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ACCURACY OF COMPUTED ORBITS OF GEOS-3 SATELLITE,(U)
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Twenty-two days of Doppler observations of the GEOS-3 satellite from 37 stations were used to optimize the description of the earth's gravity field for use in computing the GEOS-3 orbit. The improved gravity field will permit the determination of the satellite altitude to an accuracy of 2m. Comparison of altimeter measurements on intersecting tracks will permit reduction of this bias to below 70 cm, corresponding to the precision of the altimeter. Uncertainties in vertical velocity of the spacecraft will rarely contribute an error of more than .02" to the measurements of deflection of the vertical at

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20. sea, which is trivial compared to the accuracy of the altimeter.

FOREWORD

The GEOS-3 satellite was launched 9 April 1975 primarily to measure the distance from the satellite to the ocean surface with a radar altiemter. If the satellite position is accurately known, the measurements will permit the determination of mean sea level from which the earth's gravity field and deflections of the vertical at sea can be determined. This report discusses the accuracy of the determination of the satellite orbit.

The work was performed under DMATC#76-002.

RELEASED BY:

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CONTENTS

INTRODUCTION

The Department of Defense plans to rely primarily on Doppler observations of the GEOS-3 satellite in order to determine the distance of the altimeter from the center of the earth. Subtraction of the distance from the satellite to the ocean surface measured with the satellite radar altimeter from the Doppler derived satellite radius yields the radius of sea level from the center of the earth. Correction of the result of this result for sea state, tides, and currents gives mean sea level which conforms to an equipotential surface (Figure 1). From the equipotential surface, or geoid, the earth's gravity field and deflections of the vertical can be inferred.

The principal contribution to the error in the GEOS-3 satellite height computed from Doppler observations was expected to arise from uncertainty in the earth's gravity field. Prior to the launch of GEOS-3, simulations were conducted to determine the magnitude of this error. Although values of gravity coefficients through nineteenth degree and order have been computed, these coefficients have uncertainties which are difficult to evaluate. Various experiments have indicated that the coefficients are optimized for the polar Navy Navigation Satellites, and produce larger errors for satellites at other orbital inclinations or at lower altitudes. It is believed under such circumstances, the effects of errors in the coefficients on computed satellite orbits can be approximated by computing the effect of truncating a synthetic gravity field at twelfth degree and order. The effects of such a truncation on a satellite at the GEOS-3 altitude and on the higher altitude GEOS-2 are shown in the top part of Table 1. The radial error is shown to be 3m at the higher altitude and 13m at the GEOS-3 altitude. Although it was expected that these errors could be reduced by optimizing the field based on observations of the satellite, it was not expected the error would be reduced too close to the 70 cm expected accuracy of the altimeter. However, these results were based on a solution for orbit constants based on 48 hours of observation. Use of a shorter observation span would reduce the size of the error. The lower part of the table shows the actual residuals for a satellite near the altitude of the GEOS-3 satellite and for a higher altitude satellite. In this case the errors were actually larger for the higher altitude satellite for unknown reasons. Although still lower errors were desired, it was expected they could be achieved by (1) deploying a dense station network, making possible still shorter fit spans, and (3) using a gravity field specifically optimized for the GEOS-3 satellite rather than a field fitting a large number of satellites (and heavily weighted to the polar satellites) as was the case in the experiment described above.

TABLE 1

ORBIT ACCURACY CONSIDERATIONS

A. 48-HOUR FIT

	GEOS-C (450nm)	GEOS-B (760nm)
RMS Effect on Radial Error of Gravity Field Truncation		
(15,15)	7 m	2 m
(12,12)	13 m	3 m

B. 6-HOUR FIT

	TIMATION II (500nm)	GEOS-B (760nm)
RWS Residuals of Fit in Slant Range		
NWL-9B	2 m	6 m

PROCEDURE

Data Utilized

Doppler satellite observations during five time spans totalling 22 days were used in optimizing gravity coefficients for the GEOS-3 satellite. The data were distributed in 1975 as follows:

	ID	EPOCH	SPAN	NO. OBS	APPROXIMATE NO. OF PASSES	NO. STATIONS
	BGEO	169	2 days	7708	304	34
	BGEX	165	2 days	7837	285	35
	BGEZ	186	6 days	25885	1006	36
	BGEY	225	6 days	11574	731	27
	BGEW	176	6 days	22876	971	35
TOTAL	BE	---	------	75880	3297	37

The stations used in the solution are listed in Table 2 and shown in Figure 2. Evaluations of certain geodetic solutions made with these data were conducted using a two day span of data starting on day 225 and for a two day span of data starting on day 113. The epochs for the data used in the geodetic solution were at zero hours UT of the days given for the six day matrices and at 68040 seconds for the two day matrices. The epochs for the test cases were also not usually at zero hours. The short arc is designed to provide an accurate ephemeris for one revolution of the satellite starting at the ascending equator crossing. The short arc orbit fit is normally extended a half revolution before and after the revolution for which the results are desired. If insufficient data are found in this time period, the computer program will automatically extend the span of the fit another half revolution before and/or after the original two revolution fit. While the epoch of the day 225 long arc was at zero hours, the epoch of the first short arc was at 3600 seconds, and successive short arc epochs were at 6120 second intervals. The epoch of the day 113 long arc was at 68040 seconds (and the span of fit extended 48 hours through day 114 and part way through day 115), the epoch of the first short arc was at 74340 seconds, and successive short arc epochs were also at 6120 second intervals. Subsequent references to these orbit fits in this report will not include a complete description of the epochs in order to simplify the discussion.

TABLE 2

STATIONS USED IN GEODETIC SOLUTION

STATION NO.	LOCATION	STATION NO.	LOCATION
8	Brazil	10070	Olympia, Washington
14	Anchorage, Alaska	10073	Thailand
16	England	20184	Chagos
18	Thule	20208	Arizona
19	Antarctica	20284	Sicily
20	Seychelles	30120	La Paz
21	Uccles	30121	Quito
22	Philippines	30122	Paraguay
23	Guam	30123	St. Helena
24	Samoa	30124	Teheran
27	Japan	30126	Zaire
28	Ottawa	30130	Cyprus
103	New Mexico	30188	Hawaii
105	So. Africa	30203	Nairobi
111	Maryland	30414	Calgary
112	Australia	30448	New Zealand
192	Texas	30453	Easter Island
197	Shemya, Alaska		
352	Cambridge Bay, Canada		
10068	Ascension		

Parameters of Geodetic Solution

A frequency and refraction scale factor were included as parameters of each pass used in the solution. (The nominal refraction was assigned an accuracy of 10%.) For each of the five arcs, the six orbit constants, a scale factor for atmospheric drag for each day, a solar radiation pressure scaling factor, and pole position components were considered unknown. Gravity parameters included in the formation of the normal equations were the pairs of coefficients at each order m=0,1...19 corresponding to degree n=m and n=m+1 except that (n,m)=(1,0) was replaced by (n,m)=(3,0), (n,m)=(1,1) was replaced by (n,m)=(3,1), (n,m)=(0,0) was added, and (n,m)=(20,19) was omitted. The total number of coefficients was 77. The three coordinates of each station appeared as parameters in the normal equations, although (except for station 28 for which refined coordinates were not used at the time of matrix formation) these as well as the gravity coefficients for (n,m)=(0,0) and (19,19) were suppressed in the final solution selected. Love's number was in the matrix but not in the solution. The number of parameters included in the solution were:

	MATRIX	SOLUTION
Bias	∿6500	∿6500
Arc	67	67
Station	111	3
Love's Number	1	0
Gravity	77	74
	∿6756	∿6644

Mathematical Model

The computer program used for the geodetic solution is called "GEO" while the program used to conduct the tests is called "CELEST". The mathematical model is described in detail by Anderle (1975a) and will not be repeated here. Three significant changes made since the last geodetic normal equations were formed by the Laboratory in 1969, were the use of range difference as the class of observations rather than Doppler (as a result of the change in the station equipment), the inclusion of refraction bias as a parameter of each pass, and the deletion of frequency drift as a parameter of each pass. The program had also been converted from the IBM 7030 computer to the CDC 6700 computer with minimum program change otherwise.

Careful checkout of the computer program "GEO" was conducted against the computer program "CELEST" which had already been checked against the Aerospace Corporation program "TRACE" and earlier programs used in the Laboratory.

Synthetic observations generated with CELEST for a 100,000 second time span were matched to a few centimeters by evaluating the equations of condition generated by GEO for a perturbed gravity field. This check validated the observation equations, the force model, variational equations, integration and partial derivatives. A valid test of the formation and solution of the normal equations from the equations of condition is difficult because it is expensive to generate sufficient data to extract accurate parameters from computational noise. The test conducted recovered the disturbance in the gravity parameter to either a few percent of the disturbance or to a small absolute error for coefficients which were only slightly disturbed.

