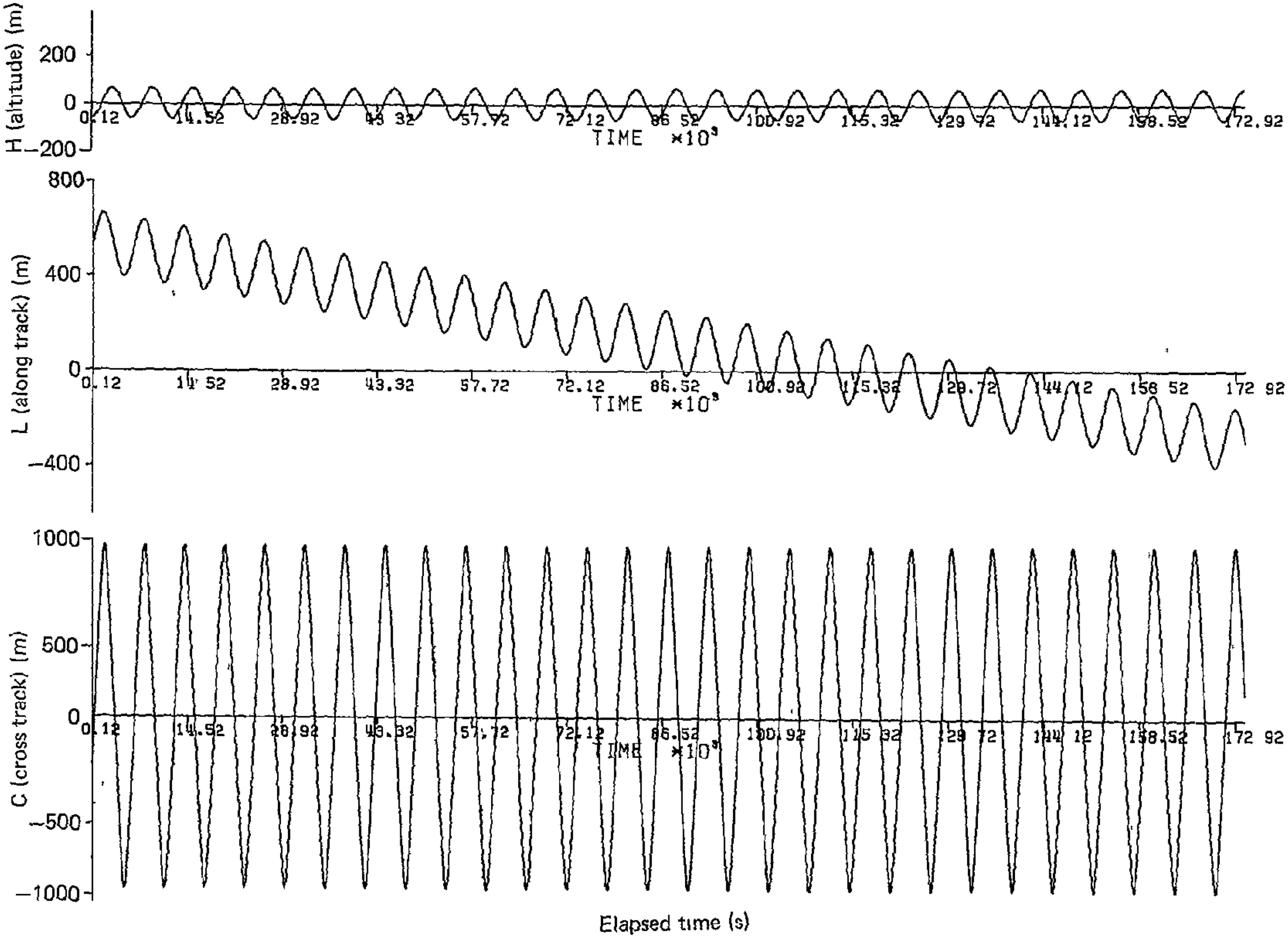


Fig 13 GEOS-3 Ephemeris Differences, Two Passes, Station 4150 (no altimeter) Track, Reference Track, 1976 Days 64 to 65

A. All Data, Reference Runs

Although altimeter data did not contribute to the establishment of the reference ephemerides, it is against these ephemerides that we can assess the available data. We had 36 altimeter passes: 15 for Span 1 (days 62 to 63) and 21 for Span 2 (days 64 to 65). (Spatial distribution of altimeter data is illustrated in Figs. D-9 and D-10.) Individual pass residuals are plotted in Figs. 14 to 17. Figure 18 summarizes the pass results as a function of time. Table 11 presents the individual pass results. The bulk of the data was in the southern hemisphere. Span 1 has about equal distribution of north- and south-going passes, while Span 2 has predominantly north-going passes.

An altimeter range bias is clearly evident in Figs. 14 to 18. The fitted bias for Span 1 is 6.3 m with a drift of -0.8 m/day (5.5 m at the center of the span). The fitted bias for Span 2 is 3.2 m with a drift of 2.04 m/day (5.24 m at the center of the span).

The mean of the pass residuals over the four days was -5.4 ± 2.2 m (Table 11). The range bias and residuals are related to the altimeter height as follows:

$$ALT_B = -ALT_R = H_{EXP} - H_{THEO},$$

where ALT_B = altimeter height bias,

ALT_R = altimeter height residual,

H_{THEO} = theoretical altimeter height, and

H_{EXP} = experimental (data) altimeter height.

A negative residual implies that the distance from the satellite to the ocean surface (geoid) is larger than the true distance by an average of 5.4 m. The 2.2-m standard deviation about the mean is a good order-of-magnitude measure of the precision of the GEOS-3 altimetry data. The majority of the passes show little residual structure. A few passes (355 and 373 in Fig. 16, and 407 in Fig. 17) show a definite structure that correlates well with the theoretical geoidal heights. It is interesting to note that the three passes traversed the same geographic areas (Fig. D-10) just off the west coast of Central and South Africa.

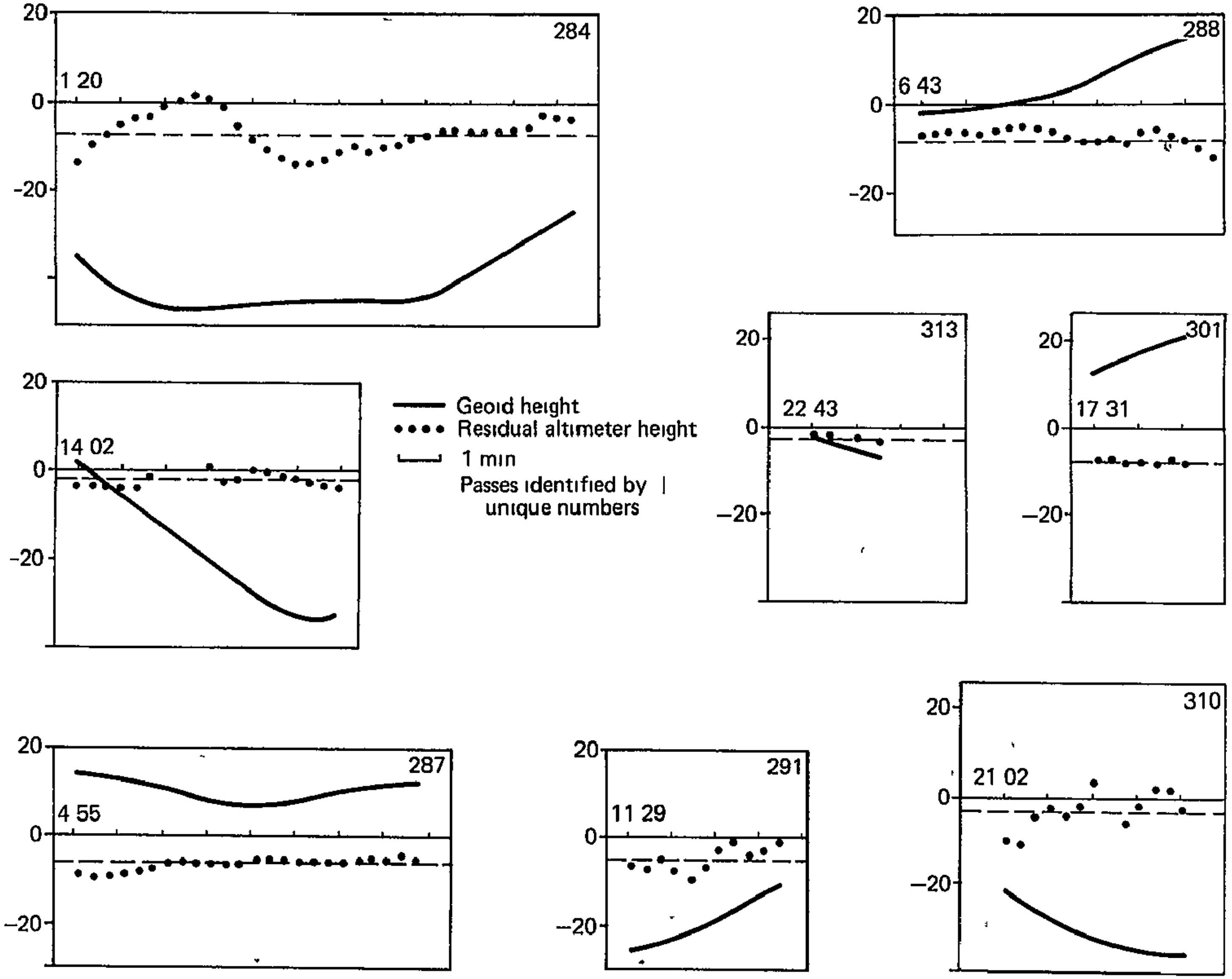


Fig 14 GEOS-3 Altimeter Height Residuals (m) versus Time (h, min) for Reference Orbit, 1976 Day 62

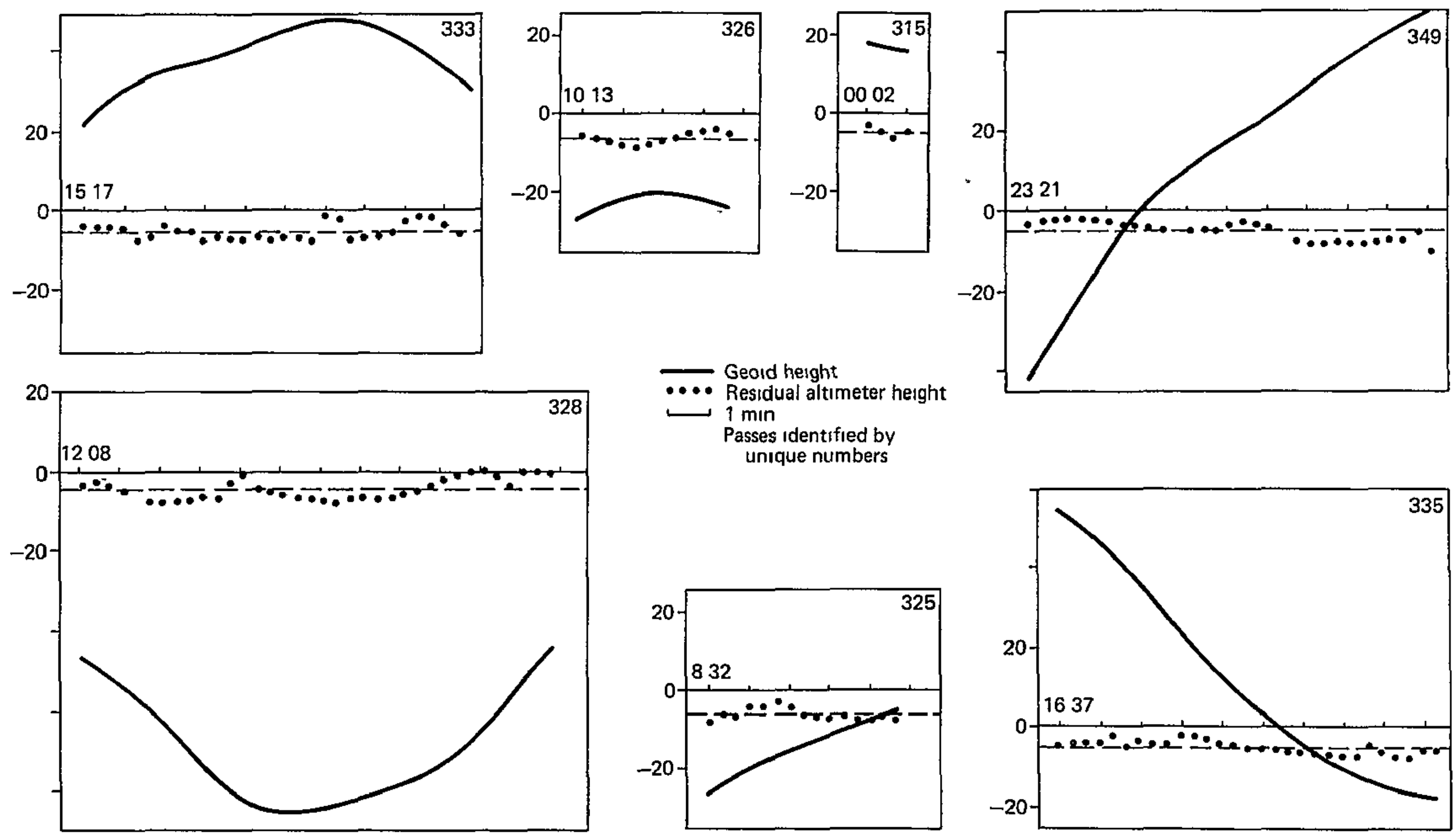


Fig 15 GEOS-3 Height Residuals (m) versus Time (h min) for Reference Orbit, 1976 Day 63

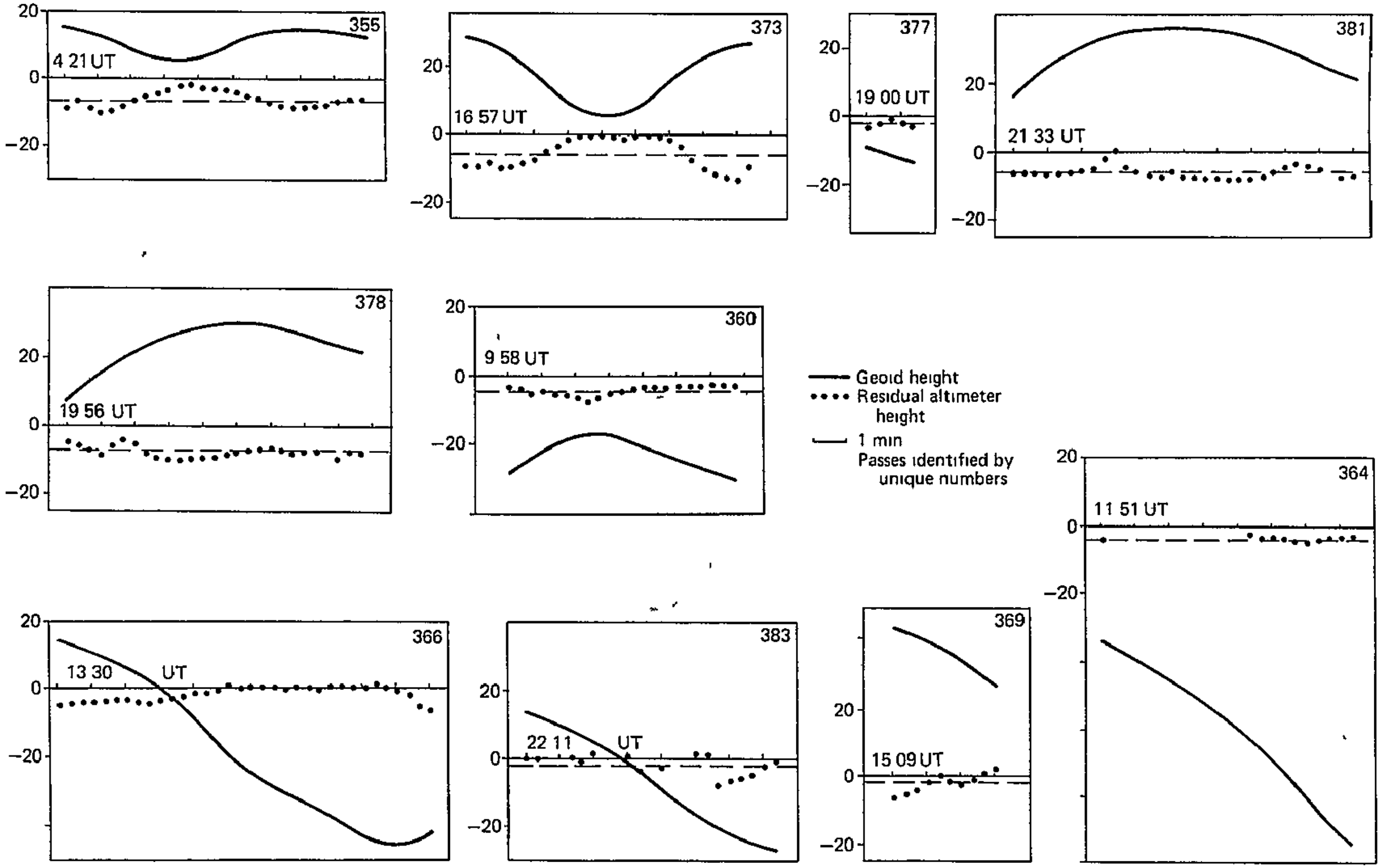


Fig. 16 GEOS-3 Altimeter Height Residuals (m) versus Time (h, min) for Reference Orbit, 1976 Day 64

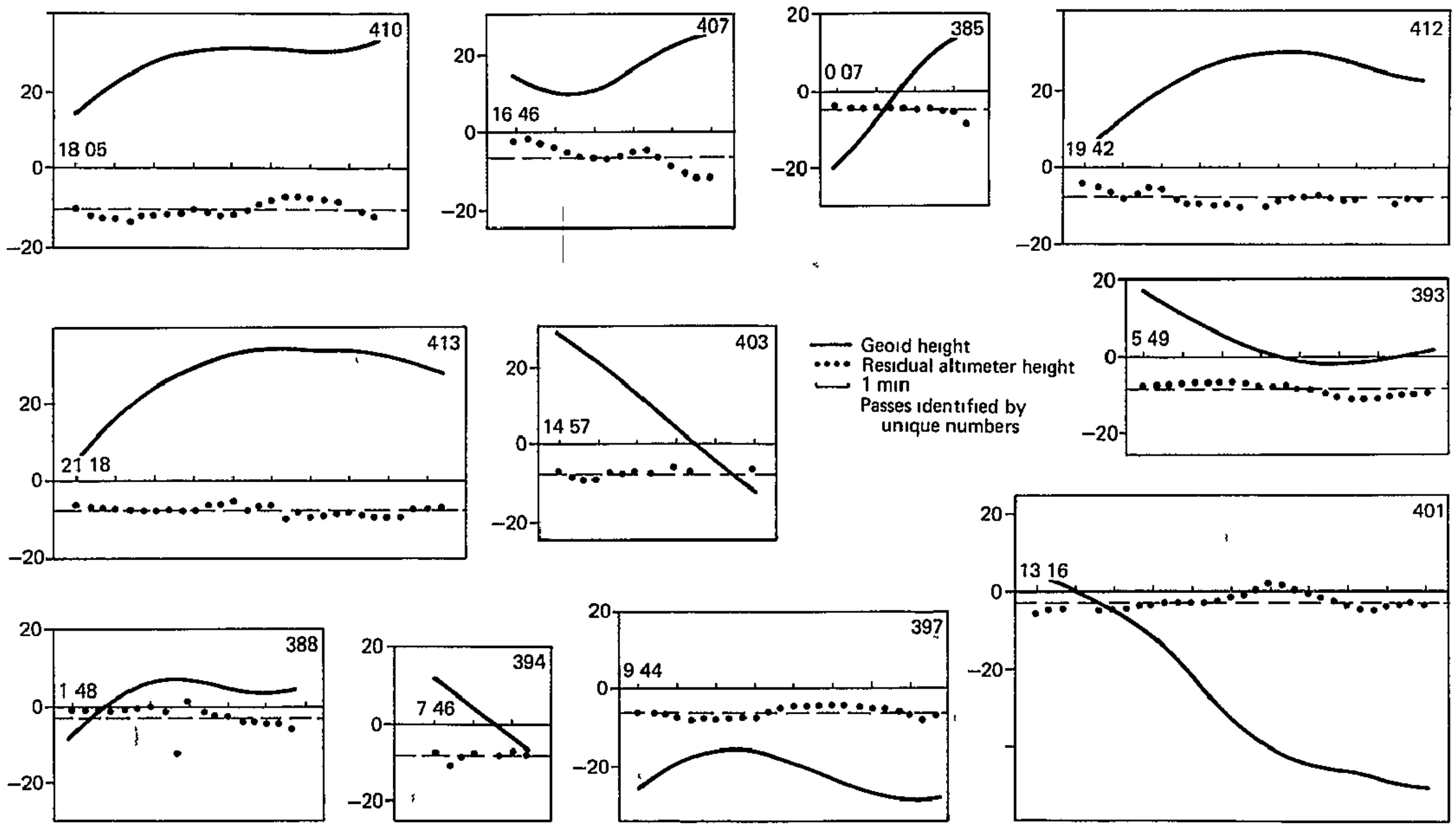


Fig. 17 GEOS-3 Altimeter Height Residuals (m) versus Time (h min) for Reference Orbit, 1976 Day 65