Evaluation

Evaluation consisted of comparison of the root mean weighted squares (RWS) of navigation residuals obtained in long or short-arc orbit fits in which the computed orbit was based on a trial gravity field. Navigation is the procedure of determining, simultaneously with bias parameters, the observing station movement in 2 well determined directions (the slant-range and along-track directions at closest approach) best fitting the data of each satellite pass. Along-track navigation residuals respond to orbit errors in the same direction while slant-range residuals reflect both radial and cross track orbit errors (and are subject to some aliasing from misestimation of atmospheric refraction and oscillator frequency drift). The RWS approach, using weights inversely proportional to navigation parameter variances, yields estimates more representative of the true orbit error than the RMS method. As gravity field improvements are made, more dramatic improvements are expected in the long-arc residuals, while the short-arc residuals are more directly representative of orbit errors to be encountered in proposed orbit calculations.

In those data spans chosen for evaluation, some overlap was obtained with the data spans used in forming the normal equations. To avoid possible prejudicial results, non-overlapping spans were chosen for final evaluation.

RESULTS

NWL-10E Residuals

An example of the along-track residuals of fit for the NWL-10E gravity field in use before the solution described below is given in Figures 3a-3f for days 176-181, 1975. (Although the along-track residuals are not of direct interest in satellite altimetry applications, they are easier to interpret than range residuals, which is the only other component of orbit error which can be evaluated on a pass by pass basis from Doppler observations.) Several of the residuals which differ from the curve by 20m are due to a timing error of 3ms in station 20208, which did not submit timing corrections in real time. Others may be due to similar problems for other stations or just due to random errors. The long period trends in these residuals is primarily due to variation in atmospheric drag which was assumed to be constant with respect to time for the six day period, although a single scale factor for the time span was determined from the observations. The larger periodic residuals at the start and end of the span are probably due to the uncertainty in the nominal radiation pressure force used in the calculation. The principal other variation is in the size of the short (orbit period) effect; on most days this effect is a minimum at 10,000 and 60,000 seconds in the day, which may imply a significant error in the coefficients corresponding to (n,3) for odd n.

NWL-1G2 Solution

Weighted residuals for the NWL-1G2 series of solutions based on 16 days of observations are shown in Table 3. The largest portion of the reduction in residuals for the BGED matrix from the NWL-10E values to the NWL-1G2 values is probably due to the fact that the former is based upon 1 drag scaling factor for the time span while the latter solutions include a separate drag factor for each day. In the solution 1G2A, two pairs of coefficients of order m= (0,19)were determined of degree n=m and n=m+1 (except that (n,m)=(1,0) was replaced by (n,m)=(3,0) and (n,m)=(1,1) was replaced by (n,m)=(3,1).) The 18th and 19th order sectorialcoefficients formed in the solution were found to be about ten times the values predicted by Kaula's rule, $\bar{\sigma}_{n,m} \sim 10^{-5}/n^2$. Large values might occur if the satellite is insensitive to a coefficient of degree and order (n,m) in the solution so that abnormal sizes will occur in absorbing effects of coefficients of degree and order (n+2j,m),j=0,.... . However, the additional solutions 1G2G and 1G2S were made to test the sensitivity of the residuals to the presence of these parameters. Table 3 shows that fixing the coefficients (n,m)=(19,19) did not appreciably affect the solution (1G2G vs 1G2A), although additionally fixing the coefficients (n,m)=(19,18) (1G2S vs 1G2G) did affect the residuals somewhat. Therefore, 1G2G was adopted for testing and subsequently was called just 1G2.

Residuals for the NWL-1G2 Solution

Long arc (48 hour) along track residuals for the two day span days 225-226, 1975 are shown in figures 4a and 4b. The solid lines are the residuals for the NWL-1G2 gravity coefficients and the broken lines are those for the NWL-10E coefficients (a different radiation constant used in the two computations contributes a small portion of the difference). Note in the box on figure 4a that the along track residuals were reduced by about 50% and the range residuals by about 25%. Table 4 shows the effects on short arc residuals for day 225, 1975. The tangential residuals were reduced by 30% and the range residuals by 15%.

NWL-1G5 Solution

An additional six day matrix was formed to provide data for a total of 22 days and various solutions were made. Weighted residuals for solutions NWL-1G5 are shown in Table 5. Again, deletion of the coefficients for (n,m)=(19,19) seemed desirable. Station coordinates used in all solutions made to this point were NWL-9D positions. The matrices were adjusted to NWL-9Y1 which corresponds to slight adjustments for (1) refinement based on long term solutions for position and correction for refraction bias (Anderle, 1975) and (2) adjustment from the electrical center of the 150/400Mhz antenna pair to the 162/324Mhz antenna pair. The NWL-1G5 solution was based on the NWL-9Y1 station positions.

Residuals for the NWL-1G5 Solution

Long arc (48 hours) for days 113 and 114, 1975, and short arc (3 hour) residuals for day 113 are shown in Table 6. Both tangential and range long arc residuals were reduced by more than 50%. Short arc residuals were reduced by 25% and 40% tangentially and in range, respectively. Although the NWL-10E and NWL-1G5 solutions were based on different passes due to different manual and automatic editing, it is believed that, after deletion of revolutions 207 and 208, the difference in passes usually favors the NWL-10E solution.

NWL-1G6 Solution

The BGEW matrix based on observations made on days 176-181, 1975 had heavier weight in the NWL-1G5 solution than the other six day matrix primarily because the individual observations were filtered more strictly (at twice the standard deviation rather than close to 2.5 the standard deviation) resulting in significantly smaller random errors, or higher weights, for the observations which survived the filtering. In addition, a program limitation for passes containing more than 40 points was modified; rather than deleting the entire pass as was done for the BGEY matrix, the central 40 points was accepted.

TABLE 3

WEIGHTED RESIDUALS FOR TESTS OF NWL-1G2 SOLUTION

NWL SOLUTION	MATRIX BGEO (2 day)	BGEX (2 day)	BGEZ (6 day)	BGEY (6 day)	BE (combined)
10E	8.652	5.381	6.507	4.091	6.285
1G2A	2.420	2.160	2.699	2.228	2.486
1G2G(1)	2.419	2.171	2.701	2.226	2.489
1G2S(2)	2.425	2.171	2.726	2.256	2.508

(1) Coefficients for (n,m)=(19,19) fixed

(2) Coefficients for (n,m)≥(18,18) fixed

TABLE 4

GEOS-3 DAY 225

	1G2 Gravity 9D Stations RWS (meters) N	IN RANGE	TANGENTIAL	10E Gravity 9D Stations RWS (meters) N	IN RANGE	TANGENTIAL
Long Arc		5.5	5.9		6.9	10.7
Rev 1770	13	4.3	1.6	12	3.4	3.2
1771	12	2.2	1.4	10	1.3	1.4
1772	14	1.5	1.5	13	2.4	1.7
1773	17	1.8	2.3	17	2.0	3.4
1774	20	2.3	3.3	17	2.4	3.6
1775	23	2.7	2.3	20	3.1	2.2
1776	24	3.1	2.6	25	5.0	2.8
1777	23	3.5	1.9	23	3.2	4.0
1778	23	3.2	2.2	23	3.5	2.1
1779	22	2.7	1.8	23	4.3	5.7
1780	23	3.4	2.5	23	3.3	4.7
1781	23	2.1	1.2	23	2.3	1.5
SA RMS		2.8	2.1		3.2	3.3

TABLE 5

WEIGHTED RESIDUALS FOR TESTS OF NWL-1G5 SOLUTION

NWL SOLUTION	MATRIX BGEO (2 day)	BGEX (2 day)	BGEZ (6 day)	BGEY (6 day)	BGEW (6 day)	BE (combined)
10E	8.652	5.381	6.507	4.091	6.548	6.325
1G5A	2.681	2.316	2.833	2.347	2.966	2.625
1G5G	2.682	2.328	2.834	2.346	2.970	2.628
1G5S	2.689	2.342	2.854	2.376	2.987	2.648

TABLE 6

GEOS-3 DAY 113

	1G5 Gravity 9Y1 Station RWS (meters) N	IN RANGE	TANGENGIAL	10E Gravity 9D Station RWS (meters) N	IN RANGE	TANGENTIAL
Long Arc		4.9	5.6		8.5	11.7
Rev 197	19	2.9	5.1	17	3.6	4.2
198	16	3.0	4.9	16	5.4	5.2
199	11	3.1	3.0	14	6.0	5.8
200	11	2.1	1.9	11	4.1	6.3
201	13	5.0	3.7	10	8.0	4.9
202	18	3.7	4.5	15	5.3	7.5
203	19	4.4	3.7	17	8.8	6.1
204	11	5.1	3.5	10	11.6	9.1
205	7	4.2	3.4	15	6.0	6.2
206	6	1.3	2.0	11	4.1	4.4
207	6	1.1	.7	11	10.4*	6.4*
208	8	1.5	1.7	9	8.1*	3.6*
209	10	2.3	2.2	9	3.6	5.6
210	16	2.8	3.5	13	3.1	3.2
211	20	4.2	6.0	17	3.8	4.9
212	19	2.6	6.6	18	6.2	4.6
SA RMS		3.3	3.8			
SA RMS w/o revs 207,208		3.7	4.2		6.1	5.8

*Solution included data from bad pass

Since passes with a large number of points were usually high elevation passes, they contribute more to the solution than other passes. If the solution had no systematic errors, large weight for the last matrix would have been appropriate. However, it is evident that significant errors in the gravity solution still exist after solution, as well as occasional spurious passes, which are not represented in the weighting which is based solely on random errors of observation. Therefore, the last matrix was weighted down by a factor .455 to a level corresponding to the other six day matrices and a solution NWL-1G6 was obtained for the same parameters contained in the NWL-1G5 solution. This solution is being used in current computations and has shown the reduction in residuals expected from the test cases given in this report.

Radius Test

The NWL-9D station coordinates (and the NWL-9Z or 9Y coordinates which are derived from them) are believed to be too large in scale by one part per million for unknown reasons. If the scale error is somehow associated with the use of Navy Navigation Satellites in the determination of the coordinates, it would be possible that the NWL-1G solutions were subject to systematic errors due to the wrong scale that might cause large residuals. Therefore, long arc solutions for days 113-114, 1975 and short arc solutions for day 113 were made with systematic changes in station radii to see if the residuals could be reduced by use of a different radius. Table 7 shows that the along track residuals were not significantly affected by the radius change, as expected, and that the NWL-9D radius almost exactly fits the range data. This does not confirm that the NWL-9D radius is correct, but simply that the residuals of fit are not due to the use of a wrong radius.

Accuracy of Satellite Altitude

The experiments described to this point do not give direct information on the accuracy of the satellite altitude which would be expected from short arc solutions based on NWL-1G gravity coefficients. Table 4 gave 2.8m rms range residuals for day 225 while Table 6 gave 3.3m rms range residuals for day 113. These values include a component of the satellite altitude error, but also include a component of the out-of-plane error as well as the instrument error. Since the instrument error is below 1m for most passes, the principal question is the relative size of the radial and out-of-plane errors and how they enter in the weighted residuals across passes. Although high elevation passes (which determine height error) have higher weight in the weighted residuals because of the longer passes and smaller satellite distances, only a small percentage of the total passes occur at high elevations (there are considerably more passes at elevation angles between 0^{o} or 5^{o} and 45^{o} elevation than between

TABLE 7

RADIUS TEST
DAY 113

	9D-5m	9D	9D+5m
Tangential Residuals			
Long Arc	5.6 m	5.6 m	5.7 m
Short Arc	3.7	3.7	3.9
Range Residuals			
Long Arc	5.2	4.1	5.1
Short Arc	4.1	3.1	3.7

45^{o} and 90^{0} elevation because more of the satellite subtracks occur within the lower elevation angles.

One measure of the ratio of out-of-plane to radial errors is the standard error of these errors obtained from the covariance of the solution. Figure 5 is a typical graph of these residuals. The radial standard errors are typically 30% of the out-of-plane (or normal) errors as shown in columns 6 and 8 of Table 8. While this is encouraging, it only considers random errors, and not systematic errors due to remaining errors in the gravity field. This is evident because the rms of the radial and normal standard errors in Table 8 is 2.05m which is 38% less than the 3.3m rms radial errors in Table 6, despite the fact that the standard errors were based on both the instrument errors and a 2m bias in each coordinate of each station pass in the solution which was intended to represent the gravity error. Therefore, differences between the NWL-10E and NWL-1G5 short arc positions for day 113 were computed to determine the effect of gravity errors. Examples of typical (revolution 197) and large (revolution 202) differences in the short arcs are shown in Figures 6a and 6b, respectively, and rms differences for each revolution are given in the three right hand columns of Table 8.

The differences between the short arcs for the two gravity fields are nearly twice the residuals in the tangential direction. The residuals can be expected to be optimistic in this direction because there are six or seven parameters (4 drag, mean anomaly and possibly orbit period and eccentricity) to fit the tangential observations. The radial residuals are only 30% less than the rms of the radial and normal errors, which is reasonably close. Note that the radial trajectory difference is 40% less than range residuals. On this basis it is concluded that the 2.8m and 3.3m range residuals obtained in the two tests of the NWL-1G5 gravity coefficients imply that short arc (2 revolution) fits of Doppler observations of GEOS-3 with the optimized gravity field will give satellite height to 2m accuracy on an rms basis across revolutions, and that vertical velocity errors should rarely exceed 4m/3000 sec $\sim$.1 cm/sec $\sim$.02" deflection. The velocity error is a trivial contribution to measurements of deflection of the vertical while the 2m height error will be reduced to the 70 cm precision of the altimeter by solving for the bias by comparing altimeter measurements on intersecting tracks. (Ten intersections are required to reduce the bias to 70 cm; the expected interval of crossings is smaller than one degree, giving at least 10 crossings per 1000 km of track of within each 2 1/2 minutes of observation. The change in bias at the ends of this interval would be only $\pm$ 7 cm.)

TABLE 8

SHORT ARC RESULTS FOR DAY 113

	NWL-10E			NWL 1G5				RMS (m)		
		RWS Residuals (m)			RMS Std. Error (m)			10E vs 1G5		
REVOLUTION	#PASSES	RANGE	TANG	#PASSES	RAD	TANG	NORMAL	RAD	TANG	NORMAL
197	17	3.6	4.2	19	.5	1.5	1.4	2.6	6.0	2.7
198	16	5.4	5.2	16	.5	1.6	1.5	2.0	4.4	8.0
199	14	6.0	5.8	11	.6	1.8	1.7	2.5	6.6	2.5
200	11	4.1	6.3	11	.7	1.9	2.1	2.3	6.6	6.3
201	10	8.0	4.9	13	.5	1.6	1.6	3.1	7.2	15.5
202	15	5.3	7.5	18	.4	1.3	1.3	4.0	12.4	12.0
203	17	8.8	6.1	19	.4	1.3	1.2	4.7	11.0	9.6
204	10	11.6	9.1	11	.7	2.2	1.6	9.6	24.5	7.2
205	15	6.0	6.2	7	1.0	2.5	3.4	5.4	15.3	4.5
206	11	4.1	4.4	6	1.1	3.5	3.3	1.4	5.6	8.5
207	11	10.4*	6.4*	6	1.0	2.9	2.7	2.2	6.3	10.6
208	9	8.1*	3.6*	8	.7	1.9	1.9	1.9	6.3	12.7
209	9	3.6	5.6	10	.5	1.6	1.7	2.4	4.9	3.4
210	13	3.1	3.2	16	.5	1.5	1.4	2.1	4.5	3.3
211	17	3.8	4.9	20	.4	1.3	1.3	5.2	12.0	6.3
212	18	6.2	4.6	19	.4	1.2	1.3	4.6	10.8	7.9
RMS		6.6	5.7		.67	1.99	1.96	4.0	10.3	8.4

*Solution included data from bad pass

CONCLUSION

Doppler observations of the GEOS-3 satellite will be used to determine the height of the satellite to 2m accuracy by using the NWL-1G6 gravity field to fit observations made during two revolutions (about 3 hours). Comparison of altimeter measurements on intersecting tracks will reduce the height bias to below 70 cm, which is consistent with the precision of the altimeter. The contribution of the error in vertical velocity of the satellite will rarely contribute more than .02" to the determination of the deflections of the vertical at sea, which is trivial compared to the accuracy of the altimeter.

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Anderle, R. J., "Long Term Consistency in Positions of Sites Determined from Doppler Satellite Observations", Naval Surface Weapons Center Technical Report NSWC/DL TR-3433, November 1975.