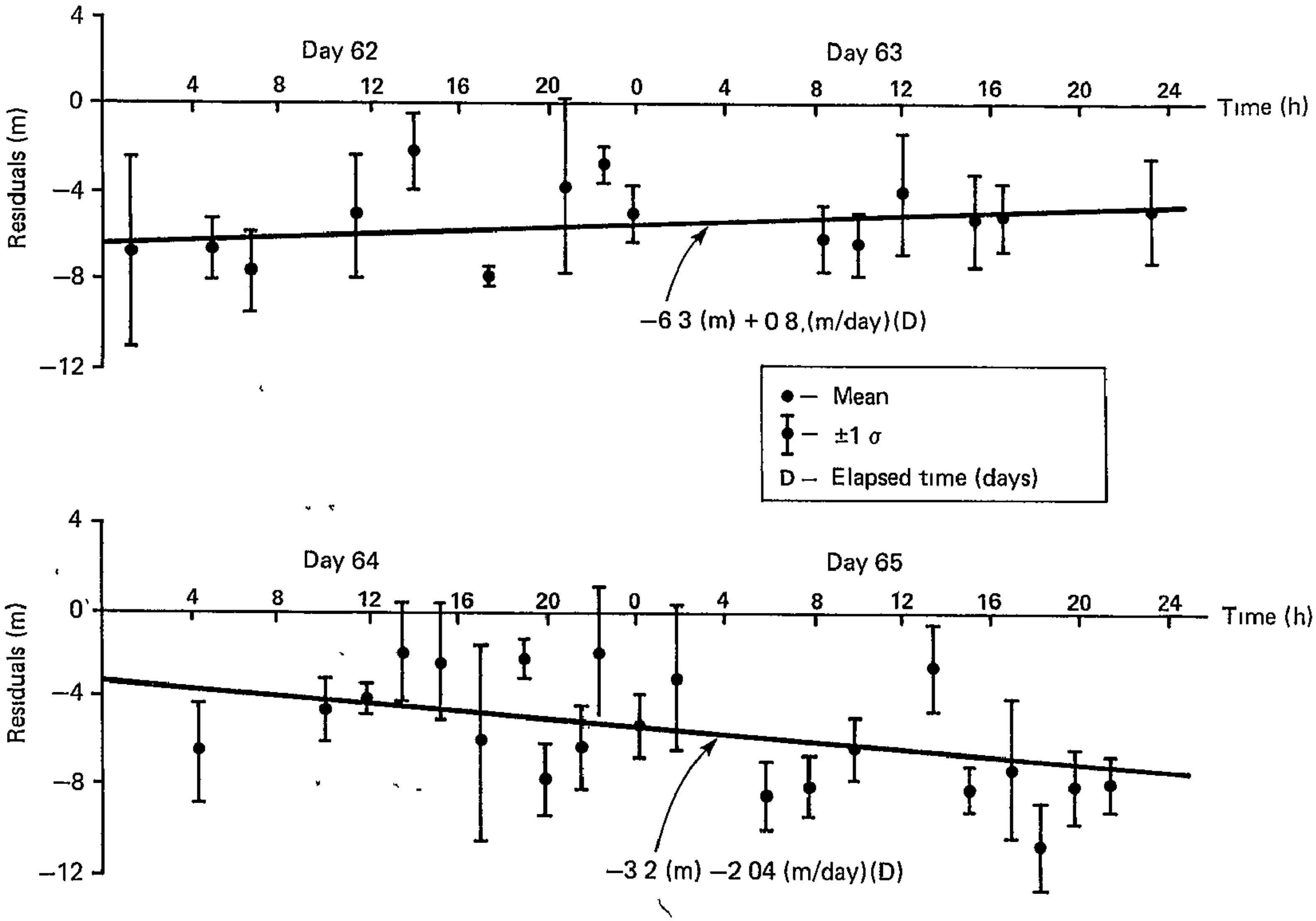


Fig. 18 GEOS-3 Altimeter Height Pass Residuals for Reference Orbits, 1976 Days 62 to 65

Table 11

Summary of Altımeter Data, 1976 Days 62 to 65

Pass I.D Rev No	Pass I.D Unique No	Pass* Heading	Starting Epoch Yr	Starting Epoch Day	Starting Epoch H Min	Pass Duration (min)	Mode	Residual** Mean (m)	Residual** Standard Dev (m)
4627	284	S	1976	62	01 20	12	Intensive	-6 7	4 3
4629	287	S	1976	62	04 55	8	Intensive	-6 6	1 4
4630	288	S	1976	62	06 43	7	Intensive	-7 6	1.8
4633	291	S	1976	62	11 29	4	Intensive	-5 1	2 8
		N	1976	62	14.02	6	Intensive	-2 2	1 7
4636	301	N	1976	62	17 31	2	Intensive	-7 8	0 4
4639	310	N	1976	62	21 02	4	Intensive	-3 8	3 9
4639	313	N	1976	62	22.43	2	Intensive	-2 8	0 8
4640	315	N	1976	63	00 02	1	Intensive	-5 0	1 3
4645	325	N	1976	63	08 32	5	Intensive	-6 1	1 5
4646	326	N	1976	63	10 13	4	Intensive	-6 4	1.4
4647	328	N	1976	63	12 08	12	Intensive	-4 2	2 6
4649	333	N	1976	63	15 17	10	Intensive	-5 3	2 1
4650	335	S	1976	63	16 37	10	Intensive	-5 2	1 5
4654	349	S	1976	63	23 21	10	Intensive	-4 9	2 4
4657	355	S	1976	64	04 21	9	Intensive	-6 3	2 2
4660	360	N	1976	64	09 58	7	Intensive	-4 4	1.4
4661	364	N	1976	64	11 51	8	Intensive	-3 9	0 7
4662	366	N	1976	64	13 30	11	Intensive	-1 8	2 2
4663	369	N	1976	64	15 09	3	Intensive	-2.3	2 6
4664	373	N	1976	64	16 57	9	Intensive	-5 9	4 4
4666	377	N	1976	64	19 00	2	Intensive	-2 1	0 9
4666	378	S	1976	64	19 56	9	Intensive	-7 5	1.6
4667	381	S	1976	64	21 33	10	Intensive	-6 1	1 9
4668	383	N	1976	64	22 11	8	Intensive	-1 8	2 9
4669	385	N	1976	65	00 07	4	Intensive	-5 1	1 4
4670	388	N	1976	65	01 14	6	Intensive	-3 0	3 2
4672	393	S	1976	65	05 49	8	Intensive	-8 3	1 5
4673	394	S	1976	65	07 46	3	Intensive	-7 5	1 3
4674	397	N	1976	65	09 41	8	Intensive	-6 1	1 4
4676	401	N	1976	65	13 16	10	Intensive	-2 4	2 0
4677	403	N	1976	65	14 57	5	Intensive	-7 9	1 0
4678	407	N	1976	65	16 46	5	Intensive	-7 0	3 1
4679	410	N	1976	65	18 05	8	Intensive	-10 5	2 0
4680	412	S	1976	65	19 42	9	Intensive	-7 8	1 7
4681	413	S	1976	65	21 18	10	Intensive	-7 7	1 2
Summary		13 S 23 N	Mean Duratıon = 3 min				Mean Residual = -5 4+2 2(m) Mean Bıas = +5 4+2 2(m)		

* S - south, N - north

** Residual relative to reference ephemerıs

B. Altimeter + All Data from a Single C-Band Site (SCB)

Adding altimeter data did not affect the solution to any great extent. A comparison of Tables 10 and 12 (column headed SCB) shows that the changes from the reference Keplers are essentially the same. The fitted altimeter bias and drift terms are slightly different from their reference counterparts. All we can say is that altimeter data neither enhanced nor detracted from the nonaltimeter solution.

The resulting tracked and extrapolated ephemerides are essentially identical to their nonaltimeter counterparts. Tables 7 and 9, lines 3 and 8, give the results for both cases.

C. Altimeter + All Data from a Single Doppler Site (SDP)

Like the single C-band site case above, we find that altimeter data do not add anything to the solution but neither do they hurt. A comparison of Tables 10 and 12 (columns headed SDP) gives similar results for the single doppler site with or without altimeter data.

D. Altimeter + Two Passes from a Single C-Band Site (2CB)

This presents the first interesting case for the introduction of altimetry data. Without altimeter data, this case (see previous section) resulted in hundreds of meters' deviation from the reference ephemerides. The introduction of altimeter data into the orbit determination process essentially recovers the reference cases. The largest correction to the reference Kepler elements is 10 m (as opposed to almost 700 m), and the tracked as well as extrapolated ephemerides differ only by a few meters (rms) from their reference counterparts. The column headed 2CB in Table 12 (with altimeter) shows dramatic improvement over column 2CB in Table 10 (without altimeter). Table 7, lines 5 and 10, can be compared to lines 4 and 9, respectively, for the tracking results. Adding altimeter data reduces the deviation from the reference ephemerides from 462 m to 9 m (Span 1) and from 690 m to 11 m (rms results). Similarly, the extrapolated ephemerides (Table 9, lines 5 and 10) are only slightly worse than their reference counterparts: 12.4 m versus 5.2 m for Span 1 and 14.2 m versus 7.1 m for reference 2. Figures 19 and 20 are plots of the ephemeris deviation from their reference counterparts (tracks). (The extrapolated navigation results are plotted in Figs. D-11 and D-12.)

Table 12

GEOS-3 Orbit Determination with Altimeter and Other Data, 1976 Days 62 to 65 (deviations from reference orbit)

	SCB		SDP		2CB		2LR	
	S1	S2	S1	S2	S1	S2	S1	S2
δa(m)	0	0	0	0	0	0	0.3	0.2
$R_0 \delta e$(m)	0	-6.4	0	2.6	0.6	1.3	0.6	0
$R_0 \delta i$(m)	2.5	4.3	3.5	-0.5	5.4	10.5	-84.3	129.2
$R_0 \delta \Omega$(m)	-2.0	-0.9	1.3	-0.7	-6.8	-7.8	106.1	87.6
$R_0 (\delta \omega + \delta M)$(m)	0.8	-1.8	-4.3	-1.4	-6.2	-0.9	81.2	12.4
Altimeter Bias (m)	-0.4	0.5	0.7	0	-0.4	0.3	-0.7	0.4
Altimeter Drift (m/day)	0.2	0.1	-0.2	-0.2	-0.2	-0.3	-0.2	-0.3

SCB - All passes from a single C-band site (sta 4150)
SDP - All passes from a single doppler site (sta 111)
2CB - Two C-band south-going passes (one/day sta 4150)
2LR - Two laser south-going passes (one/day sta 7067)
S1 - 1976 days 62 to 63
S2 - 1976 days 64 to 65
R_0 - 6378.166 km

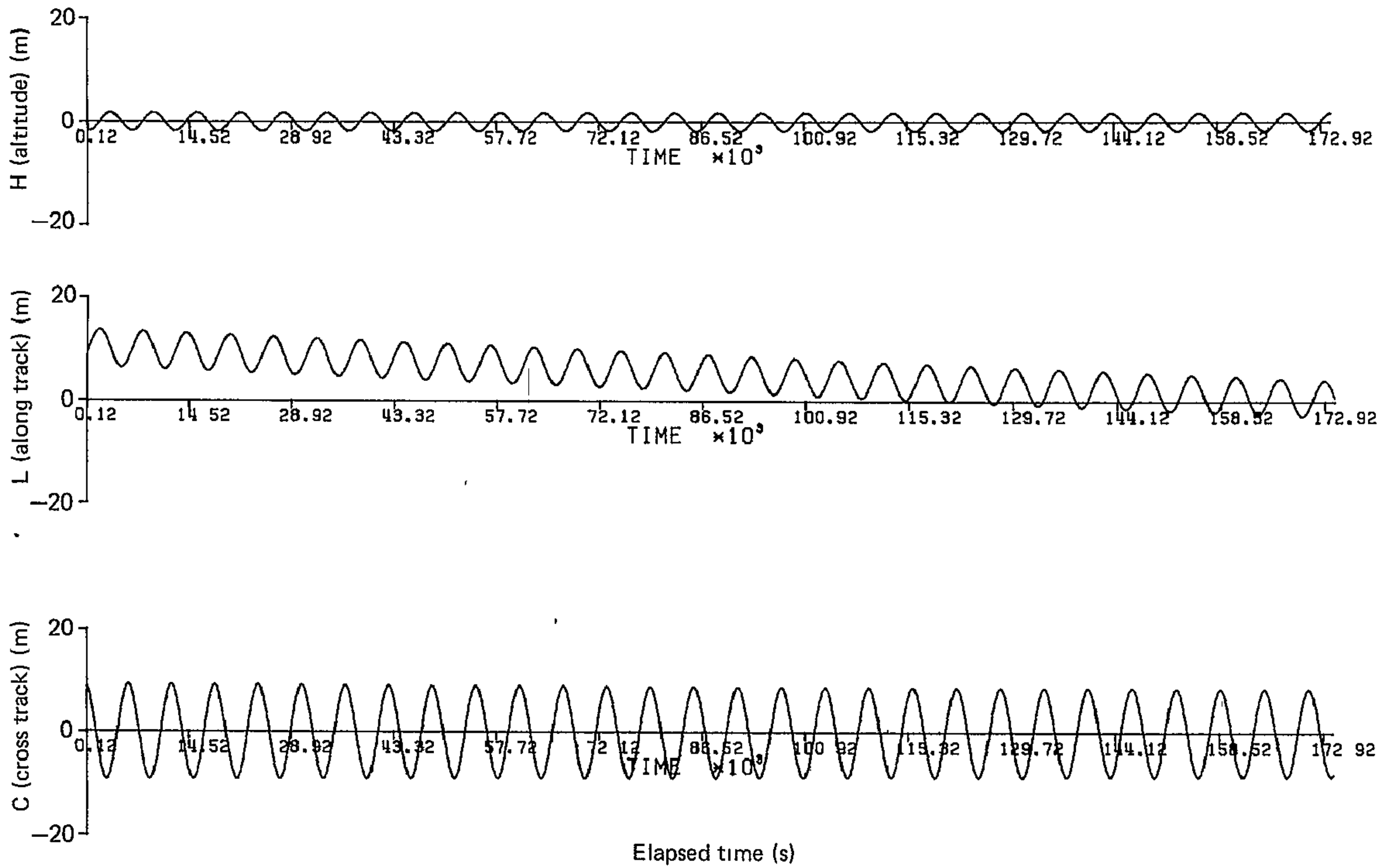


Fig. 19 GEOS-3 Ephemeris Differences, Two Passes, Station 4150 (with altimeter) Track, Reference Track, 1976 Days 62 to 63

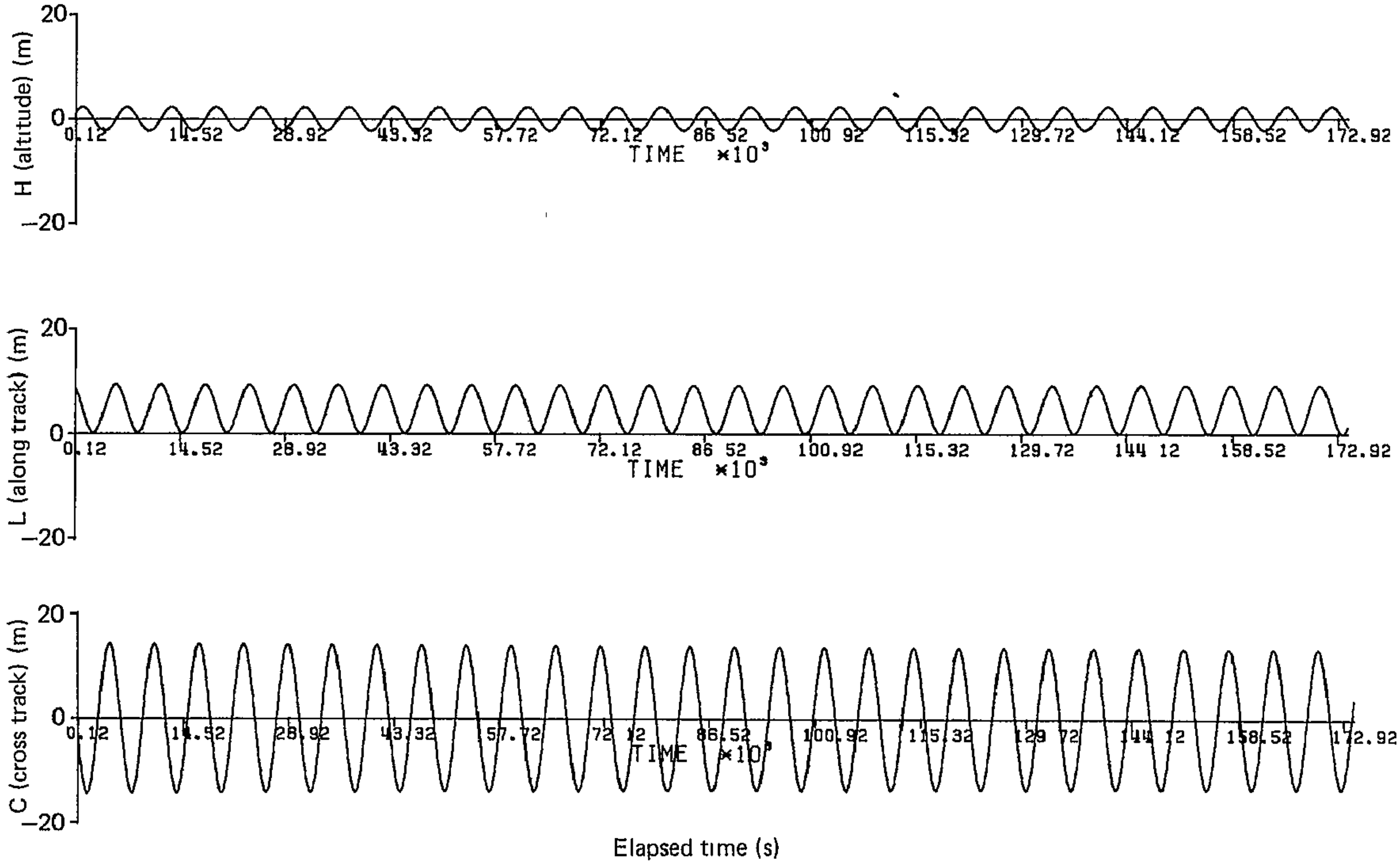


Fig 20 GEOS-3 Ephemeris Differences, Two Passes, Station 4150 (with altimeter) Track, Reference Track, 1976 Days 64 to 65

E. Altimeter + Two Passes from a Single Laser Site (2LR)

Since the addition of altimeter data to two C-band passes improved the orbit determination solution, we expected similar results with the two laser passes. We were surprised to discover that adding altimeter data did not improve the results. A comparison of Tables 10 and 12 (columns headed 2LR) shows that Span 1 was left unchanged by the introduction of the altimeter data, whereas, for Span 2, δi and $\delta\Omega$ show a reversal in sign and no improvement in magnitude.

At first glance the results are surprising, but a closer look at the situation uncovers the following pertinent facts:

1. Most of the altimeter data were confined to the South Atlantic and Indian Oceans;

2. Span 2, which contained a few passes in the North Pacific Ocean, had predominantly north-going passes;

3. The C-band site (Green River, UT) is located at 39° N, 110° W. All passes were heading south; and

4. The laser site (Bermuda) is located at 32° N 65° W. Span 1 had two south-going passes and Span 2 had two north-going passes.

We can now examine the differences in the two cases. The C-band site, located in the northwestern portion of the United States, was clearly enhanced by the addition of altimetry data that were predominantly from the south and east parts of the world. The laser site, located 45° E and 7° S of the C-band site, gained little by the introduction of altimetry data. Furthermore, for Span 2 there were four altimeter passes in the northern hemisphere, two of them in the Pacific Ocean. Unfortunately, all four had the same heading (north) as the laser passes and did not adequately complement the laser data.

F. Altimeter Data Only

This last case is only interesting as an exercise. We knew from the synthetic noise-free data experiment that orbit determination with altimeter data alone is not well-conditioned. In Table 13 we present a series of orbit determination results with altimeter data alone, starting with the unconstrained solution (A) and ending with the most constrained case (C).

Table 13

GEOS-3 Altimeter Orbit Determination, Altimeter Data Only, 1976 Days 62 to 65

	A		B		C		D	
	S1	S2	S1	S2	S1	S2	S1	S2
δa(m)	5.0	-1 0	-4 9	-5 0	-5 1	-6 2	-0 7	-2 2
$R_0 \delta e$(m)	0 6	-0 6	-0 6	0	-0.6	-1 3	0	-0 6
$R_0 \delta i$(m)	599 6	460 4	208 6	584 6				
$R_0 \delta \Omega$(m)	25 679 7	32 463 5	-32 626 4	11 813 6				
$R_0(\delta\omega+\delta M)$ (m)	507 2	-47 8	-433 6	-67 1				
Altimeter Bias(m)	3 6	-0 8					-1 1	-1 5
Altimeter Drift(m/day)	-0 2	-0 44					-0 2	-0 34

A - fit a, e, i, Ω, ω, M, bias drift
B - fit a, e, i, Ω, ω, M
C - fit a, e
D - fit a, e, bias, drift
S1 - 1976 days 62 to 63
S2 - 1976 days 64 to 65
R_0 - 6378 166 km

Case A does very poorly in δi, $\delta\Omega$, $\delta\omega + \delta M$. Removing the bias and drift parameters (B) does not improve the solution. In the last two cases, we eliminated δi, $\delta\Omega$, and $\delta\omega$ from the fitting space. Here it is interesting to note that case C is actually overconstrained, and as a result the altimeter bias corrupts the semimajor axis (as it did for case B). The last case (D) illustrates that altimeter data are useful in determining satellite semimajor axis, eccentricity, altimeter bias, and drift. All we need is another data type to determine the node, inclination, and perigee.

7.0 SUMMARY

The objectives of the GEOS-3 orbit determination experiment were to determine the nature and improvement in satellite orbit determination when precise altimetric height data are used in combination with conventional tracking data. To accomplish this, a digital orbit determination program was developed that could singly or jointly use laser ranging, C-band ranging, doppler range difference, and altimetric height data. The program edits and weights the data and solves for the orbit initial conditions and five auxiliary parameters. The software integrity was verified by using synthetic data, thus permitting an investigation of the orbit determination procedure using several types of tracking data as well as altimeter data alone.

Soon after data became available, two intervals were selected and used in a preliminary evaluation of the GEOS-3 altimeter data. Since the altimeter data were inordinately sparse and were confined principally to one geographic region, this effort served primarily to validate the integrity of the digital orbit determination program.

After all the tracking data had become available, a detailed study was made using a span of time for which an intensive effort had been made to collect tracking data on a worldwide basis. However, again the distribution of the altimeter data was far from ideal.

With rather sparse altimeter data alone it was possible to determine the semimajor axis and eccentricity to within several meters and the along-track position to within several kilometers, in addition to determining an altimeter height bias. When used jointly with a limited amount of either C-band or laser range data, it was shown that altimeter data can improve the orbit solution.

Had altimeter data been available continously around the orbit and on a worldwide basis, more precise results could have been obtained. But this is of no consequence here; our intent was to demonstrate the practicality of using altimeter data in the ephemeris computation. The data distribution was certainly adequate to accomplish this goal.

8.0 CONCLUSIONS

The investigations undertaken here indicate that altimeter height data can be a useful source of tracking information. However, quantitative measures for the efficiency of the altimeter data for GEOS-3 were somewhat obscured by the sparsity of the data. A good distribution of data either around the orbit or geographically was not available. With the sparse altimeter height data alone it was possible to determine the semimajor axis and eccentricity within several meters of the reference orbit and an altimeter height bias. The along-track position of the spacecraft was determined to a precision of a few kilometers.

Conventional tracking data, i.e., doppler, C-band range, and laser range, from a single midlatitude site provides enough information to determine the satellite ephemeris. Consequently, combining altimeter height data with the conventional data does not permit orbit improvement. However, in such an approach it is possible to determine a measure of the altimeter bias.

The study does show that for near-polar orbits, data from a conventional tracking site at the middle latitudes operating on a regular but time-sharing 8-h shift will produce inferior orbits. However, high-precision orbits can be obtained if these data are supplemented by altimeter height data.

It had been anticipated that a part of the study would be devoted to short-arc orbit solutions. However, the intensive tracking data from several sites in the same geographic region were not available.

9.0 RECOMMENDATIONS FOR FURTHER STUDY

This study, although not conclusive, shows that altimeter height data of the quality obtained from GEOS-3 can be useful for orbit determination. From the nature of the structure of the altimeter residuals, it can be concluded that the availability of a more precise geoid model would have improved the orbit determination precision. Such a geoid should be available as a result of the geoid determination studies undertaken as part of the GEOS-3 efforts.

The SEASAT spacecraft appears to be an ideal vehicle for further orbit determination studies using altimeter data. Since SEASAT altimeter data will be stored in the spacecraft for telemetry to ground sites, the problems experienced on GEOS-3 with data distribution should not occur. Most of the software developed for GEOS-3 investigation should be usable, with modest changes, for SEASAT.

ACKNOWLEDGMENTS

We are indebted to the personnel at NASA, Wallops Island, particularly to H. Ray Stanley who listened patiently to our complaints and did his best to satisfy our needs; to NASA, in general, for the opportunity to participate in an interesting and meaningful scientific experiment; and to our secretaries, Irene Hamil and Jessie Hicks, for assisting us whenever possible.

REFERENCES

1. J. Marsh, private communication, 1976.

2. F. J. Lerch, S. M. Klosko, R. E. Laubscher, and C. A. Wagner, "Gravity Model Improvement Using GEOS-3 (GEM 9 and 10)," GSFC X-921-77-246, September 1977.

Appendix A
DESCRIPTION OF THE SOFTWARE MODULES

EPHEMERIS GENERATOR

The ephemeris generator converts a set of initial conditions (state vector) into a table of satellite positions as a function of time by numerical solution of the initial value problem

$$\vec{f} = m\vec{a} \quad .$$

The table so constructed is stored on the ephemeris file, a data set residing on an external storage device.

The numerical integrator is a predictor-corrector scheme using a Cartesian coordinate system and calling a large package of subroutines to obtain the force vector, $\vec{f}$. This integrator is in turn invoked by a higher level routine on a step-by-step basis until the required ephemeris table has been created and stored on the ephemeris file. The forces modeled and integrated are:

1. Earth gravity (inputable geoid),

2. Third-body perturbation: sun and moon,

3. Earth body tides: sun and moon,

4. Atmospheric drag (Jacchia model),

5. Sun's radiation,

6. Nutation and precession effects, and

7. Polar motion.

ALTIMETER FORMATOR/SIFTOR

The altimeter FORMATOR/SIFTOR is the first processor to handle incoming altimeter data. Altimeter data consist of 80-character records, one record per altimeter data point. Since altimeter data rates are high (10 or 100 points/s), the volume of data is large. For example, at the high data rate, a 10-min segment will result in 60 000 data records. Tracking altimeter data requires many such segments (passes) simultaneously. The high data rate exceeds by far even the most stringent tracking requirements. A rate of one point every 10 s is quite sufficient. Clearly, one of the functions of the FORMATOR/SIFTOR is to collapse the incoming data into an equivalent but much smaller set. The functions performed by the FORMATOR/SIFTOR can be summarized as follows:

1. Detect and eliminate any data point with non-numeric characters,

2. Check for monotonically increasing data time and eliminate data points that do not conform (detect bad time, etc.),

3. Eliminate points with unreasonable sea-surface height (overland data),

4. Eliminate points with unreasonably large smoothing sigma,

5. Fit a polynomial of given order to data points in a given time segment of data (i.e., 10 s), detect and eliminate bad points; slide the time segment along until all incoming data are processed,

6. Break up data into pseudo passes defined by an inputable time gap (i.e., start a new pass if the time gap between two successive data points is greater than x minutes),

7. On option, compute an equivalent altimeter range for each fitted time segment at an existing data point time near the center of the span, replace the former with the fitted value and the latter with the rms of the fitted residuals for the segment, eliminate bad points based on the rms of the fitting interval, eliminate all points in the interval if (a) rms is greater than the given threshold and (b) not enough data are available for fit, and

8. Save either the full or collapsed data for subsequent processing by the Altimeter EDITOR/PEF Program.

LASER/C-BAND DATA FORMATOR/SIFTOR

Laser and C-band range data for the GEOS-3 satellite consist of 80 character records, one record per laser or C-band measurement. Our experience with short-count doppler has demonstrated clearly that the high-density data (one per 4 s) are not necessary for good orbit determination. Typically choosing every fourth and fifth point is quite sufficient. Reducing the laser (C-band) data density is therefore both realistic and desirable, consequently, one of the features of the Laser/C-band SIFTOR is to aggregate or collapse the incoming raw data. The functions of the Laser/C-band Data FORMATOR/SIFTOR are as follows:

1. Detect and eliminate data points with non-numeric characters,

2. Check for monotonically increasing data times within a given pass, eliminate data that do not conform,

3. Fit a polynomial of given order to data points in a given time segment (i.e., 10 s), detect and eliminate bad points, slide the time segment along until all passes are processed,

4. Detect pass boundaries in the incoming data (a new station number signals a new pass) and create new pass headers,

5. On option, compute an equivalent range for each fitted segment at an existing data point time near the center of the span,

6. Compute and save tropospheric parameters for later use by the EDITOR/PEF Program, and

7. Save either the full or collapsed data for subsequent processing by the Laser/C-band EDITOR/PEF Program.

DOPPLER FORMATOR/SIFTOR

Source doppler data can be defined as strings of numeric characters. The function of the FORMATOR is to format source data into arithmetic data and then to convert the data according to the formulation for that source. The FORMATOR processes one data group (pass) at a time. The definition of a data group is a numeric string of source data that is uniquely identified by a header record preceding the data and may have a record that trails the data. The trailing record usually provides weather information associated with the data.

The FORMATOR performs the following tasks:

1. Preliminary processing of data.

    a. Correction to observed epochs and time intervals in accordance with time calibration information provided in the header or otherwise.

    b. Preliminary editing to delete defective data such as incomplete information (missing epochs, refraction counts) or unreasonable data (fails reasonable value tests).

    c. Ionospheric refraction corrections to data where necessary.

2. Weather data recovery (when present).

3. Computation and saving of troposphere parameters for later use by the EDITOR.

The SIFTOR or Orbit Independent Data Editor performs data editing that does not require a satellite orbit. Data are checked for smoothness and poor data are sifted out. The scheme used is second-differencing, which requires a fairly dense data sample for proper operation. A second function performed by the SIFTOR is data aggregation. After sifting we may elect to aggregate or condense the data for more efficient handling downstream (EDITOR/PEF).

ALTIMETER EDITOR/PEF

The Altimeter EDITOR/PEF processes all sifted altimeter data passed to it in the sifted altimeter data file. The program ignores pass boundaries and treats all data points in the same manner. Data are retrieved sequentially and for each data point a set of nine partials and a residual are computed. The residual is computed using an ephemeris file that must be supplied. The partials are computed using a propagated Kepler orbit. The partials and residuals for each data point are accumulated into the normal matrix and R.H.S. vector and are saved on a file for subsequent processing by the SOLVOR. The nine partials are with respect to.

1. Six orbit parameters,

2. Altimeter range bias,

3. Altimeter range-rate bias, and

4. Along-track force bias.

Data editing is limited to stripping individual noisy data points.

LASER/C-BAND EDITOR/PEF

The Laser/C-band EDITOR/PEF processes all sifted laser/C-band data passed to it via the sifted laser/C-band data files. The laser/C-band processor performs a dual function. The program navigates each pass in the MSR coordinate system. Ignoring pass boundaries, the program computes seven orbit partials and a residual for each data point. The partials and residual are accumulated into the normal matrix and R.H.S. vector and are saved on a file for subsequent processing by the SOLVOR. The seven partials are with respect to:

1. Six orbit parameters, and

2. Along-track force bias.

In the navigation process, a range bias and a range-rate bias are determined along with the ECA and ECR errors. The bias and rate terms are used as additional criteria for detecting bad passes. The program has an option to remove the effects of the fitted range bias and range-rate bias from the data. (This option has not been exercised in the orbit determination experiment.) Options are available to remove the effects of the neutral atmosphere on the propagation velocity and to correct for the effects of special relativity.

DOPPLER EDITOR/PEF

The Data Editor has the assigned task of detecting and removing spurious and noisy data. Local smoothing (i.e., polynomial fitting) works well in detecting spurious data but fails in detecting an entire set of data that is biased though internally consistent. Bad data are detected in the doppler editor in the navigation process. The doppler editor computes pass weights that are passed to the PEF Program along with the along-track, slant-range, and frequency errors. Options are available to remove the effects of the neutral atmosphere on the propagation velocity and to correct for the efforts of special relativity.

The PEF Program computes a set of nine partials and a residual for each set of pass navigation results: ECA, ECR, and frequency. The partials and residuals are accumulated into a normal matrix and R.H.S. vector and are saved on a file for subsequent processing by the SOLVOR. The nine partials are with respect to

1. Six orbit parameters,

2. Satellite frequency,

3. Satellite frequency drift, and

4. Along-track force bias.

THE SOLVOR

The SOLVOR combines the four sets of normal matrices and R.H.S. vectors generated by the three EDITOR/PEF programs into a single combined matrix and R.H.S. vector. The separate data types are weighted by the number of passes each contributes to the combined normal matrix. Corrections to the 11 parameters are computed, and the initial state vector is updated. The 11 parameters solved for are as follows:

1. Six orbit elements (A_0 - A_5),

2. Satellite frequency,

3. Satellite frequency drift,

4. Altimeter range bias,

5. Altimeter range-rate bias, and

6. Along-track force bias.

SOLVOR operates on any one or a combination of the four data types. Options are provided such that fewer than 11 parameters may be solved for. The six orbit parameters (A_i, $i = 0, 1, \ldots 5$) are related to the Kepler corrections as follows:

$$\delta a = - 2/3 \, A_1 \, ,$$

$$\delta e = \frac{1}{2a} A_3 \, ,$$

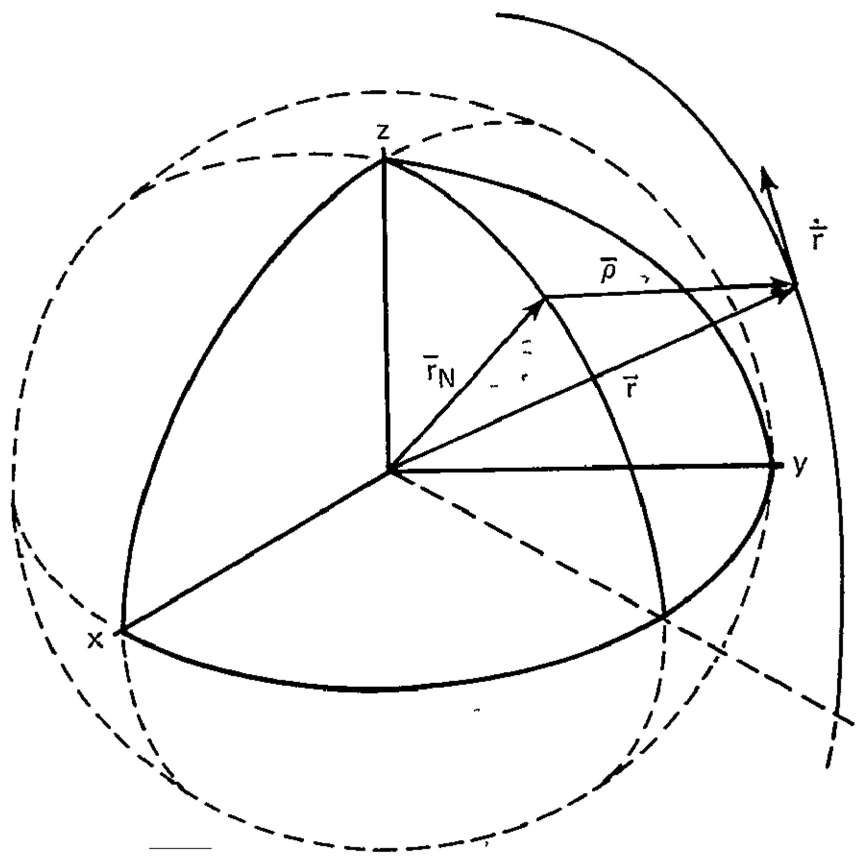
$$\delta i = \frac{1}{a} A_5 \, ,$$

$$\delta \Omega = \frac{1}{a \sin(i)} A_4 \, ,$$

$$\delta \omega = \frac{1}{a} \left(A_0 - \frac{1}{2e} A_2 + \cot(i) \, A_4\right), \text{ and}$$

$$\delta M = \frac{1}{2ae} A_2 .$$

Appendix B
MSR COORDINATE SYSTEM (DEFORMATION)



$\bar{r}(t)$ = satellite inertial Cartesian position,

$\dot{\bar{r}}(t)$ = satellite velocity,

$\bar{r}_N(t)$ = navigator (tracking station) inertial Cartesian position,

$\dot{\bar{r}}_N(t)$ = navigator velocity,

$\bar{\rho}(t)$ = slant range from navigator to satellite,

$\dot{\rho}(t)$ = range rate,

$\bar{\mathfrak{p}}, \bar{\mathfrak{L}}, \bar{\mathfrak{S}}$ = right-hand orthogonal coordinate system at the time of satellite closest approach to the navigator (tca),

f_g = ground (navigator or station) frequency,

f_s = satellite frequency,

$$\bar{\rho} = \bar{r} - \bar{r}_N, \text{ and}$$

$$\dot{\rho} = \frac{d}{dt} \left| \bar{r} - \bar{r}_N \right| = \frac{\bar{r} - \bar{r}_N}{\left| r - r_N \right|} \cdot (\dot{\bar{r}} - \dot{\bar{r}}_N) \quad .$$

At the tca (MSR), $\dot{\rho} = 0$

$$(\bar{r} - \bar{r}_N) \cdot (\dot{\bar{r}} - \dot{\bar{r}}_N) = 0$$

or

$$\bar{\rho} \cdot \dot{\bar{\rho}} = 0 \quad .$$

Therefore, we can define an orthogonal right-hand system at tca as

$$\bar{\mathfrak{p}} \triangleq \frac{\bar{\rho}}{|\bar{\rho}|} \quad , \quad \bar{\mathfrak{L}} \triangleq \frac{\dot{\bar{\rho}}}{|\dot{\bar{\rho}}|} \quad , \quad \bar{\mathfrak{S}} \triangleq \bar{\mathfrak{p}} \times \bar{\mathfrak{L}} \; ,$$

where $\mathfrak{p}$ is the slant range and for near-earth satellites $\bar{\mathfrak{L}}$ is roughly the along-track direction.

Appendix C
PRELIMINARY ORBIT DETERMINATION RESULTS (SUPPLEMENTARY MATERIAL FOR SECTION 5.0)

Table C-1

Doppler Pass Navigation Results, 1975 Days 113 and 114

No	Yr	Day	Time (h)	Along Track (m) Obsvd	Along Track (m) Pred	Along Track (m) Resid	Slant Range (m) Obsvd	Slant Range (m) Pred	Slant Range (m) Resid
1	75	113	1.60	-2.55799000E+01	1.72252920E+00	-2.73024292E+01	1.78545000E+01	1.12367422E+01	6.61775780E+00
2	75	113	1.79	-4.35898000E+01	-5.80673420E+00	-3.77830658E+01	1.33997000E+01	8.12403662E+00	5.27566338E+00
3	75	113	3.27	4.59070000E+00	4.26141313E+00	3.29286873E-01	1.18620000E+01	1.05734353E+01	1.28856468E+00
4	75	113	3.41	-1.87050000E+00	-2.58071092E+00	7.10210919E-01	2.42488000E+01	1.25247523E+01	1.17240477E+01
5	75	113	3.76	-3.60454000E+01	-1.70948385E+01	-1.89505615E+01	1.21774000E+01	6.99412001E+00	5.18327999E+00
6	75	113	4.94	1.84848000E+01	6.69624199E+00	1.17885580E+01	2.13481000E+01	1.01618960E+01	1.11862040E+01
7	75	113	5.08	1.49090000E+00	9.99307652E-01	4.91592348E-01	3.09190000E+01	1.07622007E+01	2.01567993E+01
8	75	113	5.59	-4.00584000E+01	-1.85098313E+01	-2.15485687E+01	-3.85820000E+00	-4.20747684E-01	-3.43745232E+00
9	75	113	6.72	9.28150000E+00	4.87318053E+00	4.40831947E+00	2.37359000E+01	7.23745640E+00	1.64984436E+01
10	75	113	6.93	-1.76783000E+01	-6.51513777E+00	-1.11631622E+01	3.96316000E+01	1.13250052E+01	2.83065948E+01
11	75	113	7.24	-4.28341000E+01	-1.58594143E+01	-2.69746857E+01	6.89430000E+00	5.88054611E+00	1.01375389E+00
12	75	113	7.83	2.56900000E+01	2.55741638E+00	2.31325836E+01	-2.77908000E+01	-9.32531538E+00	-1.84654846E+01
13	75	113	8.37	3.29650000E+01	8.48115906E+00	2.44838409E+01	2.11960000E+01	4.82447900E+00	1.63715210E+01
14	75	113	8.58	-1.44750000E+00	-1.39804099E+00	-4.94590066E-02	3.67358000E+01	9.36902449E+00	2.73667755E+01
15	75	113	9.47	6.04160000E+00	2.56597210E+00	3.47562790E+00	-4.05903000E+01	-1.18112167E+01	-2.87790833E+01
16	75	113	9.83	4.78496000E+01	1.33658811E+01	3.44837189E+01	-3.08260000E+00	-3.36648989E+00	2.83889890E-01
17	75	113	10.01	3.76379000E+01	1.15180880E+01	2.61198120E+01	1.74372000E+01	4.44582122E+00	1.29913788E+01
18	75	113	11.47	3.84182000E+01	1.54469323E+01	2.29712677E+01	-1.73580000E+01	2.16845703E-03	-1.73601685E+01
19	75	113	11.66	3.55744000E+01	1.41020184E+01	2.14723816E+01	1.23163000E+01	6.29104766E+00	6.02525234E+00
20	75	113	13.32	3.60052000E+01	1.64733854E+01	1.95318146E+01	2.33800000E-01	6.84024722E+00	-6.60644722E+00
21	75	113	16.35	-1.68990000E+00	1.16708225E+01	-1.33607225E+01	-3.14283000E+01	-9.07971296E+00	-2.23485870E+01
22	75	113	16.66	3.02181000E+01	1.90478396E+01	1.11702604E+01	-1.86776000E+01	-2.30603323E+00	-1.63715668E+01
23	75	113	17.44	-1.22223000E+01	-9.60815567E+00	-2.61414433E+00	-2.63740000E+00	-1.68956736E+00	-9.47832644E-01
24	75	113	18.31	3.71886000E+01	2.10655226E+01	1.61230774E+01	-3.08780000E+00	1.58109191E+00	-4.66889191E+00
25	75	113	19.08	1.39038000E+01	-5.90276433E+00	1.98065643E+01	6.06460000E+00	5.25384981E+00	8.10750186E-01
26	75	113	19.66	3.58190000E+01	9.51530432E+00	2.63036957E+01	-1.29548000E+01	-8.94072663E+00	-4.01407337E+00
27	75	113	19.70	4.86693000E+01	2.02728614E+01	2.83964386E+01	-7.67170000E+00	-4.97429991E+00	-2.69740009E+00
28	75	113	21.30	4.10416000E+01	9.29419399E+00	3.17474060E+01	9.87700000E-01	-1.20172515E+01	1.30049515E+01
29	75	113	22.18	-1.08660000E+00	7.36030990E+00	-8.44690990E+00	7.26220000E+00	1.11526982E+01	-3.89049816E+00
30	75	113	23.69	5.75080000E+00	1.80614356E+01	-1.23106356E+01	2.57270000E+00	1.23504348E+01	-9.77773476E+00
31	75	113	23.82	-3.46100000E+00	1.26945481E+01	-1.61555481E+01	1.42803000E+01	7.88569532E+00	6.39460468E+00
32	75	114	0.47	3.55056000E+01	5.25055176E-02	3.54530945E+01	2.52090000E+00	-2.80351616E+00	5.32441616E+00
33	75	114	1.36	-6.71990000E+00	2.07554723E+01	-2.74753723E+01	2.42020000E+00	1.14947249E+01	-9.07452488E+00
34	75	114	1.55	-1.61024000E+01	1.23935564E+01	-2.84959564E+01	1.57694000E+01	8.11879671E+00	7.65060329E+00
35	75	114	2.14	8.06530000E+00	5.37215245E-01	7.52808475E+00	1.11319000E+01	-1.96534140E+00	1.30972414E+01
36	75	114	3.03	-9.68210000E+00	2.33757461E+01	-3.30578461E+01	-6.20620000E+00	1.07556835E+01	-1.69618835E+01
37	75	114	3.17	-6.89240000E+00	1.59871013E+01	-2.28795013E+01	3.10500000E+00	1.30625157E+01	-9.95751572E+00
38	75	114	3.52	-1.76582000E+01	1.89575508E+00	-1.95539551E+01	6.73480000E+00	5.61315789E+00	1.12164211E+00
39	75	114	4.70	-6.10610000E+00	2.57738133E+01	-3.18799133E+01	-3.46430000E+00	1.02509729E+01	-1.37152729E+01
40	75	114	4.83	-1.99870000E+00	2.00356933E+01	-2.20343933E+01	2.14700000E+00	1.14294497E+01	-9.28244972E+00
41	75	114	5.35	-3.09870000E+00	8.51610707E-01	-3.95031071E+00	-1.34840000E+00	-2.11280567E+00	7.64405668E-01
42	75	114	6.37	1.80340000E+00	2.78050785E+01	-2.60016785E+01	-1.24750000E+00	1.00166602E+01	-1.12641602E+01
43	75	114	6.49	1.22199000E+01	2.39678916E+01	-1.17479916E+01	-7.26000000E+00	8.05206131E+00	-1.53120613E+01
44	75	114	7.00	1.57324000E+01	3.14558226E+00	1.25868177E+01	1.35655000E+01	4.87876103E+00	8.68673897E+00
45	75	114	8.13	2.96739000E+01	2.76203989E+01	2.05350113E+00	-7.69240000E+00	5.24556158E+00	-1.29379616E+01
46	75	114	9.23	1.06271000E+01	2.23673296E+01	-1.17402296E+01	-1.98471000E+01	-1.14185426E+01	-8.42855740E+00
47	75	114	9.59	3.68507000E+01	3.28237892E+01	6.02691078E+00	-9.54970000E+00	-3.46042178E+00	-6.08927822E+00
48	75	114	9.77	4.53936000E+01	3.08404222E+01	1.45531778E+01	-5.02250000E+00	4.37971500E+00	-9.40221500E+00
49	75	114	9.98	4.83641000E+01	2.23350015E+01	2.60290985E+01	3.45900000E-01	7.06050438E+00	-6.71460438E+00
50	75	114	11.23	2.16877000E+01	3.47597816E+01	-1.30720816E+01	-1.65062000E+01	-1.55644580E-01	-1.63505554E+01
51	75	114	11.42	2.23297000E+01	3.35386729E+01	-1.12089729E+01	-7.14600000E-01	5.94308719E+00	-6.65768719E+00
52	75	114	19.42	-5.57386000E+01	2.90764482E+01	-8.48150482E+01	1.52533000E+01	-8.56493730E+00	2.38182373E+01
53	75	114	21.06	-2.30893000E+01	2.95220892E+01	-5.26113892E+01	2.15293000E+01	-1.16522338E+01	3.31815338E+01
54	75	114	21.94	5.36722000E+01	2.57061661E+01	2.79660339E+01	-1.30074000E+01	1.16419530E+01	-2.46493530E+01
55	75	114	22.55	7.34282000E+01	1.91681597E+01	5.42600403E+01	2.85996000E+01	-3.81005271E+00	3.24096527E+01
56	75	114	23.59	6.62421000E+01	3.13929636E+01	3.48491364E+01	-1.90241000E+01	8.41178257E+00	-2.74358826E+01
57	75	114	23.67	7.16167000E+01	2.50337990E+01	4.65829010E+01	-5.97430000E+00	1.09186443E+01	-1.68929443E+01