FIGURE 1

GEODESY FROM SATELLITE ALTIMETRY

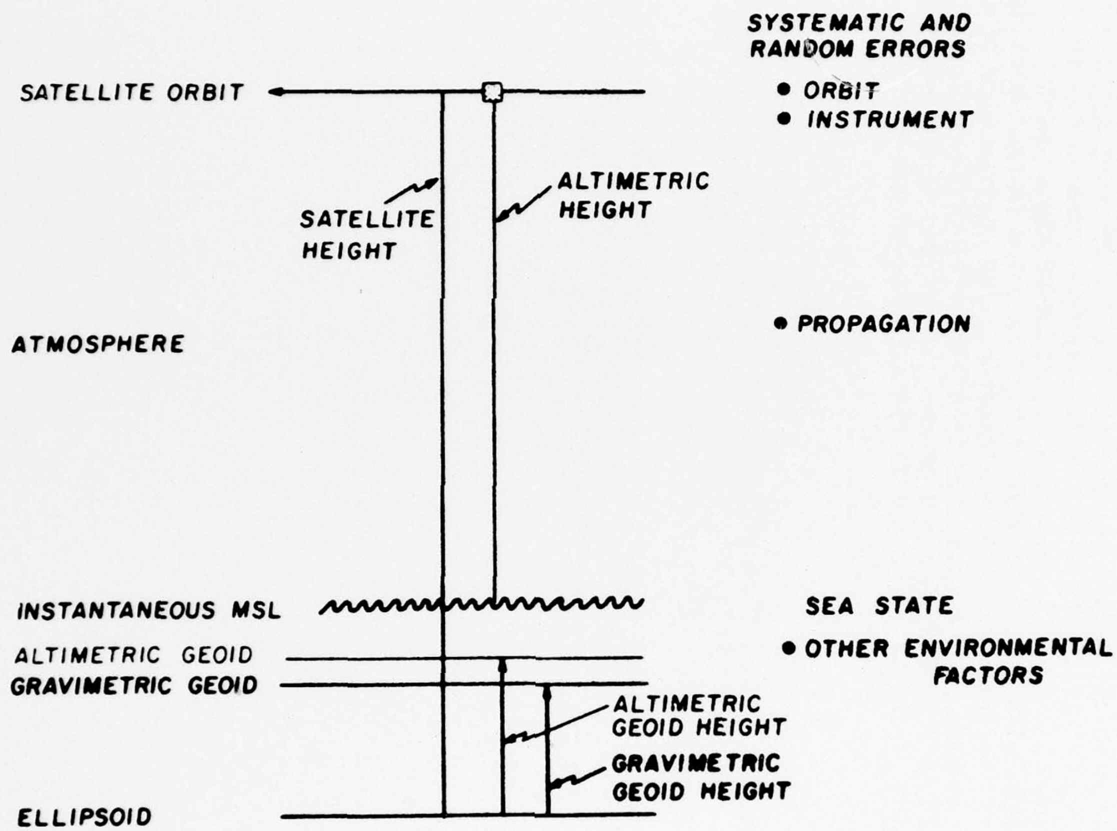
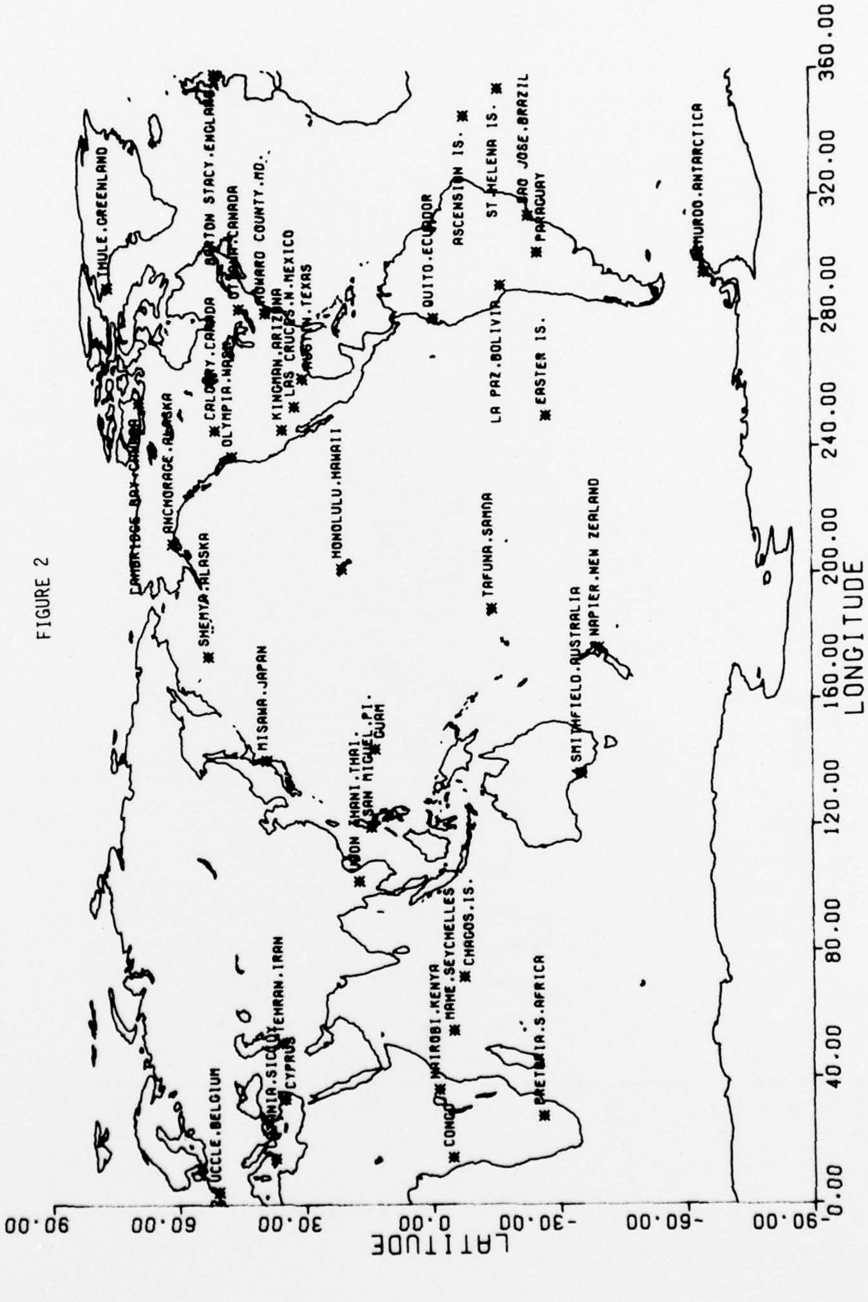