Table C-2
Orbit Initial Conditions for 1975 Days 113 and 114

Cartesian Elements

System	Epoch			Frequency Offset (ppm)	$X(R_0)$	$Y(R_0)$	$Z(R_0)$	$\dot{X}(R_0/s)$	$\dot{Y}(R_0/s)$	$\dot{Z}(R_0/s)$
	yr	day	s							
True of Date	75	113	0	-50 014940	-0 4714078877	0 4278658466	0 9359088321	$1\ 17353858 \times 10^{-4}$	$1\ 07530042 \times 10^{-3}$	$-4\ 31526935 \times 10^{-4}$
Mean of 1950	75	113	0	-50 014944	-0 4666234493	0 4305314782	0 9370831834	$1\ 22430225 \times 10^{-4}$	$1\ 07462273 \times 10^{-3}$	$-4\ 31804916 \times 10^{-4}$

Osculating Kepler Elements

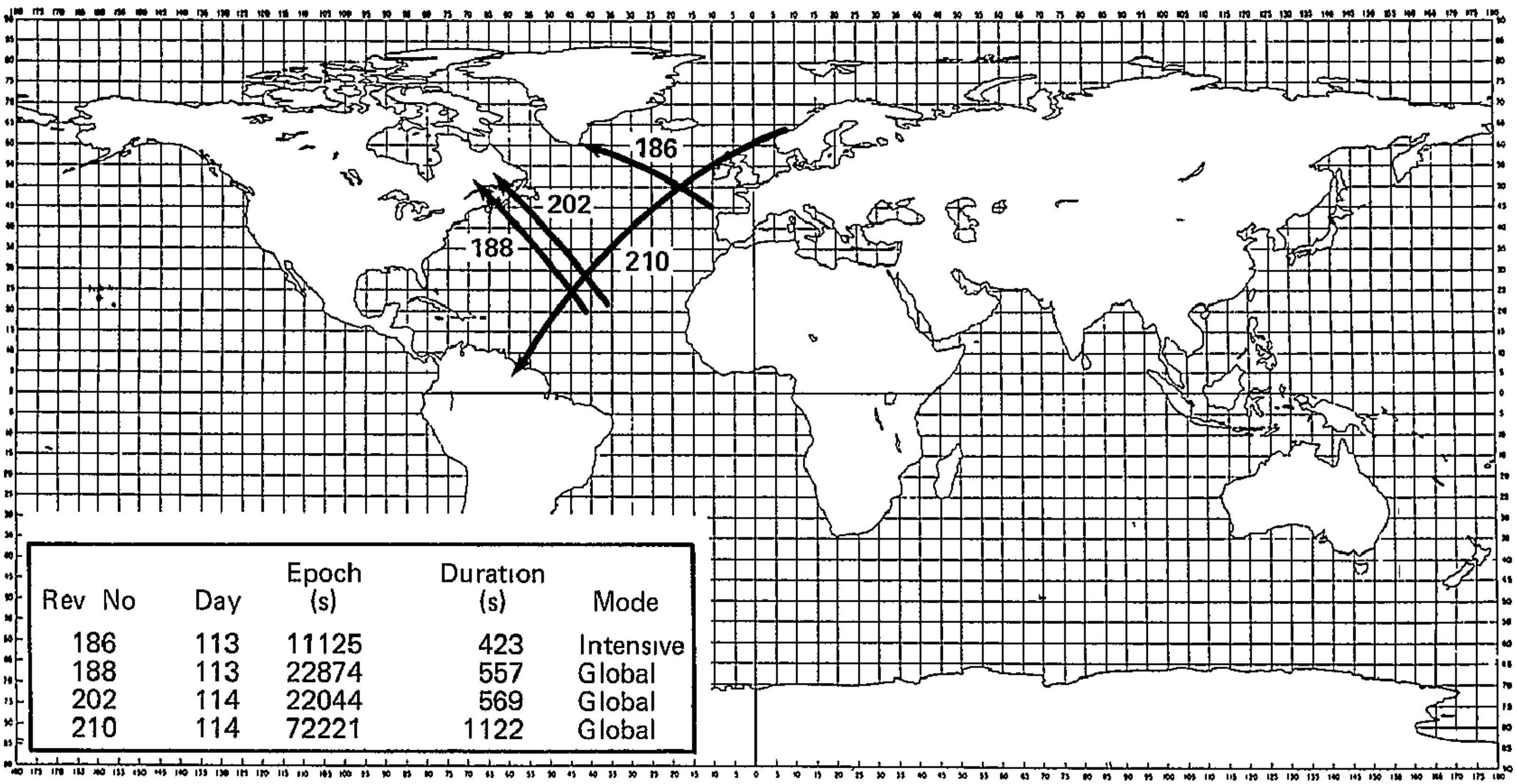
System	Epoch			Frequency Offset (ppm)	$a\ (R_0)$	e	i (rad)	Ω (rad)	ω (rad)	M (rad)
	yr	day	s							
True of Date	75	113	0	-50 014940	1 1311360913	$9\ 626921 \times 10^{-4}$	2 0071447851	-1 4923754406	-0 3691128899	2 3604258925
Mean of 1950	75	113	0	-50 014944	1 1311360831	$9\ 626608 \times 10^{-4}$	2 0046664192	-1 4981923442	-0 369150506	2 3603359058

Table C-3

Doppler Data Navigation Results, 1975 Days 115 and 116

Yr	Day	S	ECA (m)	ECR (m)	Elev (deg)	Sta	SAT	Az (m)	Pass*	Weight code**
75	115	798.014	15.2004	6.0152	22.627	019	01175	348.601	S	
75	115	3530.615	-0.6278	17.5090	38.987	016	01175	30.947		
75	115	4014.102	3.9754	-1.1496	22.367	018	01175	153.000	S	
75	115	4744.896	-0.1605	2.9030	47.011	103	01175	307.374	S	
75	115	9440.322	-2.1865	7.6714	68.874	016	01175	230.073		
75	115	10530.797	5.7162	3.0434	11.486	014	01175	109.822	S	
75	115	18412.387	-9.3113	2.2975	32.840	112	01175	131.795	S	
75	115	21744.138	-6.8896	-9.2543	12.773	111	01175	32.016		
75	115	22047.073	0.9090	-4.1358	17.905	018	01175	221.043		
75	115	22484.461	2.0954	-1.1593	86.196	014	01175	149.809	S	
75	115	26476.453	-13.4598	-9.6019	23.002	008	01175	64.503		
75	115	27607.428	5.3035	-12.1758	52.899	111	01175	49.583		σ
75	115	28402.948	13.2030	-5.5835	62.256	014	01175	351.634	S	
75	115	32392.862	-18.2674	-5.5841	39.400	008	01175	235.580		
75	115	33670.564	-7.2624	-8.5898	23.936	103	01175	47.121		
75	115	39483.652	7.1359	17.5189	27.209	192	01175	244.199		σ
75	115	40235.232	-12.4370	6.1391	74.715	014	01175	214.181		
75	115	46196.680	-11.4348	11.3906	29.662	014	01175	234.427		
75	115	63033.772	3.4257	-5.1437	19.914	024	01175	235.858		
75	115	64172.553	-1.4738	7.2306	79.824	027	01175	235.683		
75	115	65575.475	-13.9241	16.0229	46.830	016	01175	124.983	S	
75	115	66964.207	19.5520	-25.2495	62.396	008	01175	122.256	S	σ
75	115	69036.257	3.0134	-3.7412	16.165	112	01175	67.069		
75	115	69916.232	5.3944	0.4843	33.833	022	01175	57.653		
75	115	71500.297	-0.7042	7.9524	50.987	016	01175	323.662	S	
75	115	72889.343	10.8657	0.9739	14.024	008	01175	294.026	S	
75	115	74974.446	12.2847	-0.7633	70.947	112	01175	234.622		
75	115	78109.674	76.2159	-103.7481	16.346	111	01175	112.600	S	σ,N
75	115	83222.289	20.9296	13.9758	20.505	016	01175	5.506		
75	115	84352.379	21.9030	4.5615	14.902	103	01175	112.766	S	
75	116	2679.568	7.6120	17.0523	32.666	016	01175	26.591		
75	116	3534.739	13.8502	-5.9323	17.581	111	01175	323.465	S	
75	116	9144.637	9.3029	-1.0610	26.004	018	01175	170.768	S	
75	116	9644.969	−10.7712	-1.4874	7.897	014	01175	105.420	S	E
75	116	10961.693	10.6851	-2.2729	43.427	024	01175	121.336	S	
75	116	14532.749	2.8076	2.9460	22.248	016	01175	243.871		
75	116	15659.820	1.8151	5.1236	29.728	014	01175	125.555	S	
75	116	17563.215	9.7290	-5.6689	23.268	112	01175	135.214	S	
75	116	21621.147	-11.4475	0.5224	74.743	014	01175	145.839	S	
75	116	23460.640	8.4700	-1.7268	59.960	112	01175	300.753	S	
75	116	28296.261	13.4423	5.6189	34.687	027	01175	117.890	S	
75	116	31537.829	-4.4090	-1.8914	62.975	008	01175	237.804		σ
75	116	33453.258	-11.8109	-5.5626	62.263	014	01175	8.469		
75	116	38710.258	-15.8013	1.8552	80.660	103	01175	238.216		
75	116	39371.833	-19.5112	1.3082	86.173	014	01175	209.931		
75	116	40068.778	-94.0184	80.7960	10.403	027	01175	331.026	S	σ,N
75	116	56272.202	-5.0475	16.6241	24.804	024	01175	63.323		
75	116	57437.656	-34.0555	21.3722	16.098	027	01175	35.402		σ
75	116	62942.475	-43.0929	-2.3402	17.957	023	01175	55.805		
75	116	64706.731	-32.9910	11.7104	34.309	016	01175	121.190	S	
75	116	66109.339	-7.3378	-55.0369	39.134	008	01175	124.498	S	σ
75	116	68165.251	-24.9579	-5.3136	9.390	112	01175	69.516		
75	116	70644.019	-21.4031	2.2751	64.756	016	01175	319.543	S	
75	116	77236.423	-24.0099	-10.6629	9.861	111	01175	109.774	S	
75	116	80003.803	-5.1451	3.0100	18.755	112	01175	222.557		
75	116	83194.594	3.6854	-2.1849	71.602	111	01175	123.229	S	

*Pass direction = S - south going, otherwise a north going pass
**Pass weight < 0 2 due to N navigation weight, σ noise weight, E - elevation weight



Rev No	Day	Epoch (s)	Duration (s)	Mode
186	113	11125	423	Intensive
188	113	22874	557	Global
202	114	22044	569	Global
210	114	72221	1122	Global

Fig C-1 GEOS-3 Spatial Distribution of Altimeter Data, 1975 Days 113 to 114

Doppler Sites

008	Sao Jose Dos Campos	024	Tafuna
014	Anchorage, AK	027	Mizusawa
016	Barton Stacey	103	Las Cruces
018	Thule	111	Maryland
019	McMurdo	112	Smithfield
022	San Miguel	192	Austin, TX

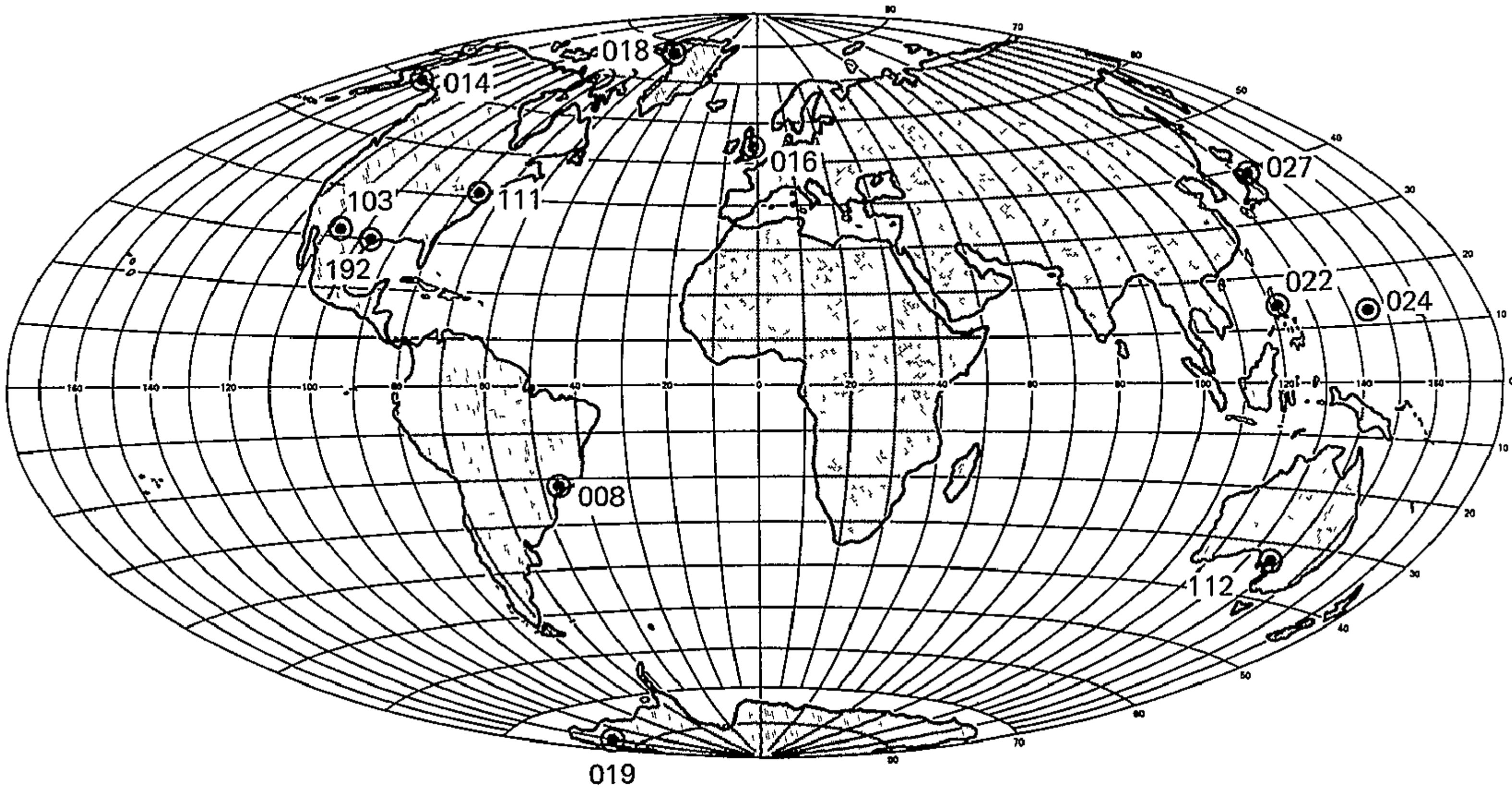


Fig C-2 Doppler Tracking Sites, 1975 Days 115 and 116

C-Band Sites		Laser Sites	
4260	Pillar Point	7063	Greenbelt, MD
4281	Canton Island	7068	Grand Turk, BWI
4282	Kaena Pt, HA		
4610	Ely, NV		
4760	Bermuda		
4840	Wallops Island, VA		
4860	Wallops Island, VA		

No data available from Station 4741
Data from stations 4281, 4282, 4260 deleted from track

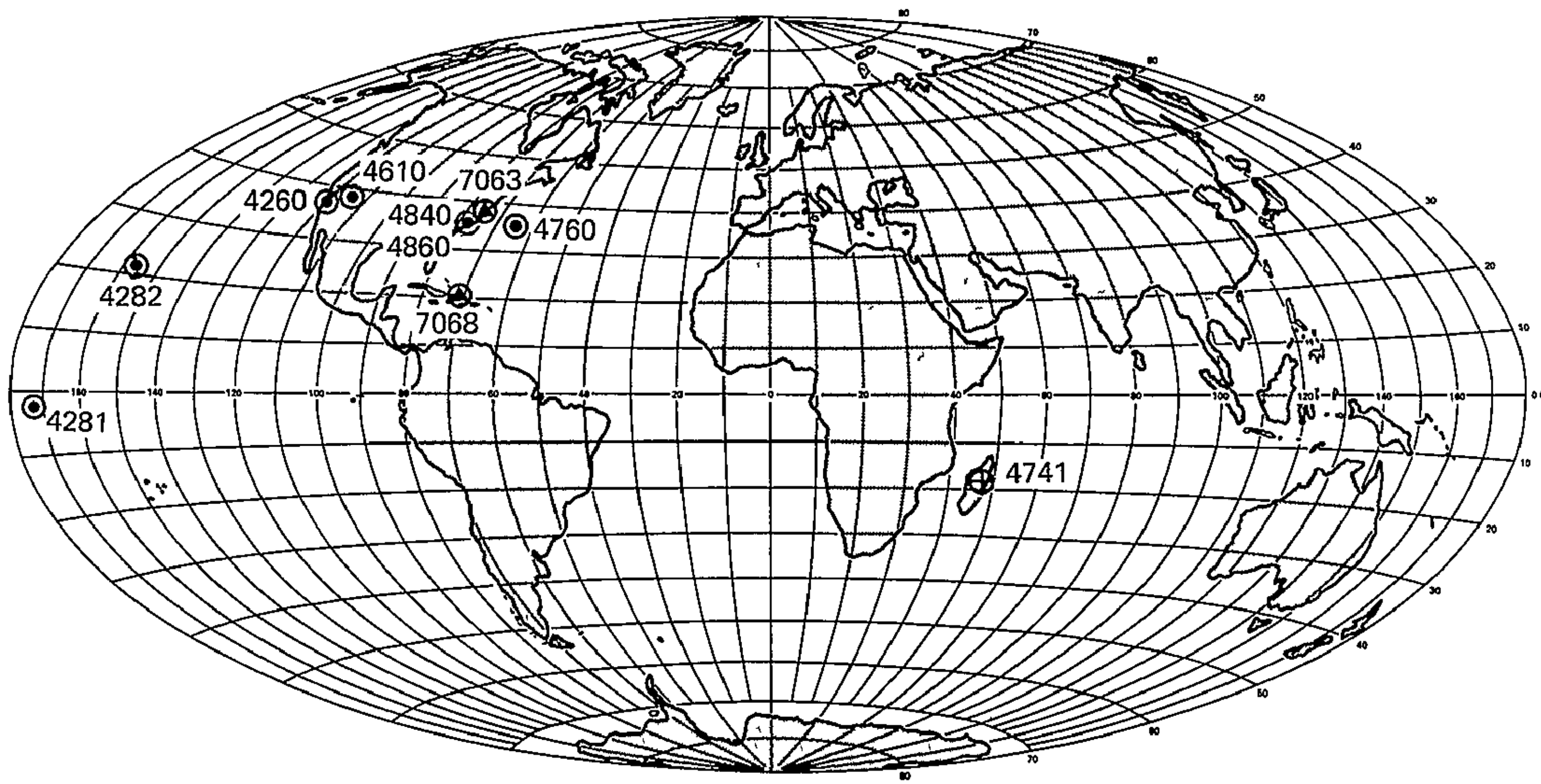
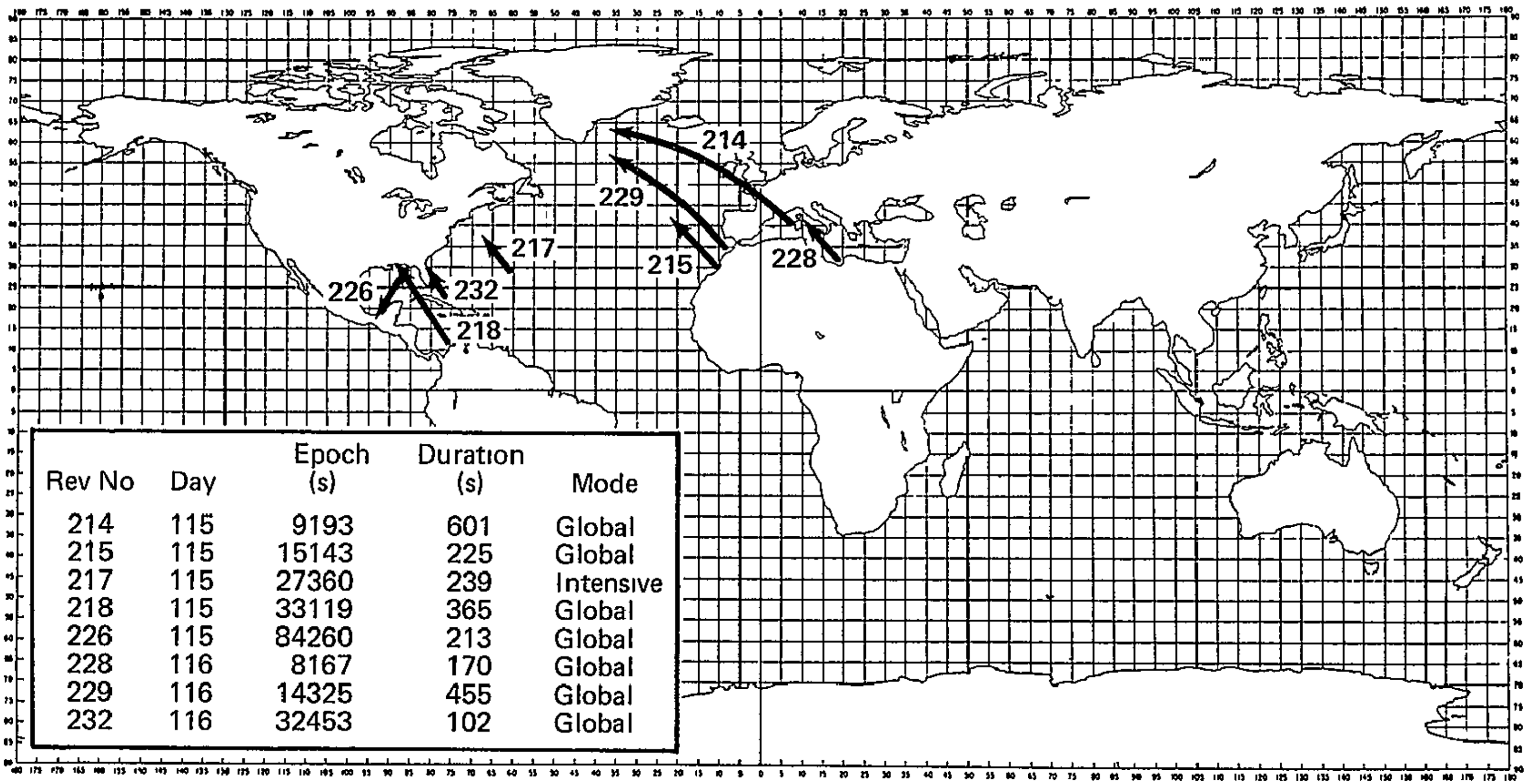