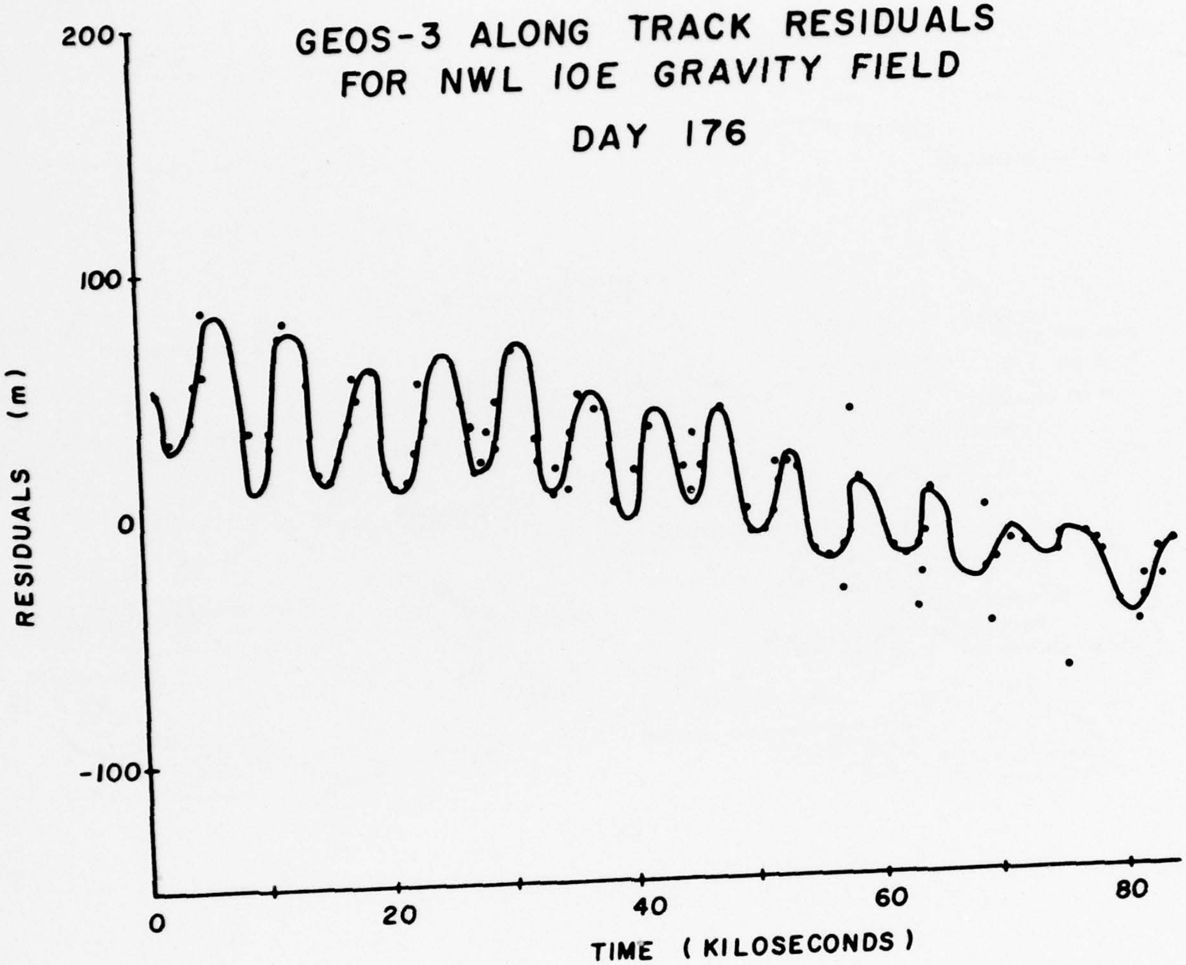
FIGURE 2



LATITUDE
LONGITUDE
90.00
60.00
30.00
0.00
-30.00
-60.00
-90.00
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
320.00
360.00
UCCLE.BELGIUM
CYPRUS
TEHRAN.IRAN
NAIROBI.KENYA
MAHE.SEYCHELLES
CHAGOS.IS.
PRETORIA.S.AFRICA
MISAWA.JAPAN
GUAM
SHEMYA.ALASKA
HONOLULU.HAWAII
TAFUNA.SAMOA
NAPIER.NEW ZEALAND
ANCHORAGE.ALASKA
KINGMAN.ARIZONA
LAS CRUCES.N.MEXICO
AUSTIN.TEXAS
OLYMPIA.WASH.
EASTER IS.
LA PAZ.BOLIVIA
QUITO.ECUADOR
HOWARD COUNTY.MD.
THULE.GREENLAND
ASCENSION IS.
ST.HELENA IS.
SAO JOSE.BRAZIL
PARAGUAY
MCMURDO.ANTARCTICA