Fig C-3 C-Band and Laser Tracking Sites, 1975 Days 115 and 116



Rev No	Day	Epoch (s)	Duration (s)	Mode
214	115	9193	601	Global
215	115	15143	225	Global
217	115	27360	239	Intensive
218	115	33119	365	Global
226	115	84260	213	Global
228	116	8167	170	Global
229	116	14325	455	Global
232	116	32453	102	Global

Fig C-4 GEOS-3 Spatial Distribution of Altimeter Data, 1975 Days 115 and 116

Appendix D
ORBIT DETERMINATION WITH GEM-9 USING 1976 DATA (SUPPLEMENTARY MATERIAL FOR SECTION 6.0)

Table D-1
GEM-9 Station Coordinates

Station No	Data Type	Location	Geocentric Coordinates		
			Latitude (rad)	Longitude (rad)	Radius (R_0)
4150	CBD	Green River, UT	0 677030269	-1 92180161	0.99888036
4198	CBD	White Sands, NM	0.56284717	-1 85686156	0 99922445
4280	CBD	Vandenburg AFB, CA	0.601896824	-2.104544838	0 99893066
4446	CBD	Pt Mugu, CA	0.592443649	-2.079644113	0 99894376
4452	CBD	Makaha Ridge, HA	0.383952408	-2 787751009	0.99960360
4742	CBD	Kauai, HA	0 383792592	-2.786692272	0 99970751
4760	CBD	Bermuda	0.561548061	-1.128416818	0 99904014
4840	CBD	Wallops, VA	0.657206826	-1 31746335	0.99873676
4860	CBD	Wallops, VA	0.657537954	-1.317889779	0 99873755
4958	CBD	Kwajalein Island	0.15121800	2 927379589	0 99992056
4959	CBD	Kwajalein Island	0 151217425	2.927379927	0 99991770
4960	CBD	Wettzel, West Germany	0 854418728	0.224758355	0 99818780
7067	LSR	Bermuda	0.5616506724	-1 12846300	0 999038305
7068	LSR	Guantanamo, Cuba	0 3722772268	-1.241486555	0 9995476591
7069	LSR	Patrick AFB, FL	0.489878977	-1 40683607	0 99924733
008	DOP	Sao Jose Dos Campos, Brazil	0.40279387	-0 80057775	0 99957400
014	DOP	Anchorage, AK	1.06675988	-2 61494325	0 997434527
018	DOP	Thule, Greenland	1.33433035	-1.20023599	0 99683783
019	DOP	Mcmurdo, Antarctica	-1.3573110	2 90900804	0 99678968
103	DOP	Las Cruces, NM	0.56034612	-1.86320747	0 99922999
111	DOP	Howard County, MD	0.680244373	-1.34210217	0 998682741
112	DOP	Smithfield, Australia	-0.60203483	2 41998025	0 99892193

R_0 = 6378.166 km, used for scale length only, no physical significance

Table D-2

Initial Conditions for Base Ephemerides

Span	Epoch			Position (R_0)			Velocity ($\bar{R}_0$/ks)			Satellite Frequency Offset (Hz/MHz)	Altimeter	
	yr	day	s	X	Y	Z	X	Y	Z		Bias (m)	Drift (m/day)
1	1976	62	0	-0 7570435916	-0 3521877288	-0 7640123509	0 3047283166	0 8776691387	-0 7030347347	-50 00491	6 3	0 8
2	1976	64	0	0 4079978211	0 9593416780	-0 4377777760	0 6494182970	0 1614902816	0 9556182991	-50 00474	3 2	2 04

Span	Epoch			Osculations Kepler Elements					
	yr	day	s	a(R_0)	e	i(rad)	Ω(rad)	ω(rad)	M(rad)
1	1976	62	0	1 1317919153	0 002024954992	2 0070065633	0 87611017645	-0 7452598993	-1 5520266718
2	1976	64	0	1 132662435	0 002099181105	2 0068392904	0 9717403124	-1 0310177288	0 5873504511

R_0 = 6378 166 km

Table D-3

Doppler Navigation Results (base run)

Span 1

YR	DAY	SEC	NAV-ERR(M) ECA	ECR	ELEV (DEG)	STA	SAT	AZY (DEG)	HD	DELETION CODE*
76	62	3710 171	-6 0883	-2 9105	30 685	014	01175	233 887		
76	62	9223 265	-11 4466	-1 4775	8 378	014	01175	254 031		
76	62	12234.873	0 0000	0 0000	3 177	105	01175	140.544	S	E
76	62	18219 729	-3.8167	0 5406	6 496	008	01175	134 942	S	E
76	62	24086 024	2 3532	1 1551	59 291	008	01175	122 746	S	
76	62	26150.096	11 3368	-5.6964	15 088	112	01175	67 398		
76	62	30010 251	6 0909	1 8057	14.870	008	01175	294 112	S	
76	62	31393.978	-3 4391	-1 3347	16 271	019	01175	39 802		
76	62	32090 149	-1 0933	3 2251	73 916	112	01175	234 615		
76	62	35228 181	-1.7431	4.3590	15 634	111	01175	112 350	S	
76	62	37418 926	-0 5374	-4 2817	21 527	019	01175	16 879		
76	62	37965 515	-6 2081	-6 7654	13 546	112	01175	219 226		σ
76	62	40615.738	0 9119	-1 4063	13 313	018	01175	124.689	S	
76	62	41174 056	-1 9050	0 4100	82 636	111	01175	306 312	S	
76	62	41471 977	-0 9755	-0 1395	14 335	103	01175	112 581	S	
76	62	43434 075	8 0308	-6 5991	22 745	019	01175	354 038	S	
76	62	46647 358	1 8459	2 0898	21 098	018	01175	147 547	S	σ
76	62	47054 648	1.8371	-3 9158	18 454	111	01175	323 025	S	
76	62	47408.731	2 6162	0 5252	74 908	103	01175	304 093	S	
76	62	49452.686	7 6164	0.1130	19 185	019	01175	331 168	S	
76	62	52658 774	-3 0364	-3 8239	26 308	018	01175	170 214	S	
76	62	53160 197	4.1806	-3 1587	7 784	014	01175	104 967	S	E
76	62	53281 976	-1.0403	1 4010	12 698	103	01175	319 015	S	
76	62	55487 769	10 4847	-12 9502	12 858	019	01175	308 131	S	σ
76	62	58663 813	-4 8918	-0 2917	25 844	018	01175	192 845		
76	62	59175.996	-10.0877	3 0250	29.410	014	01175	125 106	S	
76	62	61085.078	-8.0727	-4 5455	22.269	112	01175	135 651	S	
76	62	61551 450	374 4979	-153.1214	6 123	019	01175	284.573	S	E,σ
76	62	63021 558	0 0000	0 0000	2 694	105	01175	69 371		E
76	62	64677 115	6 7570	-0 3661	20 024	018	01175	215 537		
76	62	65137 630	6.7428	9.0687	73 691	014	01175	145.168	S	
76	62	66981.195	8 3364	1.1033	62 649	112	01175	300 796	S	
76	62	69125.546	6.0226	-1 2853	12 713	008	01175	66.226		
76	62	70268 442	-0 4953	1.6262	36 267	111	01175	45 786		
76	62	70712 506	-2 8576	-4 4223	12 132	018	01175	238 456		
76	62	71061.449	1.3051	0 3685	66 518	014	01175	346 660	S	
76	62	72937 644	-54.3641	7 3299	6 468	112	01175	289 150	S	E,σ
76	62	75052 594	0.8344	2 6103	66 150	008	01175	237 858		
76	62	76183 088	-1 6550	-1 7442	40 662	111	01175	240 812		
76	62	76339 423	630 4033	-1073 2595	16 173	103	01175	43 372		σ
76	62	76968.931	2.6854	-0.7542	62 285	014	01175	8.117		
76	62	76782 583	0 0000	0 0000	4.650	018	01175	262.037		E
76	62	80523 718	-954 2983	337 2011	7 400	008	01175	225 876		E,σ
76	62	82223 542	1 5861	0 5158	84.348	103	01175	236 878		
76	62	82886 328	2 0304	-2 3120	87 404	014	01175	208 195		
76	63	1768.576	-3.3838	0 3180	9 719	103	01175	248 837		
76	63	2436 568	-0.7010	-1 5546	38 187	014	01175	229 503		
76	63	8436 901	0 4027	-2.3435	12.036	014	01175	249 628		
76	63	23230.419	-2 4368	1 5582	37 237	008	01175	124 840	S	
76	63	25277 746	-1 9409	-1 9242	8 540	112	01175	69.838		
76	63	30507 810	-5 0352	-1 5282	14 850	019	01175	44 788		
76	63	31229 913	-10.0108	0 5611	74 460	112	01175	57 823		
76	63	36536 595	-2 5728	0 9082	20 650	019	01175	21.819		
76	63	37120 526	-2 7514	0 1892	19 131	112	01175	222.935		
76	63	39726 711	-0 0067	-3 5574	11 593	018	01175	119 682	S	
76	63	40600 362	5 0683	0 4640	7.832	103	01175	110 367	S	E
76	63	42552 743	-2.5470	7.0803	22.909	019	01175	358 972	S	
76	63	45764.512	1.2110	0 4483	19 510	018	01175	142 628	S	
76	63	46548 744	-2 5617	1 2115	73.006	103	01175	121 358	S	
76	63	48569.446	5.0757	0.2530	20 282	019	01175	336.125	S	
76	63	51779.127	-0.6910	-5 5506	25 584	018	01175	165 318	S	
76	63	52437.679	1 7699	-1 2066	18.633	103	01175	315 433	S	
76	63	54599 893	-4.8621	3 4681	14 324	019	01175	313 147	S	
76	63	57784 334	-1 7302	-5 7558	20 481	018	01175	187 958		
76	63	58259.470	-4 1677	-1 4986	23 355	014	01175	120 774	S	
76	63	60238.778	-10.0150	0 4702	15 859	112	01175	139 269	S	
76	63	60656.456	11 7715	5 2865	7.535	019	01175	289 737	S	E
76	63	62151 778	0.0000	0.0000	-1 991	105	01175	70 807		E
76	63	63794.630	4 1324	0 1305	21 580	018	01175	210 627		
76	63	63586 566	-3.3653	-6 7318	7 028	111	01175	22 847		E
76	63	64271 549	3 5899	2 4369	62 116	014	01175	140 873	S	
76	63	66119 739	0 1329	2.8535	86.849	112	01175	125 876	S	
76	63	68259 097	98 6631	10 4941	6.153	008	01175	67.574		E
76	63	69417 590	2 7438	-8 7604	26 590	111	01175	42 073		
76	63	69824.121	-3 9858	15 5379	13 859	018	01175	233 466		
76	63	70202.032	1 8188	0 7358	71.902	014	01175	341 968	S	
76	63	72064.410	-4 6758	-1 7400	12 439	112	01175	291 564	S	
76	63	74193.736	-0 2217	-0 3840	77 914	008	01175	60 238		
76	63	75317 856	1 1004	-0 4254	61 010	111	01175	237.661		
76	63	75496 353	0 0000	0 0000	11 044	103	01175	39 705		E
76	63	76110 901	4 1015	0 6271	60 556	014	01175	3 366		
76	63	75885 665	-6.1479	-8 3861	6 174	018	01175	256.848		E
76	63	80080 018	-6.6185	0 3387	12 822	008	01175	228 935		
76	63	81364 451	3 7344	1 1330	64 374	103	01175	55 069		
76	63	81286 888	-16 4166	2 1649	7 601	111	01175	251 291		E
76	63	82023 782	2 9850	-0 0076	82 676	014	01175	25.303		

SUMMARY (66 Passes) - 31 ± 4 65 - 39 ± 3 22

*σ – Deleted for post-navigation residuals
E – Deleted for low elevation
(20 Passes Deleted)

Table D-4

Doppler Navigation Results (base run)

Span 2

YR	DAY	SEC	NAV-ERR (M) ECA	ECR	ELEV (DEG)	STA	SAT	AZY (DEG)	HD	DELETION CODE*
76	64	898.010	-4 2305	0 1855	16.811	103	01175	246.583		
76	64	1565 446	1 0600	-1.3724	47 109	014	01175	225 161		
76	64	7553.619	6.7481	-2 3464	16 194	014	01175	245 267		
76	64	26281 716	-1 1581	-4 6625	39 686	008	01175	297.255	S	
76	64	29620.454	7.3415	-1 6056	13 389	019	01175	44.794		
76	64	30366.636	0.3469	-0.6658	48.161	112	01175	60.627		
76	64	33476.748	0.0000	0.0000	4.299	111	01175	106 726	S	E
76	64	35653.618	1.4298	3 3594	19.603	019	01175	26 779		
76	64	36271 961	0 1048	2 2784	26.929	112	01175	226 449		
76	64	38836 036	-5.2080	7 7009	9 903	018	01175	114.648	S	
76	64	39448 462	79.5668	25.1764	46 228	111	01175	120 016	S	σ
76	64	41671.402	-0.4959	5.6764	22.832	019	01175	3.918		
76	64	44880 528	-3.1080	0 3629	17.843	018	01175	137 695	S	
76	64	45686.097	-2.6708	-5.0834	46.901	103	01175	118.825	S	
76	64	47686.900	5 7162	-5 1480	21.221	019	01175	341 069	S	
76	64	50899.004	-2 9403	-6 6441	24 607	018	01175	160 408	S	
76	64	51569.641	1 3523	-3.2993	26 623	103	01175	312.056	S	
76	64	53713.272	2.0456	0.1604	15.758	019	01175	318.140	S	
76	64	56905.029	1.6025	-4.7623	26.630	018	01175	163.048		
76	64	57420 300	1.3551	-3 9651	18 226	014	01175	116.445	S	
76	64	59396.208	4.6368	-2.7039	11 111	112	01175	143 106	S	
76	64	59763.197	-15.2780	6.8909	8 980	019	01175	294.862	S	
76	64	62913.012	1.8758	0.7697	23.008	018	01175	205 710		
76	64	63403.571	2.5948	0.9942	51.302	014	01175	136 559	S	
76	64	65261 312	5.3736	1.1339	58.452	112	01175	127 099	S	
76	64	68570 076	96.7164	16.3243	19.889	111	01175	38 210		σ
76	64	68937.214	-8.6007	-1 4475	15.597	018	01175	228.491		
76	64	69341.474	-0.2447	0 0028	79.180	014	01175	337.554	S	
76	64	71193.573	1.0076	1.0267	20 172	112	01175	294.034	S	
76	64	73332.436	-3 7674	1 0621	47.503	008	01175	62.093		
76	64	74455 506	0 0000	0 0000	88 733	111	01175	228 774		P
76	64	74455.656	1 4182	0.4046	68.738	111	01175	232.263		
76	64	74990.830	-4.4870	-3.0063	7.757	018	01175	251.715		E
76	64	75252.921	0.7952	-2.4154	60.273	014	01175	358.773	S	
76	64	79232.337	0.6796	2.8418	20.174	008	01175	231.740		
76	64	80508 441	-3 4698	1.4354	42 518	103	01175	52 042		
76	64	81162.705	-6 5407	0 6680	74 600	014	01175	20.417		
76	65	29 662	0.0000	0 0000	28.728	103	01175	241 749		P
76	65	696.476	-4 4034	-0.6797	57.458	014	01175	220 753		
76	65	6673.232	4.3422	-3 9317	21.001	014	01175	240.917		
76	65	15536 364	0 0000	0.0000	10.040	105	01175	134.838	S	E
76	65	21529 126	-3.6943	-4.5955	15.628	008	01175	130 010	S	
76	65	27419.944	-0.3903	-2 7095	64.975	008	01175	298.974	S	
76	65	29500.726	2.1920	-1.4932	31.194	112	01175	63.293		
76	65	34770.006	-4.9408	0.9415	18.416	019	01175	31.732		
76	65	35419.973	-3.6635	0 1571	38.614	112	01175	229.780		
76	65	37943.032	6 5621	-1.9937	6.255	018	01175	109 577	S	
76	65	38581.474	-1 2964	6.6736	31.030	111	01175	117.058	S	
76	65	40790 014	-9.0769	1.1209	22.514	019	01175	6 859		
76	65	41268.938	0.0000	0.0000	7 199	112	01175	212 756		E
76	65	43995 382	-10 3459	6.7571	16.129	018	01175	132.754	S	
76	65	44820.894	0.3231	-1.2175	30 218	103	01175	116 362	S	
76	65	46804 857	9.5186	-7.2057	21 973	019	01175	346.020	S	
76	65	50018.402	2.3673	2 1878	23 410	018	01175	155.516	S	
76	65	50361.435	34.4790	20.6415	11.691	111	01175	329.719	S	
76	65	50738.065	-2.5063	-0.1769	38.605	103	01175	308.871	S	σ
76	65	52827.804	-3.1305	-2.6262	17.134	019	01175	323.116	S	
76	65	56025 890	4.4680	3.0467	26 877	018	01175	178 152	S	
76	65	56538 316	-3.2176	5 4553	13.817	014	01175	112.099	S	
76	65	58557.357	0.1177	-6.1802	7.451	112	01175	147.147	S	E
76	65	58871 630	0.8267	2 5137	10 449	019	01175	299.945	S	
76	65	62032.216	3.2229	1.9822	24 266	018	01175	200 806		
76	65	64406.063	1.0814	-0.0208	39.476	112	01175	130.179	S	
76	65	67725.882	6 3146	1 2977	15.001	111	01175	34 189		
76	65	68051 754	5 0836	-1 5342	17 322	018	01175	223.544		
76	65	70325.169	-0 9799	1.6843	31 055	112	01175	296.583	S	
76	65	72469.467	-0.0357	0.0089	29.164	008	01175	63.747		
76	65	73596.429	-1.3319	-0.1427	64.077	111	01175	51 470		
76	65	74097 936	-8.2516	-4 5044	9.391	018	01175	246 627		
76	65	78381 018	2 9498	3 4399	31 067	008	01175	234.293		
76	65	79533 216	-1 0354	0.6850	21 128	111	01175	245 599		
76	65	79655.862	3.1395	0.7759	24.032	103	01175	48.859		
76	65	80362.987	1.0122	1.1616	68.465	014	01175	15.504		
76	65	85563 673	78382.2246	59501.7714	41 300	103	01175	241 768		σ
76	65	86229.479	-1 1299	4.2051	68.861	014	01175	216.184		

SUMMARY (64 Passes) 32 ± 6 23 39 ± 4 11

*σ — Deleted for post-navigation residuals

E — Deleted for low elevation

T — Could not locate tca

P — Too few points survived navigation

(11 Passes Deleted)