FIGURE 3a

GEOS-3 ALONG TRACK RESIDUALS
FOR NWL 10E GRAVITY FIELD
DAY 176



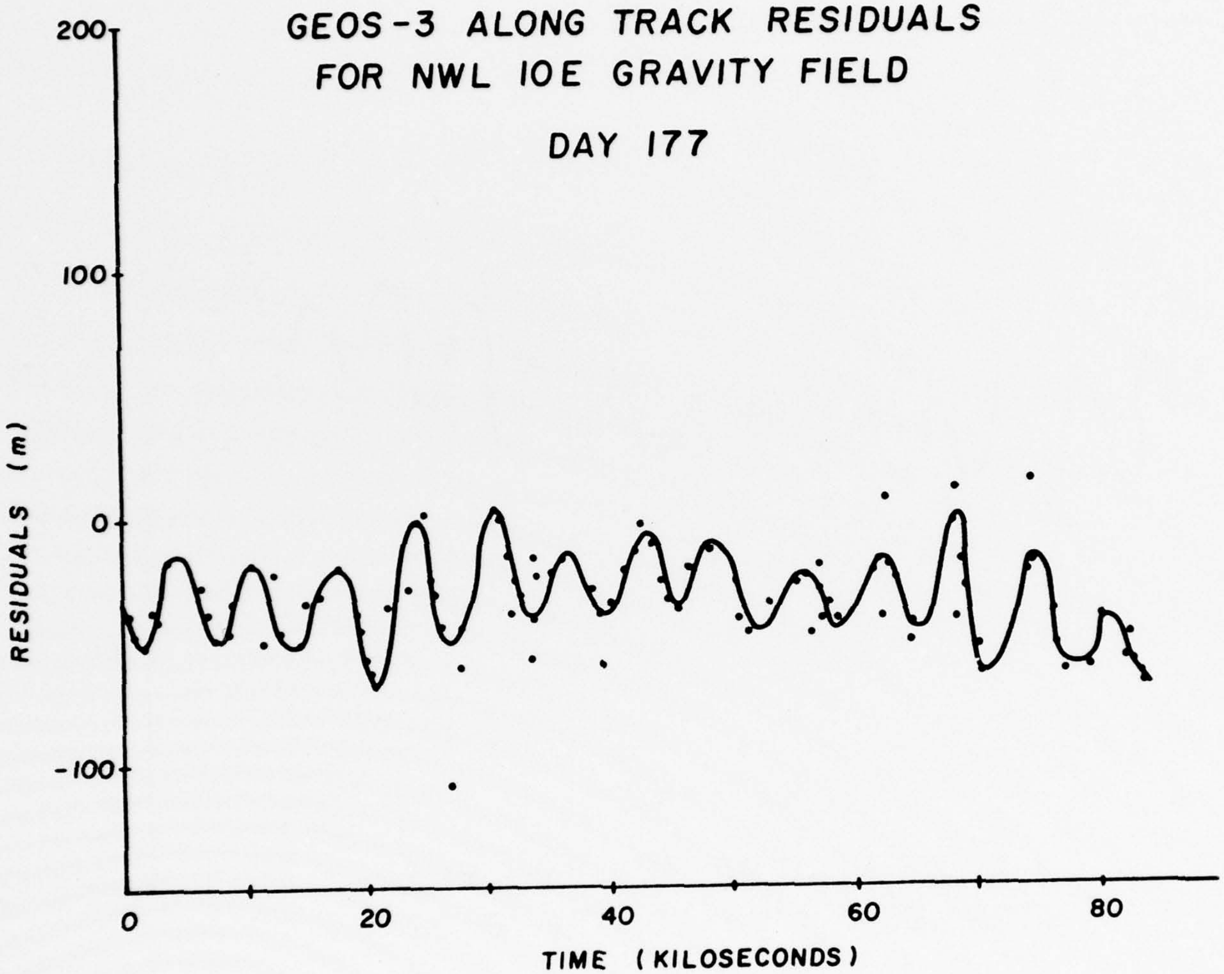


FIGURE 3b

GEOS-3 ALONG TRACK RESIDUALS
FOR NWL 10E GRAVITY FIELD

DAY 177

FIGURE 3c

GEOS-3 ALONG TRACK RESIDUALS
FOR NWL 10E GRAVITY FIELD

DAY 178

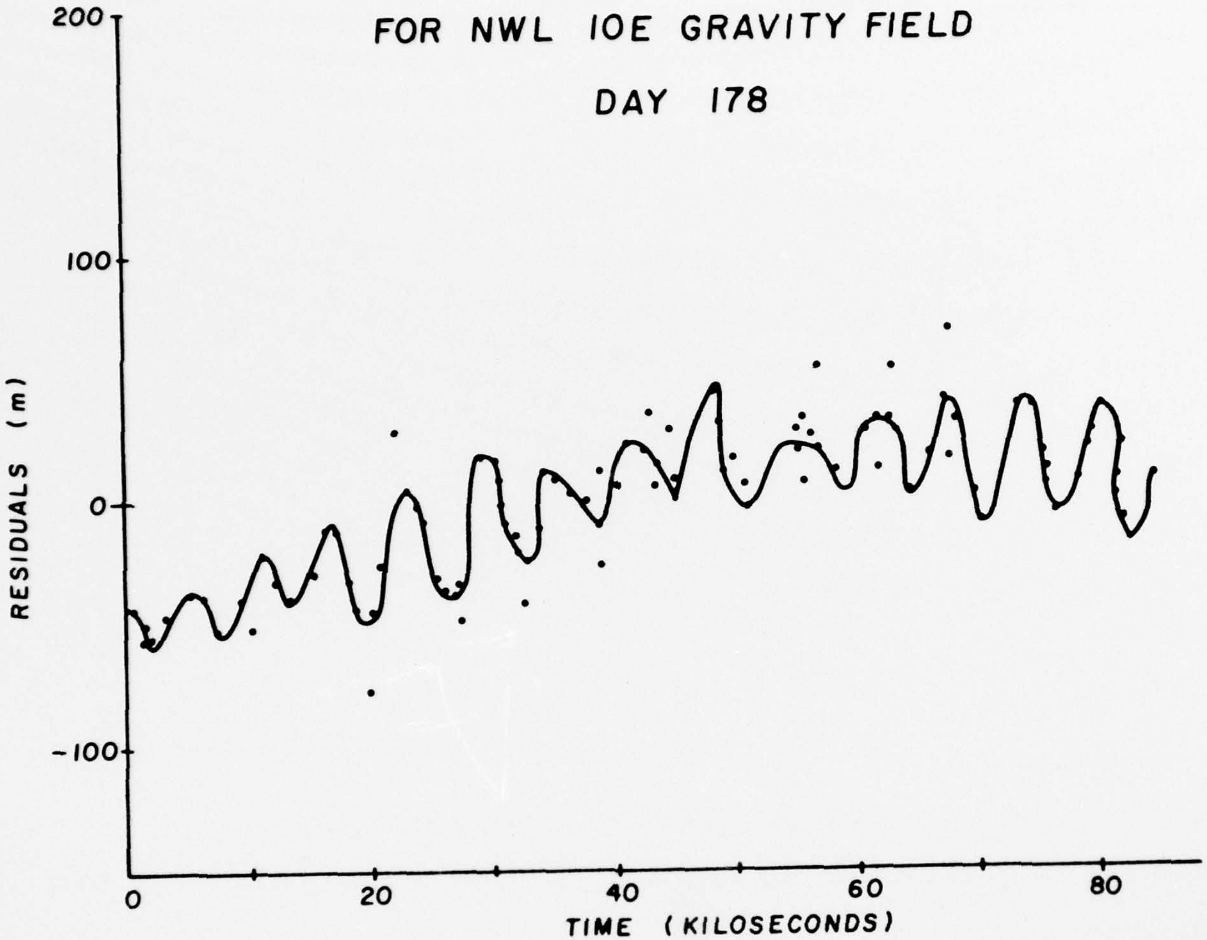


FIGURE 3d

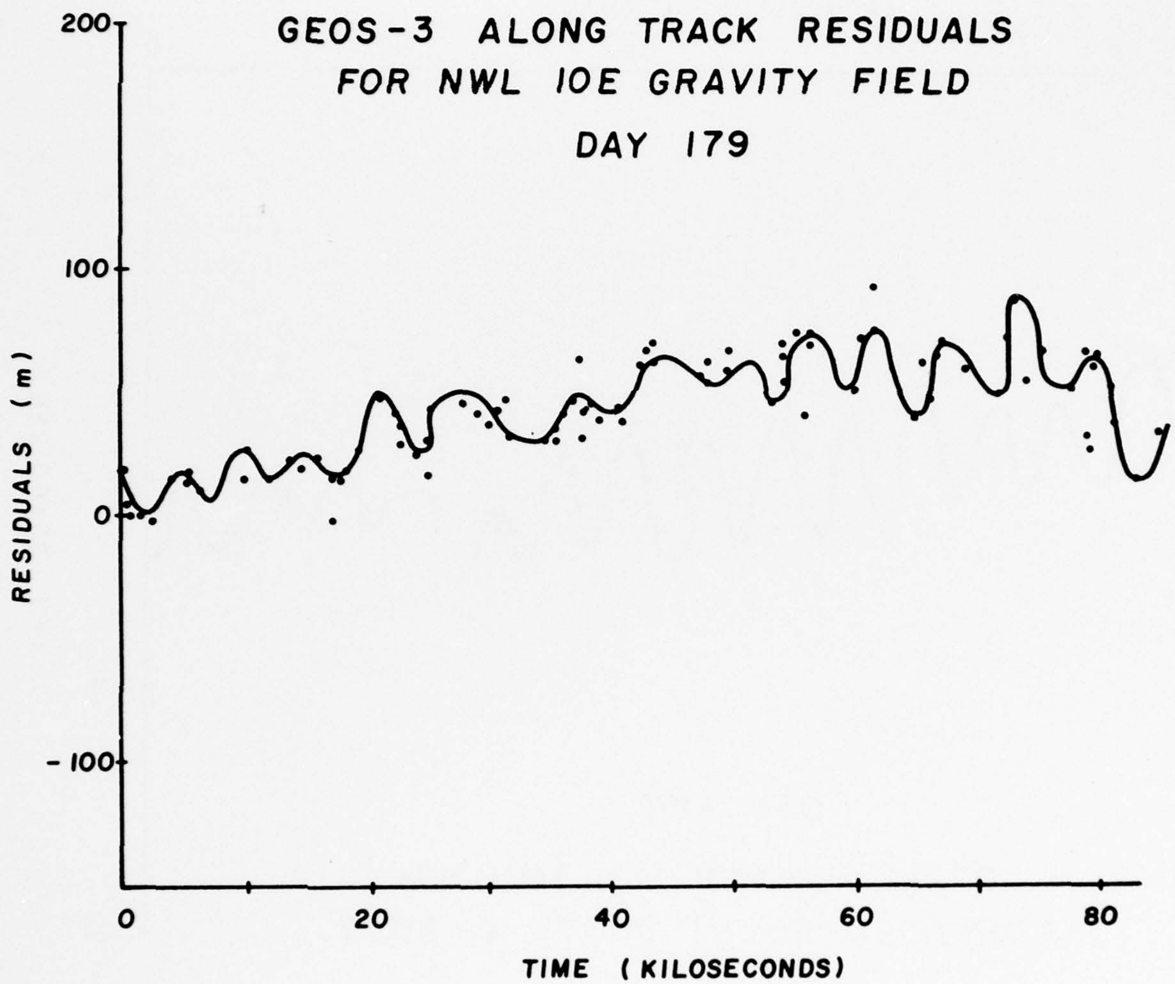

GEOS-3 ALONG TRACK RESIDUALS
FOR NWL 10E GRAVITY FIELD
DAY 179
RESIDUALS (m)
200
100
0
-100
0
20
40
60
80
TIME (KILOSECONDS)