Table D-5

C-Band Navigation Results (base run)
Span 1

YR	DAY	SEC	FCA(M)	ELR(M)	ELV	STA	SAT	AZY	N/S	RANGE BIAS (m)	RANGE DRIFT (km/day)	RESIDUALS	DELETION CODE *
76	62	47340.633	3.2075	0 1545	58.495	4150	750270	121.788	S	-1 904	001	1 727	
76	62	53241.853	-4.0496	0.0391	27.549	4150	750270	-42 549	S	3 742	317	2 250	
76	62	76447.315	-3.4774	-2 3537	22.273	4150	750270	40.408		- .886	1 830	2 616	D
76	62	82340.030	0.1517	-0.1446	73.372	4150	750270	-123.933		1 425	202	1.793	
76	63	46475 240	-1.6816	1.4320	37.169	4150	750270	118.745	S	- 146	- 837	1 882	
76	63	52390.770	-1.8019	-3 0764	37.707	4150	750270	-46.201	S	220	933	1 957	D
76	63	81479.658	4.3066	1.6341	77 637	4150	750270	53.676		-2 227	- 216	1 852	
76	62	47403.949	2.3519	-0.9569	73.537	4198	750270	-55.759	S	-5 238	- 098	1.289	
76	62	62222.766	-0.7492	0.3367	81.521	4198	750270	-122.905		-3 054	377	910	
76	63	46544 129	-3 1695	1.0341	74.482	4198	750270	121.645	S	-5 486	367	1 316	
76	63	81363.445	3.2471	0.0555	66.812	4198	750270	55.324		-5 341	074	1 333	
76	63	46604 479	-3 9655	-1.5157	71.672	4280	750270	114.476	S	2 205	- 536	1 203	
76	63	52534 272	-1 9573	0.1035	55.601	4280	750270	-52.676	S	3.958	- 007	1 089	
76	63	81514.183	-2.7227	-2.7623	28.553	4280	750270	46.955		-1 852	939	1.111	D
76	62	47471.363	-0.5466	-3.3276	38.063	4446	750270	117.839	S	827	.283	1.163	
76	62	82347.265	-2.7273	-1.6783	43.512	4446	750270	51.149		-1 341	.957	1 476	D
76	63	46604.420	-6.7601	1.5395	24 349	4446	750270	115.278	S	-4 076	1 597	1 869	D
76	63	81494 445	1.6617	-2.0355	30.387	4446	750270	47 872		-3.430	067	1 386	
76	62	8773.685	-2 3176	3.1119	71.013	4452	750270	58.923		-8 962	- 788	1 393	
76	63	7917.017	-3 0931	-2 0942	43.963	4452	750270	56.608		-7.769	420	1 554	
76	63	13835.232	-6.6146	1.0044	19.950	4452	750270	-115.235		-13 505	- 075	1 683	
76	63	58923.261	-4.0709	1.7972	78.351	4452	750270	-59.201	S	-5 648	- 405	1 294	
76	62	82381.554	1.3757	-0.6394	31.820	4610	750270	54.281		377	031	.869	
76	63	46500.449	0 9177	4.4776	26.745	4610	750270	115.988	S	- 630	- .061	.993	
76	63	52427.498	2.1980	-4.7711	52 701	4610	750270	-49.375	S	-1 369	.116	926	
76	63	81523 283	3.3604	0 5111	56.359	4610	750270	50.326		-2 746	236	1 080	
76	62	8773.068	-5.8423	-0.5817	71.337	4742	750270	58.963		-8.533	- .078	831	
76	62	59779.863	-5.9345	-4.8352	48 517	4742	750270	-56.947	S	.516	170	1.879	
76	63	13834.683	-7.1555	1.0568	19.829	4742	750270	-115.221		-2 014	.340	1 167	
76	63	58922.872	-4.9742	3.3294	77.911	4742	750270	-59.074	S	-8.743	- 074	.994	
76	62	35256.867	2.7268	4.3721	56.932	4760	750270	119.950	S	-5 631	- 582	1.075	
76	62	41154.349	-1.2198	-2.3565	22.898	4760	750270	-46.475	S	-3 590	348	.992	
76	62	70077.756	1.8485	1.3406	51 134	4760	750270	53.374		-5 385	474	.943	
76	62	76004 623	0.1595	2.4351	21.795	4760	750270	-114.697		-4.070	.128	.946	
76	63	34392.679	-0.9855	0.8759	36.534	4760	750270	117.421	S	-2.605	- .259	871	
76	63	40304.186	-0.5802	-2.7411	32.869	4760	750270	-49.738	S	-2.406	- .031	875	
76	63	69223 558	1.8744	-2.6650	34.402	4760	750270	50.269		-3 247	077	.804	
76	63	75137.525	2.4890	0.2195	33 907	4760	750270	-117.107		-2 597	.326	.914	
76	62	70240.227	2.2136	-2.4017	35.806	4840	750270	46.741		-4 951	939	1.617	D
76	62	76154.690	-1.5213	5.0212	39.202	4840	750270	-118.687		-1 462	1 240	1.602	D
76	63	40320.838	1.1860	1.8218	81.977	4840	750270	124.183	S	-5 017	.390	1.652	
76	63	46208 416	-2.0687	-2 3755	20.460	4840	750270	-39.998	S	-2.646	1.245	1.535	D
76	63	69389.865	-0.4378	2.1560	25.957	4860	750270	43 106		-11.649	-4.921	3 423	B,D,σ
76	63	75269.960	-7.3171	-4.1427	59 397	4860	750270	-121.751		-9.127	-2 231	3.062	B,D,σ
76	62	20656.579	-0.2550	3.3624	44.475	4958	750270	-118.052		-382 805	16 223	2 484	D
76	62	66134.938	16.0524	7.4557	43.409	4958	750270	-59 929	S	-382 191	11 173	2.573	D
76	63	19797.453	-10.0076	12.9902	75.966	4958	750270	-118.856		-388 009	12 841	1 932	D
76	62	14755.330	-0.0594	-25.3722	17.126	4959	750270	57.572		409.407	13 467	2.390	D
76	62	20656.596	0.1698	2.8550	44 476	4959	750270	-118.043		386.234	14.583	3 038	D,σ
76	62	66134 938	8.1973	10 2269	43.410	4959	750270	-59.929	S	381.768	12.328	2.260	D
76	63	19797.371	-14.3111	16.8738	75 966	4959	750270	-119.025		384 861	12 718	3 211	D,σ
76	62	28507.417	10 6564	1.2398	26 363	4960	750270	-25 636	S	-9 878	- 159	448	
76	62	34350.332	-11.8369	-3.6980	16 570	4960	750270	-4.451	S	5 856	3 100	1.870	D
76	62	40184.990	1.7341	-3.1592	20.161	4960	750270	17.137		5 332	- .510	2 145	
76	62	46050 403	5.3930	2.2505	44.992	4960	750270	37.374		1 034	- 220	1.518	
76	62	51969.662	-3.4556	5.3730	49 757	4960	750270	-124.655		3 514	086	1.543	
76	63	15303.964	-16.0393	7 1202	19.046	4960	750270	113.930	S	-6 101	1 309	2 131	D
76	63	21761.131	-8 0620	-3.2955	84.408	4960	750270	130.873	S	2 121	- 301	1 702	
76	63	27658.410	-2.1364	-3.3658	31 415	4960	750270	-30.002	S	2 491	290	1 560	
76	63	33506.214	-16.1230	-7.2241	17.345	4960	750270	-9.134	S	8 280	3.555	2 108	D
76	63	39341.113	2.3706	-7.1179	18.253	4960	750270	12.532		5 979	-1 903	2 407	
76	63	45197.192	-0.2370	-1.2066	36.017	4960	750270	33.166		1 313	- 581	1 721	
76	63	51133.844	-0.9096	5.9906	68.563	4960	750270	-128.491		3 413	- 504	1 509	

SUMMARY (43 Passes) - 48 ± 3 74 - 04 ± 2 76

*B — Deleted for range bias
D — Deleted for range bias drift
σ — Deleted for post-navigation residuals
(20 Passes Deleted)

Table D-6

C-Band Navigation Results (base run)
Span 2

YR	DAY	SEC	ECA(M)	ECR(M)	ELV	STA	SAT	AZY	V/S	RANGE BIAS (m)	RANGE DRIFT (km/day)	RESIDUAL (m)	DELETION CODE*
76	65	73448.651	2.7510	-22.5514	24.544	4013	750270	51.093		22 978	1 558	1.860	B,D
76	64	45037.057	1.3616	-1.2625	26.216	4150	750270	115.804	S	1.534	- 1 020	2.515	
76	64	51536.434	-0.1096	-4.2375	50.237	4150	750270	-49.096	S	694	181	1.645	
76	64	60621.909	-2.4589	0.8105	33.748	4150	750270	49.592		- 1 159	- 510	1 831	
76	65	53076.970	-0.6336	1.3346	76.656	4150	750270	-53.078	S	- 1 804	240	1 577	
76	65	79767.377	2.8319	-0.2774	37.941	4150	750270	46.436		- 3 324	299	2 006	
76	65	85684.009	0.9832	3.9037	58.110	4150	750270	-118.692		- 2 695	366	2 331	
76	64	45561.526	-4.0819	-2.7365	47.146	4198	750270	118.977	S	- 4 913	411	1 216	
76	64	51584.446	3.7291	-3.6321	26.259	4198	750270	-47.710	S	- 2 232	- 1 045	1 536	
76	64	90537.235	-4.8969	2.1645	44.088	4198	750270	52.219		- 4 422	561	1 182	
76	65	44816.413	0.1186	-0.3563	30.698	4198	750270	116.496	S	- 6 078	- 003	1 406	
76	65	50733.034	-0.1249	-0.3760	37.797	4198	750270	-50.903	S	- 1 770	- 340	1.591	
76	65	85573.388	0.9960	5.7788	39.805	4198	750270	-118.029		- 5.680	258	1 323	
76	65	50815.608	-7.8372	3.0022	66.577	4280	750270	121.479	S	3.378	.748	1 071	
76	65	56708.970	10.0533	-1.7918	21.739	4280	750270	-43.958	S	5 183	- 2 641	1.219	
76	64	1103.097	-3.6433	4.9416	42.764	4446	750270	-118.585		2 261	1 082	2 782	D, σ
76	64	51672.685	-0.5594	1.2501	72.492	4446	750270	-54.933	S	438	- 114	1 122	
76	64	30645.119	-1.6050	-2.3342	21.309	4446	750270	44.432		- 5 135	- 575	1 448	
76	64	7063.211	3.6794	-2.9306	25.079	4452	750270	54.248		- 4 087	867	2 042	
76	64	12971.403	6.1607	1.0935	32.473	4452	750270	-116.756		-10 453	023	1 653	
76	64	56063.876	6.4517	1.7269	65.921	4452	750270	119.185	S	- 6 283	- 862	1 464	
76	65	6212.717	2.0942	0.2497	16.192	4452	750270	51.696		- 4 339	- 900	2 276	
76	65	12109.112	10.2001	2.4050	53.226	4452	750270	-118.467		- 8 883	092	1 531	
76	65	57202.534	-3.0495	2.4383	40.208	4452	750270	117.473	S	- 6 688	.032	1 396	
76	65	63105.115	1.1288	-12.4947	23.768	4452	750270	-53.158	S	- 7 949	- .059	1 708	
76	64	1055.979	3.7053	-0.9519	24.149	4610	750270	-115.372		- .829	- 492	939	
76	64	51572.062	-3.2636	-1.3136	75.731	4610	750270	-52.731	S	- .385	1 478	1.582	D
76	64	80668.212	-3.9492	2.0286	40.029	4610	750270	46.758		- 2.253	137	989	
76	65	50711.631	1.5404	3.0740	75.751	4610	750270	124.057	S	- 4 034	- 131	936	
76	65	56603.342	3.7071	-5.4382	22.377	4610	750270	-39.807	S	- 991	- 036	1 127	
76	65	79816.394	2.5859	0.8303	29.119	4610	750270	43.091		- 1.317	.329	1 026	
76	65	85721.038	2.7489	1.2529	54.073	4610	750270	-121.461		- 2 114	- 4 717	917	
76	64	7052.548	0.7100	-4.9034	28.177	4742	750270	54.275		- 8.710	- .182	.524	
76	64	12970.942	9.7742	6.4347	32.291	4742	750270	-116.740		- 6.819	- .620	.694	
76	64	58063.534	6.4455	-2.1308	60.295	4742	750270	119.181	S	- 5 664	- 327	1 398	
76	65	17109.501	7.6229	4.7744	52.934	4742	750270	-118.473		-10.383	181	581	
76	65	57202.272	-3.3802	3.1317	40.470	4742	750270	117.436	S	- 6 905	.307	474	
76	65	63104.679	1.3257	-8.0428	23.627	4742	750270	-53.132	S	- 3.412	.188	884	
76	64	33526.061	1.1017	2.1354	73.509	4760	750270	115.014	S	- 2 170	- 244	808	
76	64	39450.570	-2.1086	-4.1208	48.472	4760	750270	-52.806	S	- 1 360	- 173	.912	
76	64	68372.761	1.8235	-2.1424	23.455	4760	750270	47.022		- 2.208	.009	936	
76	64	74272.838	-2.2651	0.9337	57.981	4760	750270	-119.682		- 1 101	.324	787	
76	65	38593.876	-0.6127	-1.1993	73.336	4760	750270	-55.783	S	- 1.647	- .040	818	
76	65	67575.621	11.5074	-1.9052	16.678	4760	750270	43.581		- 2.290	- .500	1 054	
76	65	73410.792	0.9893	1.3041	81.465	4760	750270	-122.957		- 3.522	381	789	
76	64	39458.101	-1.3476	-0.9705	55.265	4840	750270	121.017	S	- 4 454	.525	1 609	
76	64	45360.524	-5.1282	-1.7159	27.755	4840	750270	-43.743	S	- 2 890	1 700	1 615	D
76	65	38592.575	-1.5805	-1.7337	36.076	4840	750270	118.081	S	- 4 141	1 025	1 680	D
76	65	44509.251	2.5445	-0.3668	38.424	4840	750270	-47.309	S	- 3 462	485	1 726	
76	64	68542.475	19.1575	11.1452	19.162	4860	750270	39.324		-16 373	-10 696	3 219	B,D, σ
76	64	74427.710	-16.5069	-5.2370	87.507	4860	750270	-127.150		- 6 671	- 451	1 505	
76	65	73568.508	-15.6984	-5.2243	64.413	4860	750270	52.377		- 6 914	.188	1 364	
76	65	79503.085	14.1324	11.3030	20.787	4860	750270	-114.060		-23 405	- 8 444	2.317	
76	65	18082.030	14.8196	-0.5970	33.406	4958	750270	59.721		-389 460	13 022	1 736	B,D
76	65	23991.308	9.9089	-20.6487	13.207	4958	750270	-117.438		-360 370	16 351	2 097	B,D
76	65	69462.237	2.6988	-12.4028	19.497	4958	750270	-57.864	S	-362 147	14 089	2.152	B,D
76	65	18082.029	0.4010	9.0347	38.407	4959	750270	59.721		385 313	16 593	2 356	B,D
76	65	23991.308	16.4395	-17.6521	19.208	4959	750270	-117.438		402 680	13 377	2 332	B,D
76	65	69462.234	-10.1893	-10.5427	19.497	4959	750270	-57.864	S	397 808	16 523	1 694	B,D
76	64	20897.493	-10.6777	-3.4375	62.721	4960	750270	127.256	S	3 003	- 051	1 662	
76	64	26807.091	-7.9788	0.8231	38.441	4960	750270	-34.264	S	8 640	135	1 769	
76	64	32665.263	9.0649	-5.5514	18.786	4960	750270	-13.777	S	7 393	- 2 234	1 824	
76	64	38498.390	2.6083	-5.5721	17.019	4960	750270	7.874		5 843	- 2.211	1 904	
76	64	44346.445	-2.9433	-2.1992	29.666	4960	750270	28.658		2 408	- 1.092	1.514	
76	64	50240.843	-1.8346	-0.3443	89.213	4960	750270	53.108		12 011	1 621	1 050	B,D
76	64	56194.539	9.2842	12.1925	20.809	4960	750270	-115.007		- 2.231	- 3 095	2 288	
76	65	20030.944	-12.2690	2.2448	45.596	4960	750270	123.488	S	2 150	280	1 699	
76	65	25953.354	1.4414	5.2603	46.400	4960	750270	-38.435	S	1 123	366	1 486	
76	65	31821.113	3.2376	-0.5444	20.933	4960	750270	-18.362	S	2 952	677	1 929	
76	65	37656.443	3.9485	-9.5399	16.381	4960	750270	3.182		7 783	- 1 347	2 223	
76	65	43497.984	0.4870	-8.9609	25.085	4960	750270	24.457		7 386	- 546	1 761	
76	65	49380.720	1.6310	6.2181	63.414	4960	750270	44.042		2 421	376	1 396	
76	65	55321.049	5.0689	7.0637	29.197	4960	750270	-118.645		4 153	- 155	1 686	
SUMMARY (60 Passes)										90 ± 5 92	- 27 ± 4 52		

*B – Deleted for range bias

D – Deleted for range bias drift

σ – Deleted for post-navigation residuals

(13 Passes Deleted)

Table D-7
Laser Navigation Results (base run)
Span 1

YR	DAY	SEC	FCA(M)	ECR(M)	ELV	STA	SAT	AZY	N/S	Range Bias (m)	Range Drift (km/day)	Residuals (m)	Deletion Code*
76	62	41154 305	-0.0434	-2.4161	22.913	7067	750270	-46.476	S	- 2 037	334	059	
76	63	34392 621	-1.6596	12.7506	36 516	7067	750270	117.424	S	-12 113	2 558	058	D
76	63	40304 143	0.2476	-4.0325	32.888	7067	750270	-49.742	S	- 1 047	- 034	046	
76	63	69223.662	0.8745	-2.3332	34 410	7067	750270	50.264		- 527	-12 051	046	
76	63	75137.634	2.1254	-0.3646	33.900	7067	750270	-117 105		- 249	011	050	
76	62	35460 917	5.7507	-2.1780	58.386	7068	750270	118.673	S	598	- .345	042	
76	62	75886.743	0.0038	0.7470	64 781	7068	750270	-119.179		3 096	- 416	040	
76	62	41349.895	-2.9210	0.0118	54.670	7069	750270	-55.471	S	- 617	336	068	
76	63	40492.134	-3.8576	-0.1377	84.466	7069	750270	-57.984	S	- 660	- .059	063	
76	63	75193.404	1.3936	-1.4451	53 026	7069	750270	55 421		- 1 507	096	068	
SUMMARY (10 Passes)			40 ± 2 63	-1 36 ± 1 44									

*B – Deleted for range bias

D – Deleted for range bias drift

σ – Deleted for post-navigation residuals

(1 Pass Deleted)

Table D-8
Laser Navigation Results (base run)
Span 2

YR	DAY	SEC	FCA(M)	ECR(M)	ELV	STA	SAT	AZY	N/S	RANGE BIAS (m)	RANGE DRIFT (km/day)	RESIDUAL (m)	DELETION CODE*
76	64	68372.859	-0.6588	1 9297	23.862	7067	750270	47.020		-4 133	467	054	
76	64	74272.989	-1 8088	0 6276	52.975	7067	750270	-119.649		- 355	- 065	050	
76	65	38593.748	0.0776	-2.1155	73.377	7067	750270	-55.753	S	- 956	039	063	
76	65	73410 892	0.2375	-0.2105	81 955	7067	750270	-122.965		- 563	048	058	
76	64	33735.971	-10.9453	1.3363	21 994	7068	750270	115.535	S	-2.264	5 454	034	D
76	64	39651 446	2.7609	-1.3450	40 718	7068	750270	-56 339	S	-1 353	- 038	035	
76	65	38795.441	3.7034	0.4610	65 428	7068	750270	-58.477	S	- 514	.057	037	
76	64	39631 743	-5.7845	-1.3154	62.529	7069	750270	119.721	S	- 331	088	070	
76	64	74341.806	-3.4792	-1.6170	34.586	7069	750270	52.642		-2 446	433	055	
76	64	80255.931	-5.2369	5.9136	29.685	7069	750270	-116.331		-1 525	- .080	.073	
76	65	73490.572	-0.0748	-3.3703	23 254	7069	750270	49.703		-1 034	- .084	.073	
76	65	79391.731	0.0762	2.7462	47.535	7069	750270	-118.519		- 719	- .029	071	
SUMMARY (11 Passes)			- 93 ± 2 84	15 ± 2 50									

*B – Deleted for range bias

D – Deleted for range drift

– Deleted for post-navigation residuals

(1 Pass Deleted)

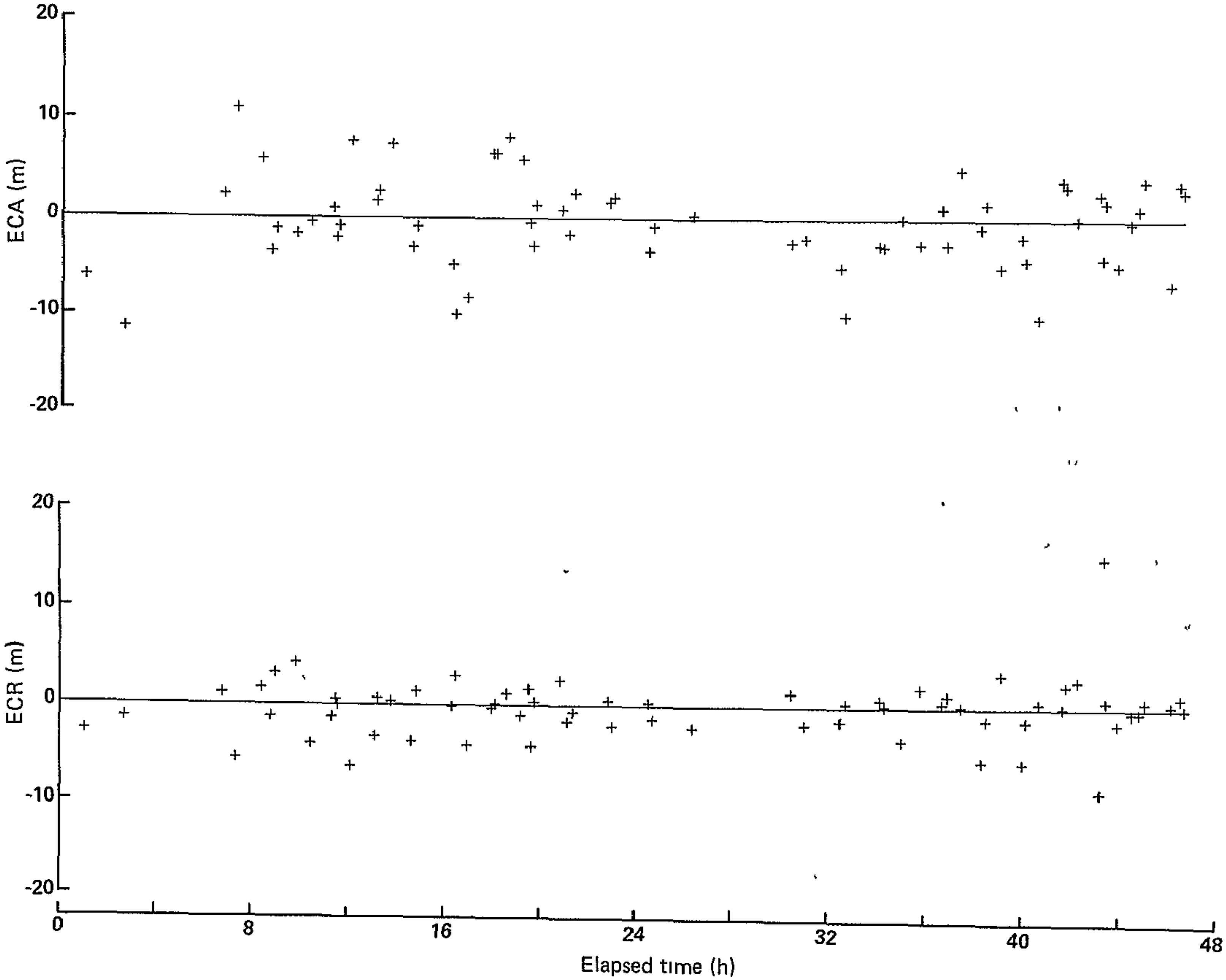


Fig D-1 GEOS-3 Doppler Navigation Residuals (reference track), 1976 Days 62 to 65