FIGURE 3e

GEOS-3 ALONG TRACK RESIDUALS
FOR NWL 10E GRAVITY FIELD
DAY 180

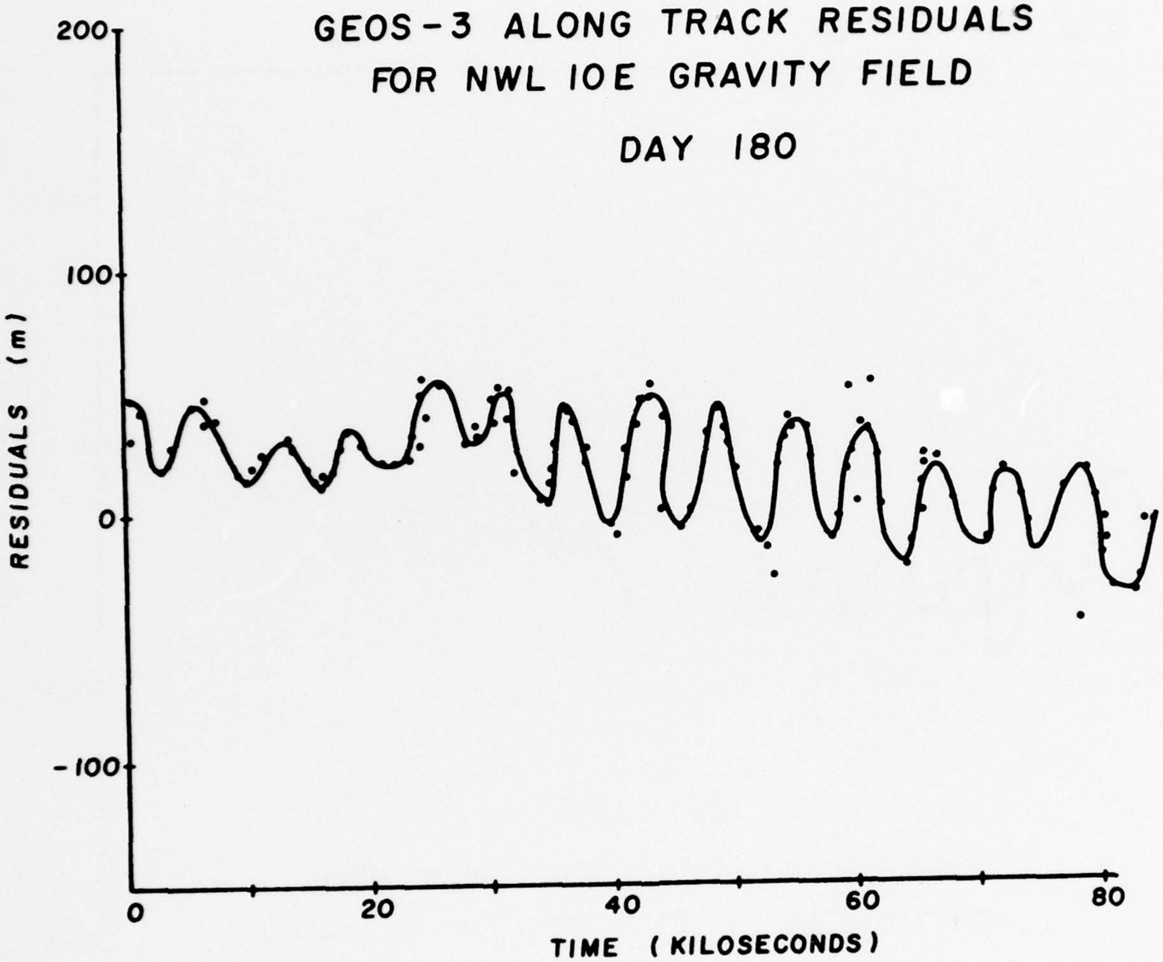


FIGURE 3f

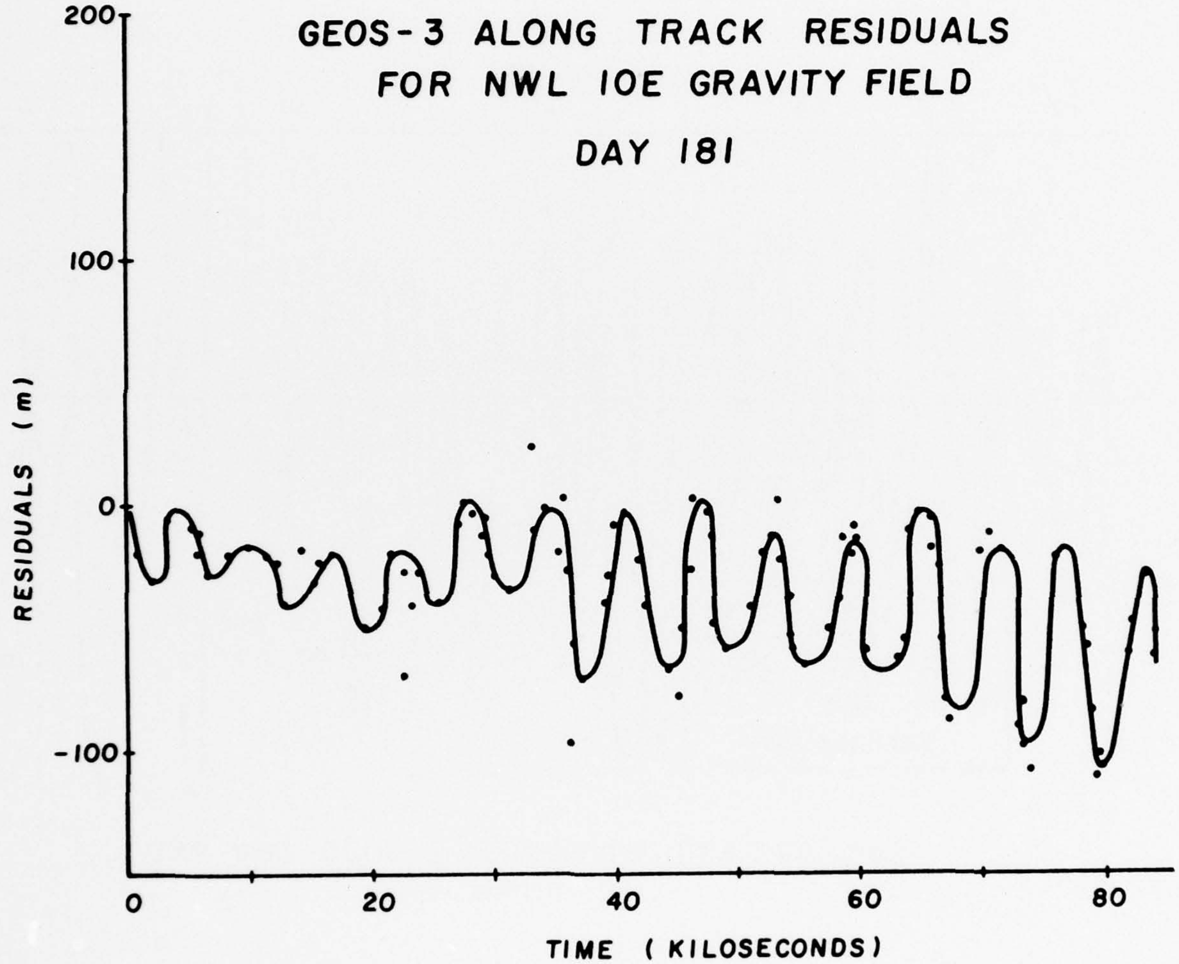

GEOS-3 ALONG TRACK RESIDUALS
FOR NWL 10E GRAVITY FIELD
DAY 181
200
100
0
-100
RESIDUALS (m)
0
20
40
60
80
TIME (KILOSECONDS)