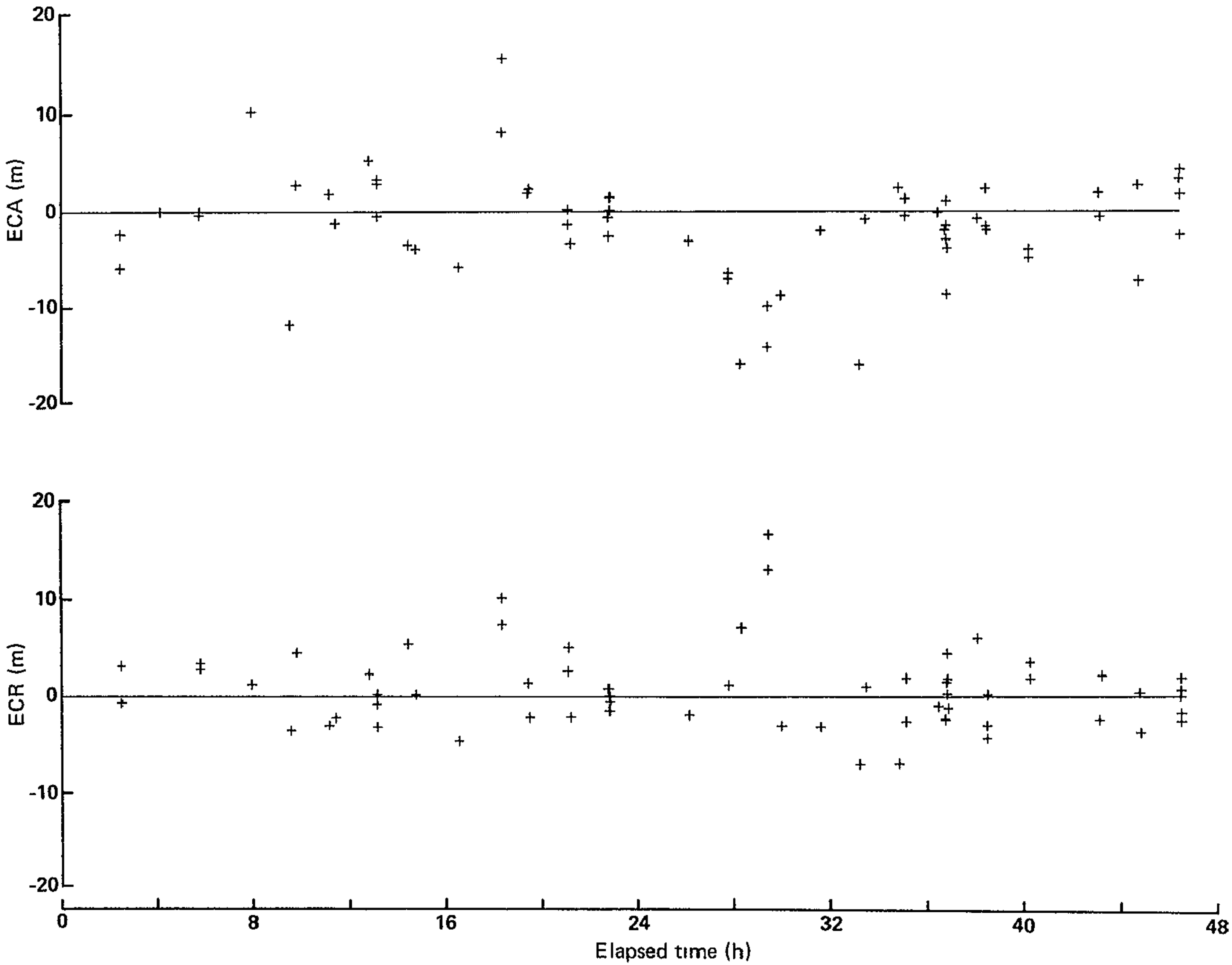


Fig. D-2 GEOS-3 C-Band Navigation Residuals (reference track), 1976 Days 62 to 63

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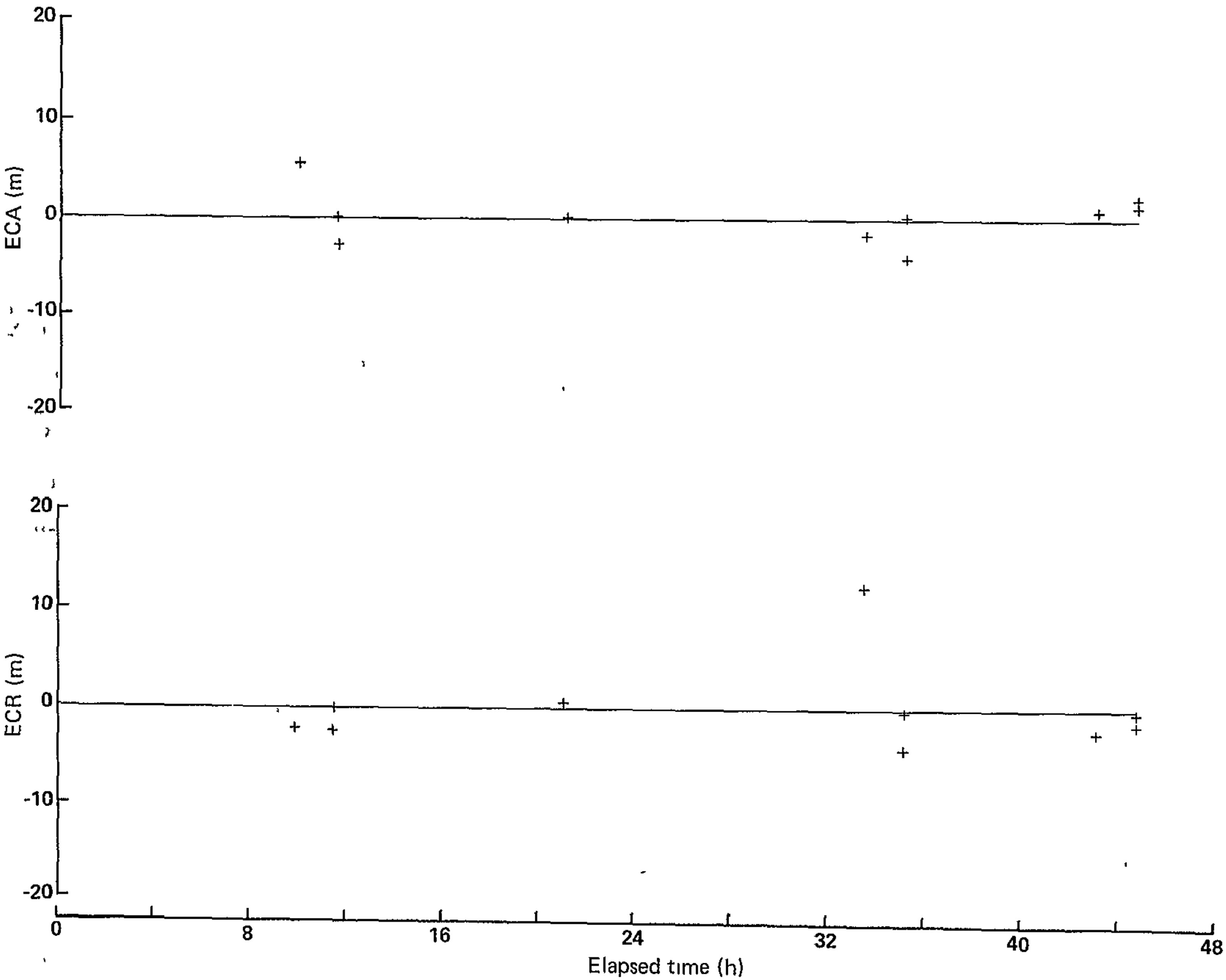


Fig D-3 GEOS-3 Laser Navigation Residuals (reference track), 1976 Days 62 to 63

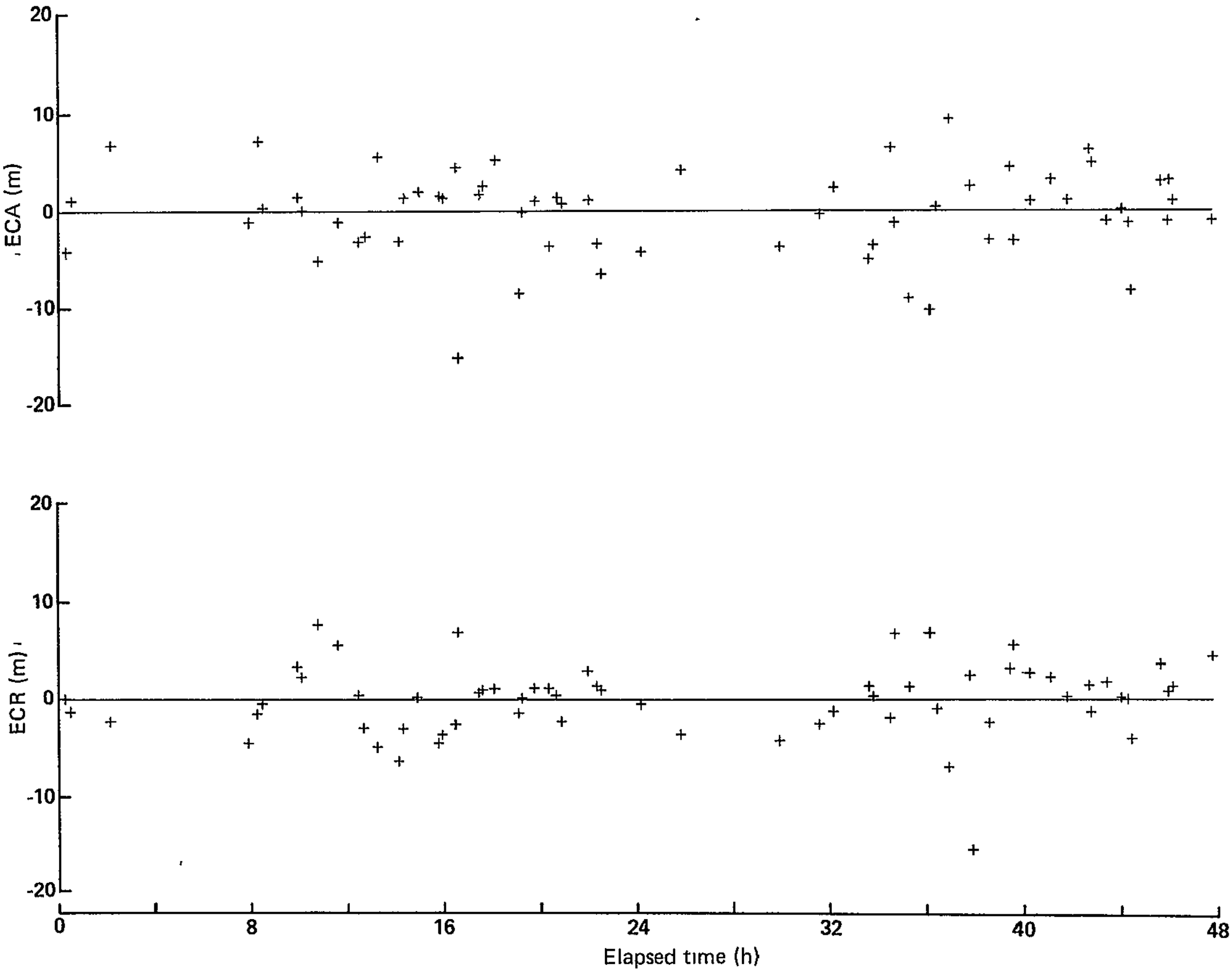


Fig. D-4 GEOS-3 Doppler Navigation Residuals (reference track), 1976 Days 64 to 65

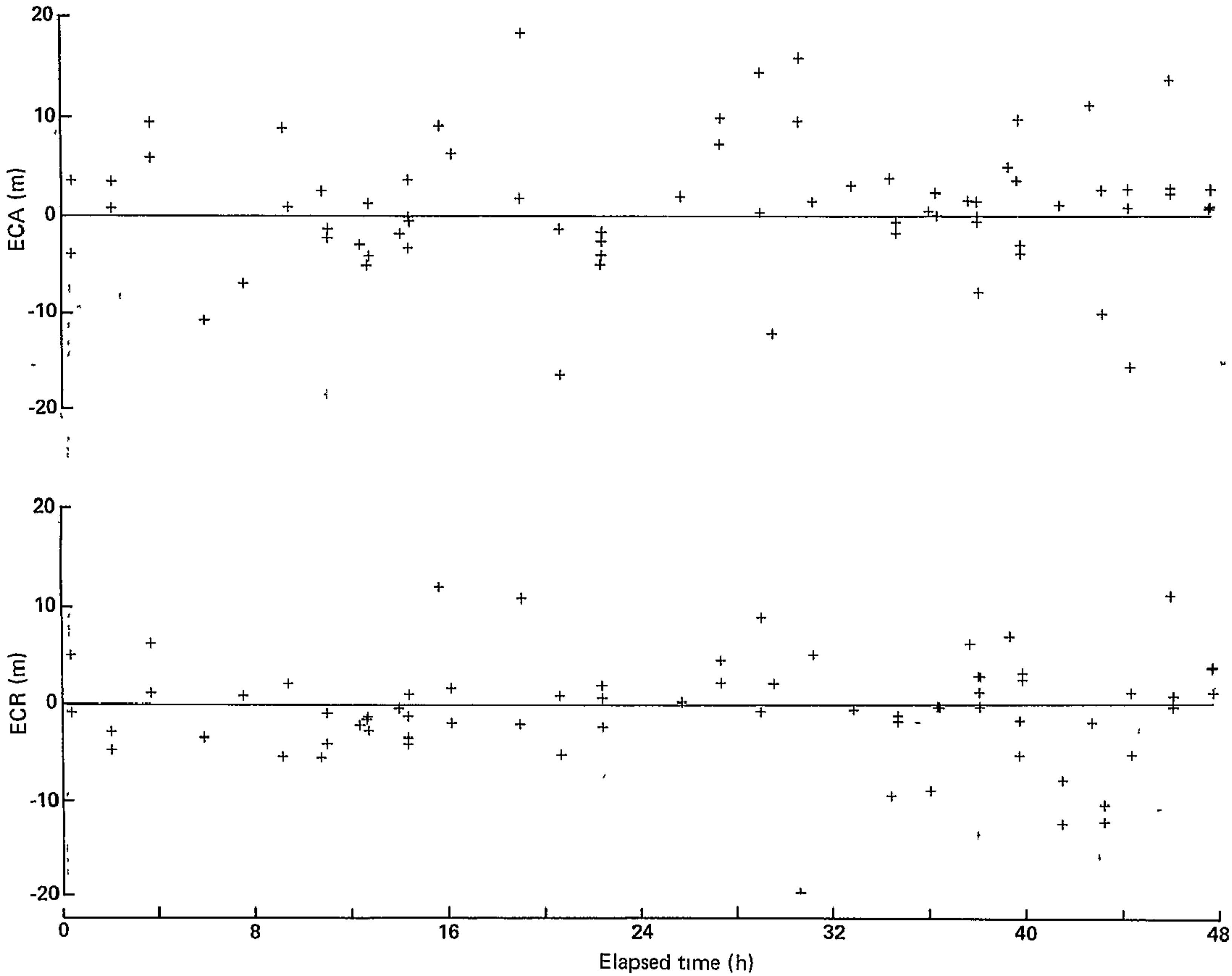


Fig D-5 GEOS-3 C-Band Navigation Residuals (reference track), 1976 Days 64 to 65

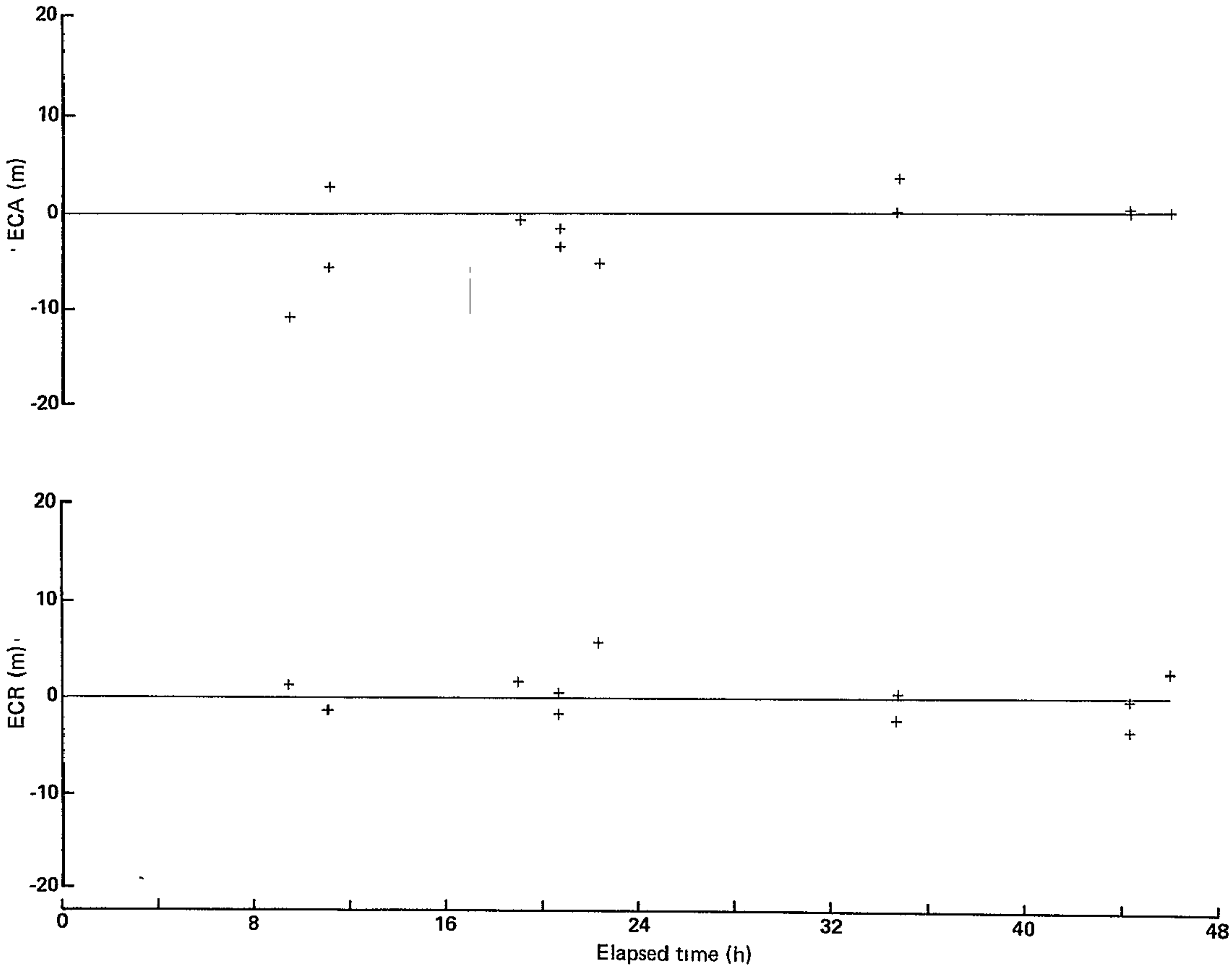


Fig. D-6 GEOS-3 Laser Navigation Residuals (reference track), 1976
Days 64 to 65

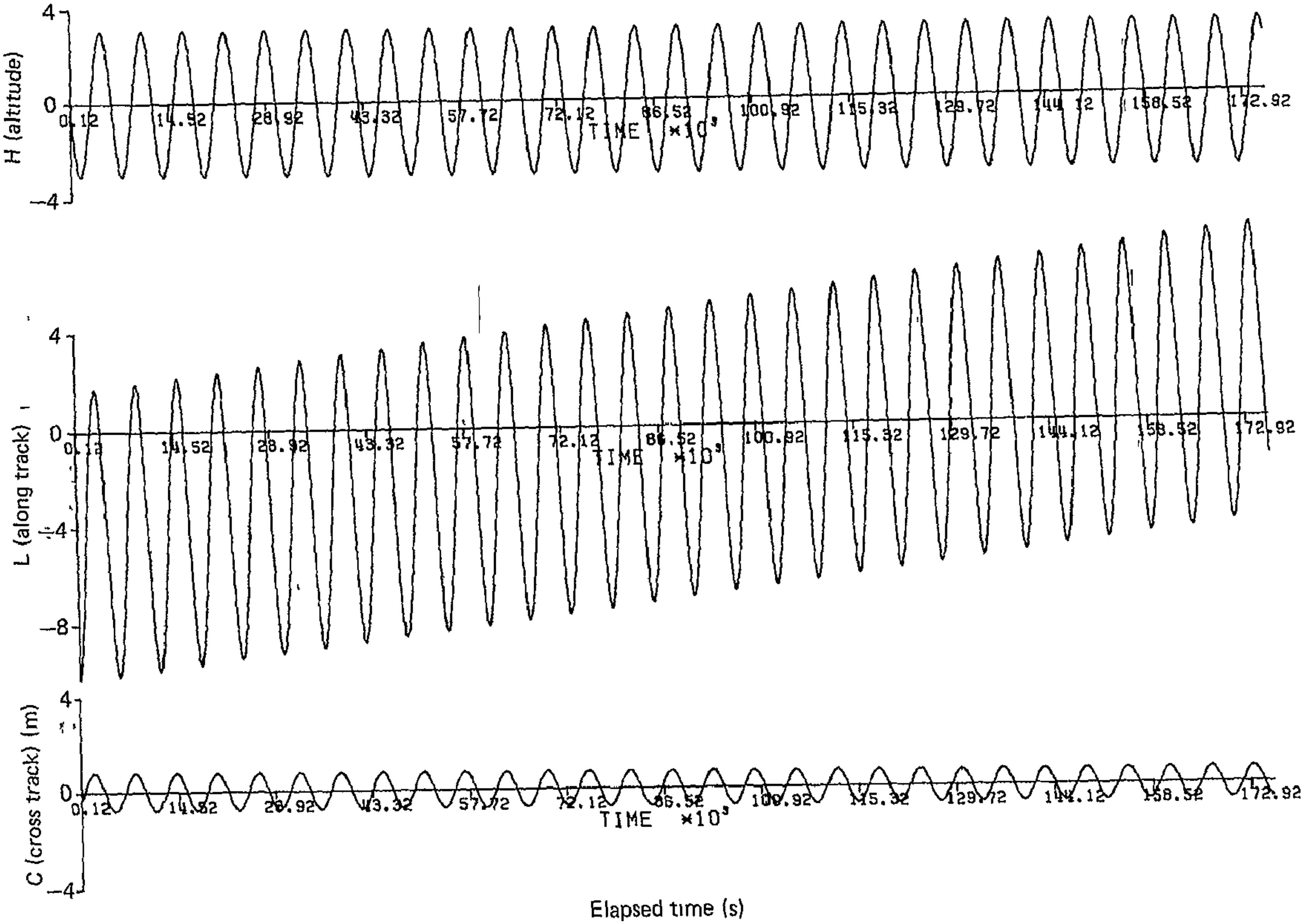


Fig D-7 GEOS-3 Ephemeris Differences (reference backdate - reference track), 1976 Days 62 to 63