FIGURE 4a

LONG ARC GEOS-3 RESIDUALS DAY 225 1975

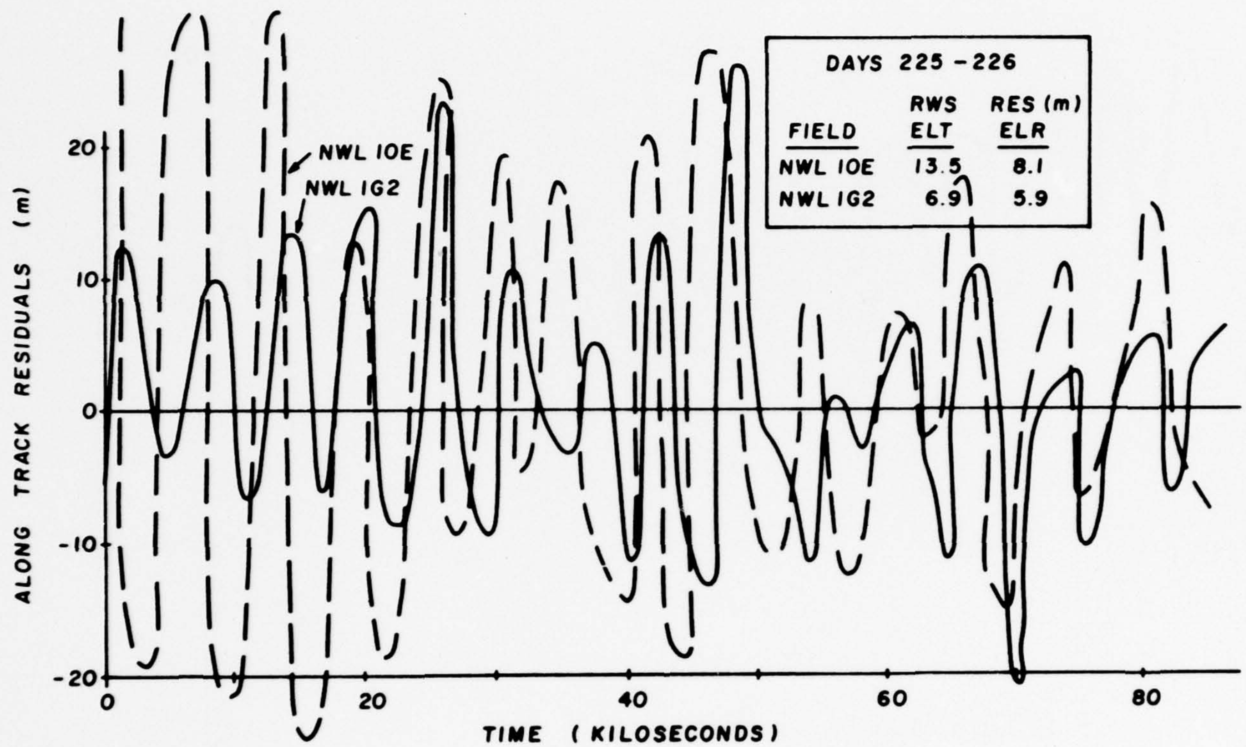


FIGURE 4b

GEOS-3 ALONG TRACK RESIDUALS DAY 226 1975

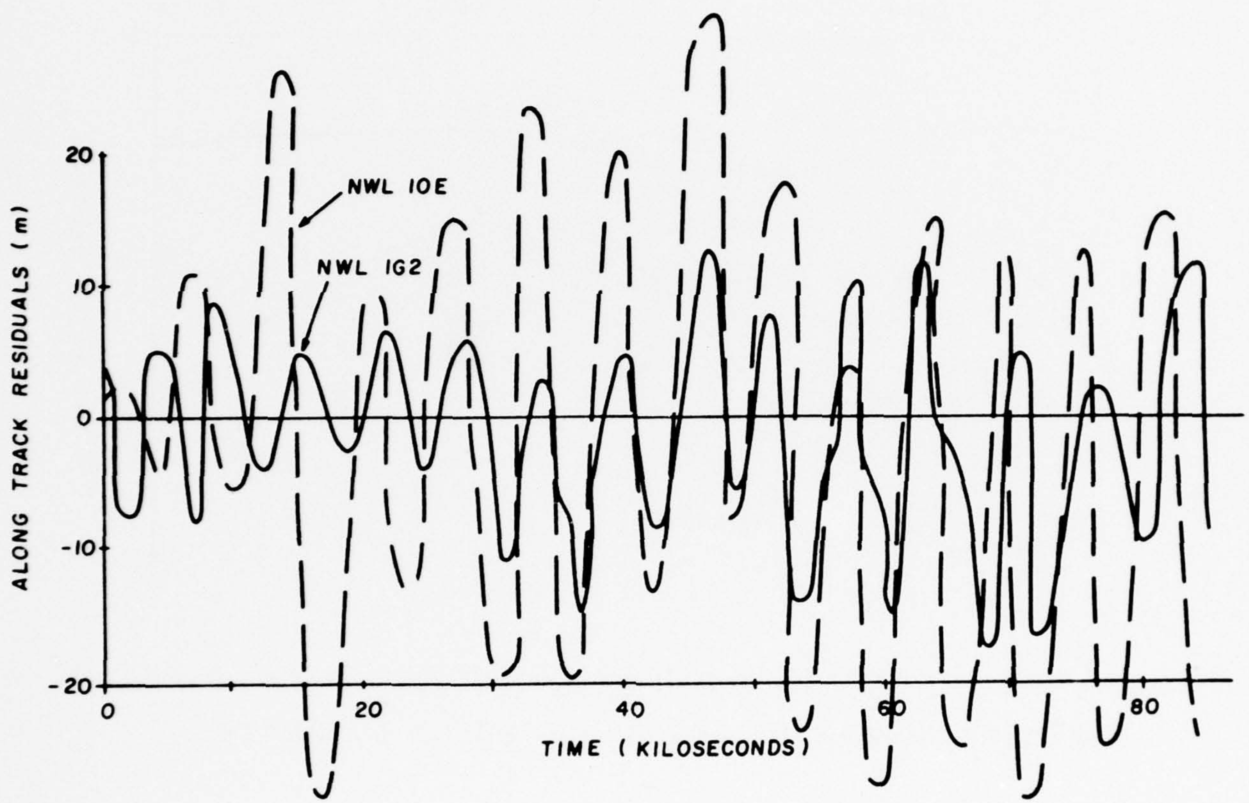


FIGURE 5

STANDARD ERROR OF GEOS-3 SHORT ARC EPHEMERIS
DAY 113 REVOLUTION 113

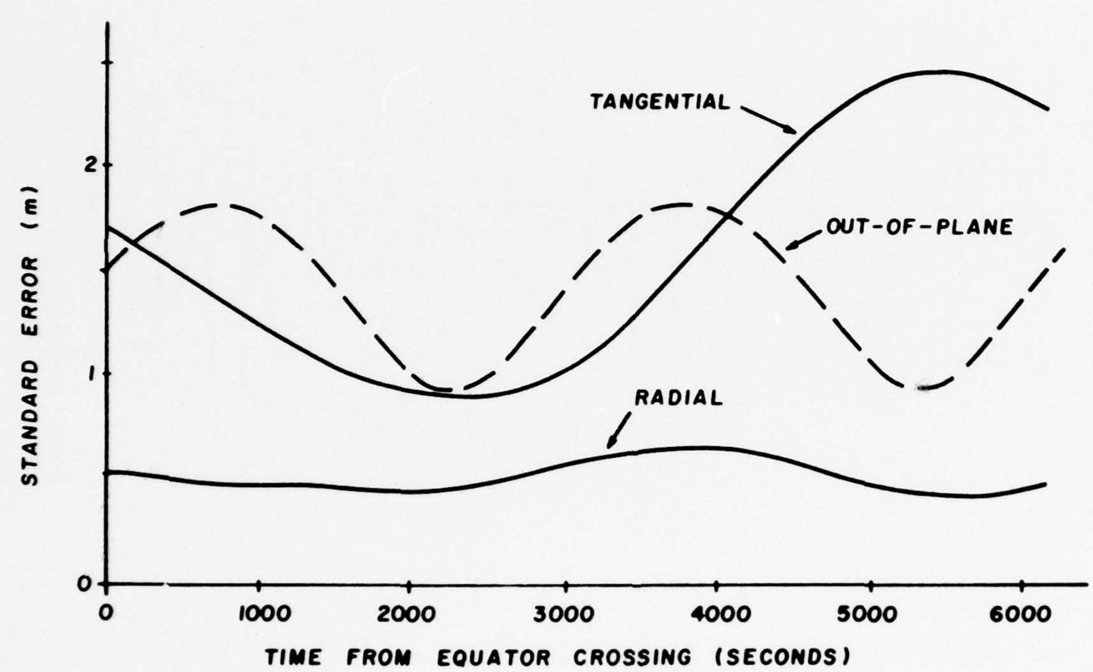


FIGURE 6a

ORBIT DIFFERENCE
NWL 10E vs NWL 1G5
DAY 113 REVOLUTION 197

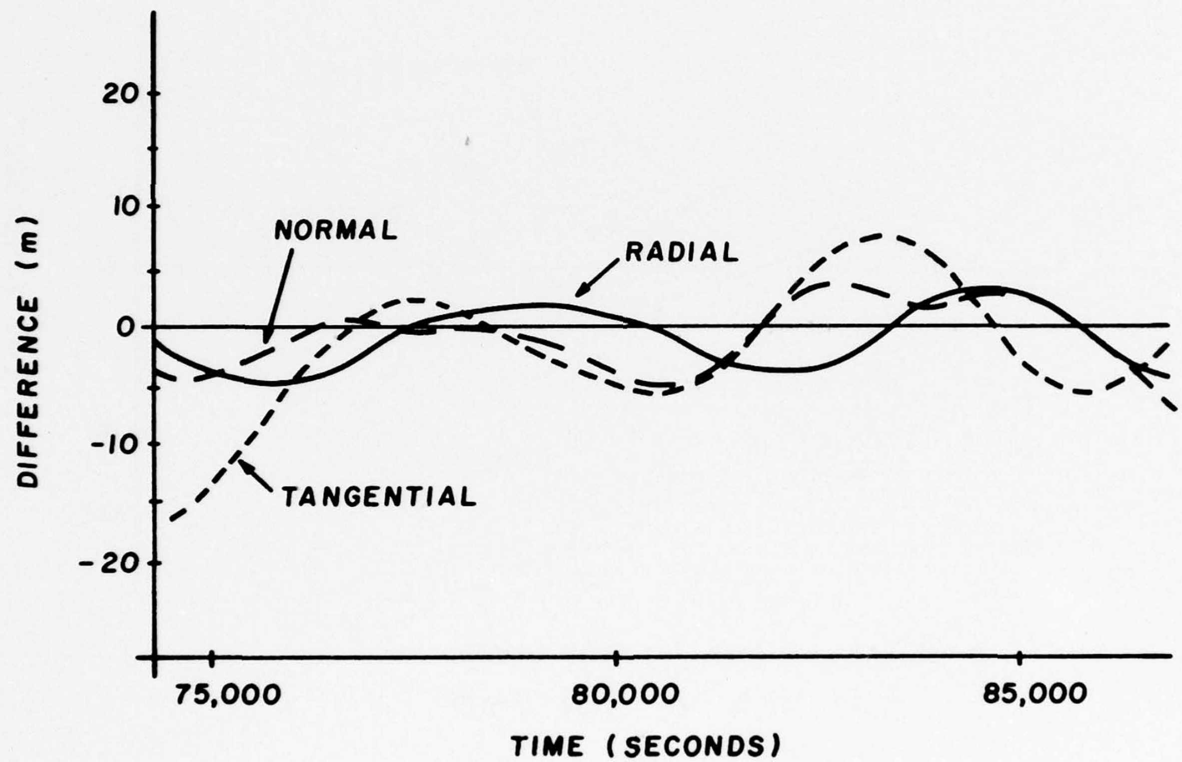


FIGURE 6b

ORBIT DIFFERENCE
NWL 10E vs NWL 1G5
DAY 114 REVOLUTION 202