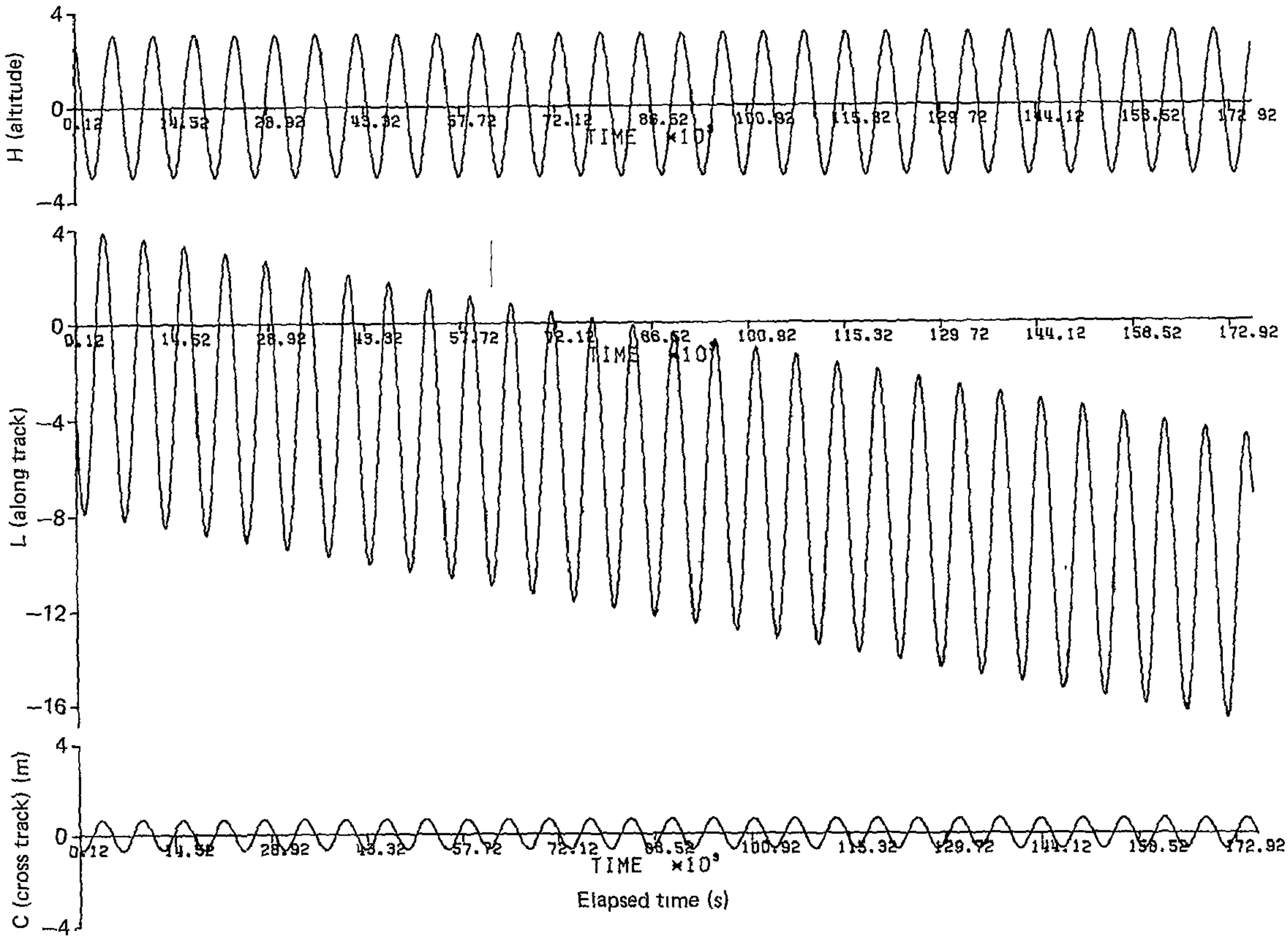
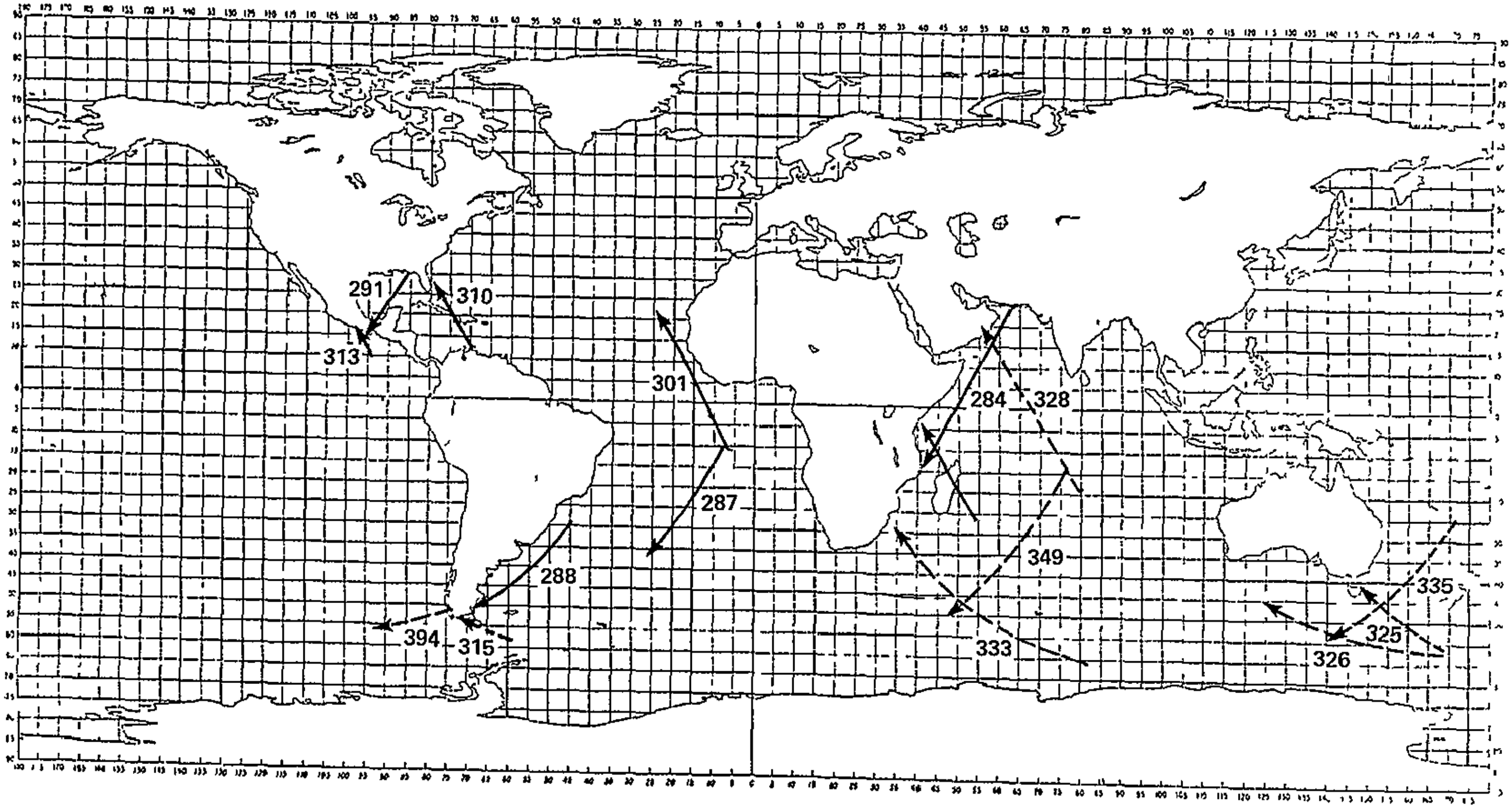


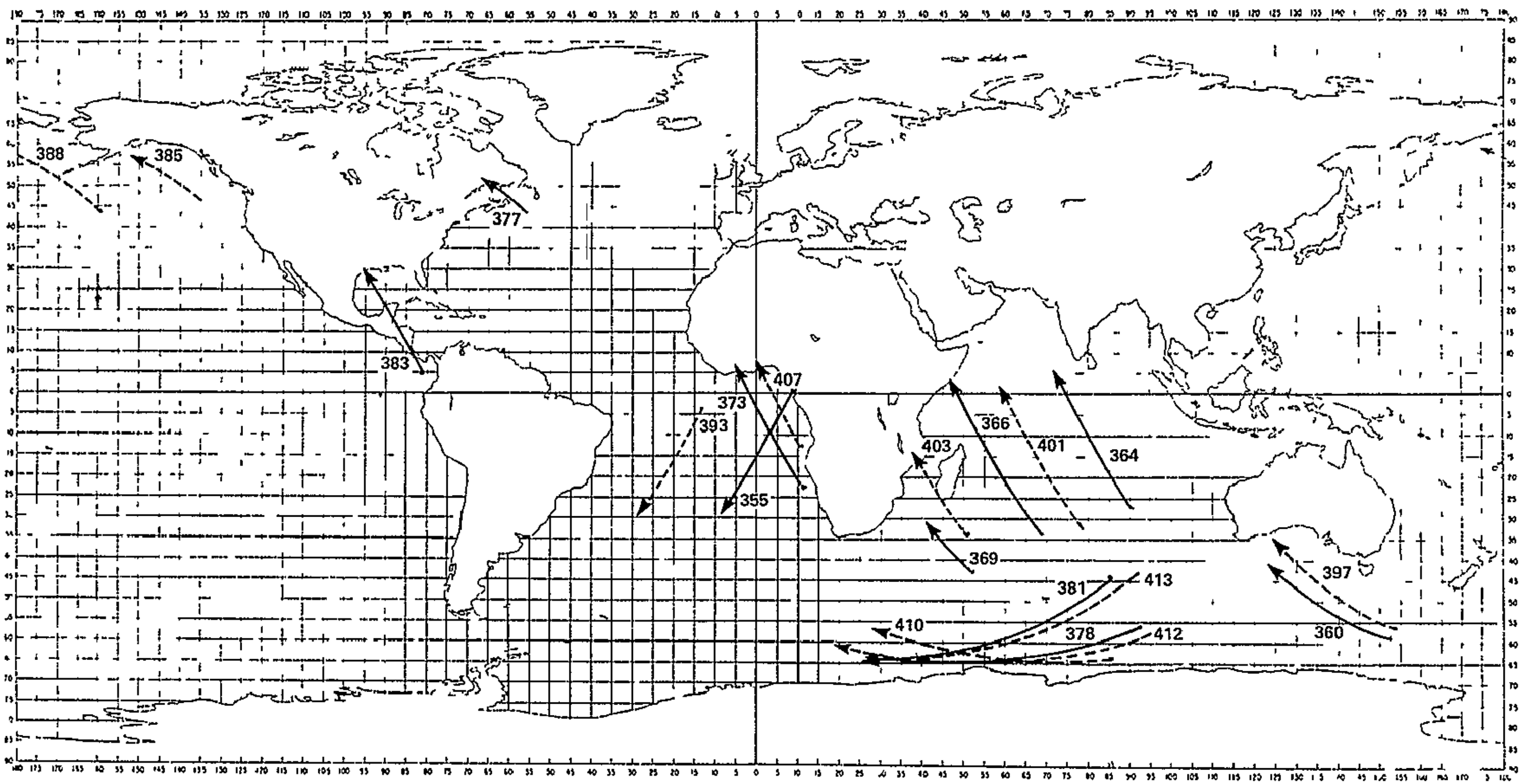
Fig D-8 GEOS-3 Ephemeris Differences (reference update - reference track), 1976 Days 64 to 65



Day 62 ——— Day 63 – – – –

(numbers refer to unique number of altimetry data)

Fig. D-9 GEOS-3 Spatial Distribution of Altimeter Data, Altimeter Coverage 1976 Days 62 and 63



—— Day 64 ------ Day 65

(numbers refer to unique number of altimetry data)

Fig. D-10 GEOS-3 Spatial Distribution of Altimeter Data, Altimeter Coverage 1976 Days 64 and 65

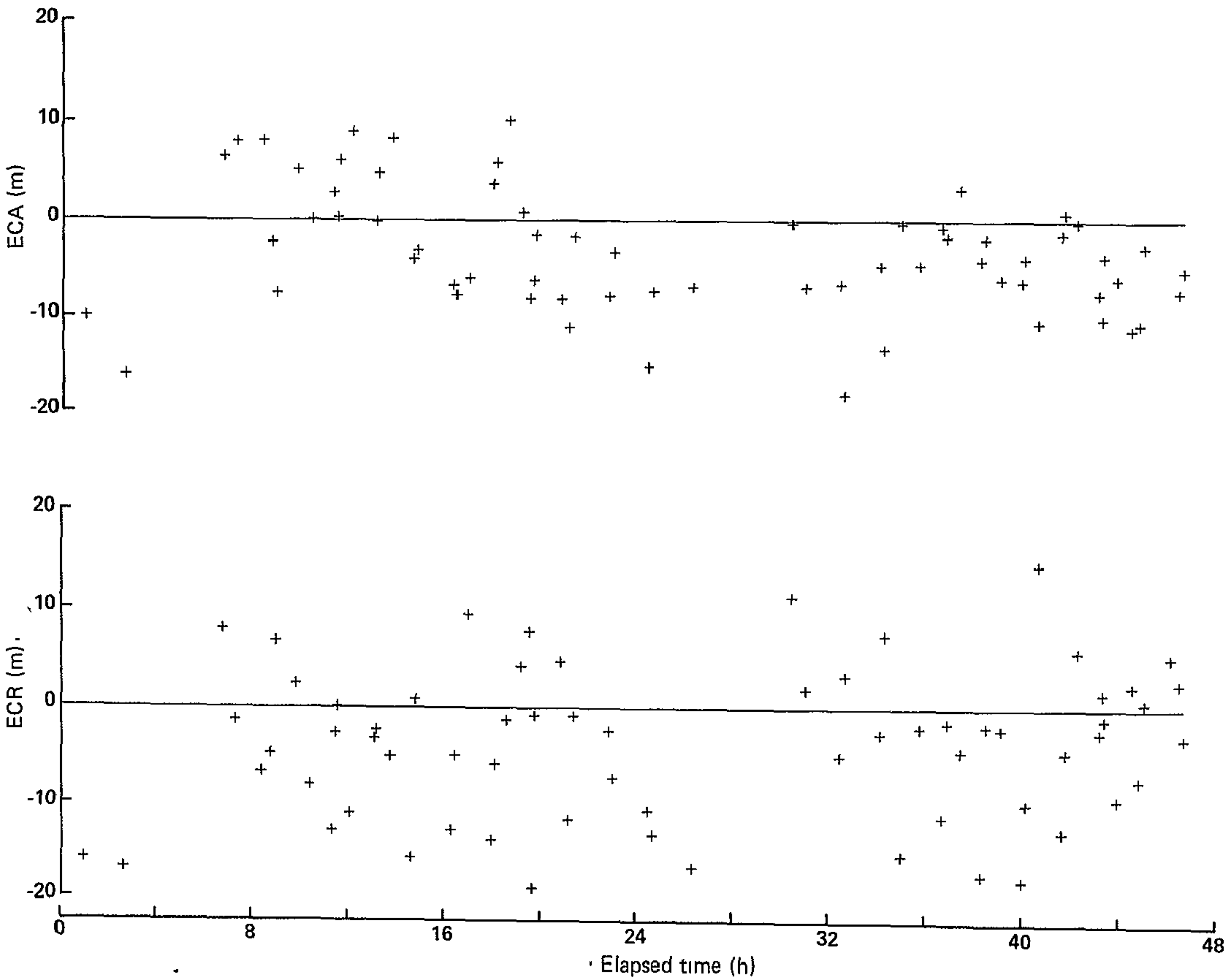


Fig D-11 GEOS-3 Doppler Residuals (backdate from two passes, station 4150 with altimeter track), 1976 Days 62 to 63

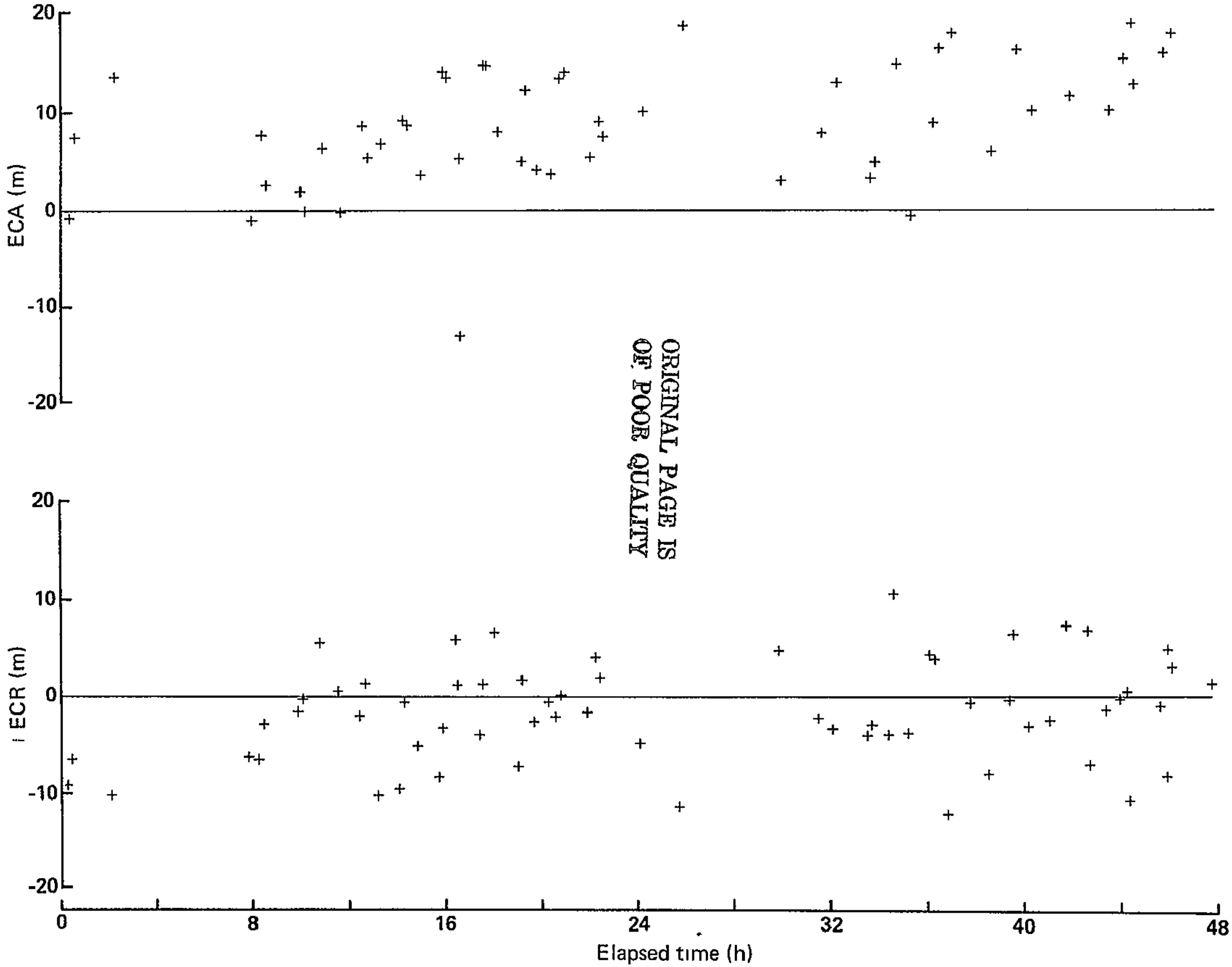


Fig. D-12 GEOS-3 Doppler Residuals (update from two passes, station 4150 with altimeter track), 1976 Days 63 to 65

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16 Abstract

The objectives of the experiment were to determine the nature and improvement in satellite orbit determination when precise altimetric height data are used in combination with conventional tracking data To accomplish this, a digital orbit determination program was developed that could singly or jointly use laser ranging, C-band ranging, doppler range difference, and altimetric height data Soon after data became available, two intervals were selected and used in a preliminary evaluation of the altimeter data After all the tracking data had become available, a detailed study was made over a four-day period With the rather sparse altimeter data available, it was possible to determine the semimajor axis and eccentricity to within several kilometers, in addition to determining an altimeter height bias When used jointly with a limited amount of either C-band or laser range data, it was shown that altimeter data can improve the orbit solution

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