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GRAVITY MODEL COMPARISON USING GEOS-I LONG ARC ORBITAL SOLUTIONS

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GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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SUMMARY

Satellite tracking data has been analyzed using three different sets of coefficients in the mathematical model that describes the earth's gravitational field. The results were not intended to be used as a definitive evaluation of the different coefficients but as an assessment of the effects that different sets of coefficients, station coordinates, and earth parameters that have been published, have on orbital geodetic results.

Orbital solutions were estimated from optical tracking data from the GEOS-I satellite, taken by five major geodetic optical tracking networks. The networks and camera types consisted of the SAO Baker-Nunn, GSFC STADAN and SPEOPT MOTS 40" and 24", USAF PC-1000, and the US C&GS BC-4. The three sets of gravity coefficients used were the SAO M-1 set (modified by the GEOS-I resonant harmonics), APL 3.5 set, and the NWL 5E-6 set. The semi-major axis, gravitational constant, and flattening consistent with each set of coefficients were also used. The station coordinates used were referenced to the SAO C-5 standard earth as no other complete set of optical station coordinates were available.

Several long arc orbital analyses were completed using each set of coefficients and the results were compared. Orbits were fitted to two overlapping

data sets; the arc lengths of these orbits were 5-1/4 days and 1 day. The orbital solutions obtained with each set of coefficients were compared. Furthermore, the trajectory differences were computed, and were resolved into radial, cross track and along track components. The along track differences were as great as 400 meters for the 5-1/4 day arc and 200 meters for the 1 day arc.

The range measurements of the Goddard Range and Range Rate (GRARR) S-Band Tracking System at Rosman were evaluated for 15 passes recorded during the first week in January 1966. The actual measurements were compared with values computed from the optical orbital solutions previously mentioned. The residual differences between the observed and computed ranges were analyzed for zero set range bias errors, timing errors, and random errors. The error estimates obtained from the orbital solutions determined using the SAO M-1 gravitational coefficients displayed a much greater degree of consistency from pass to pass. Also, the error estimates obtained from the 5-1/4 day arc were in good agreement with those obtained from the 1 day arc when the SAO M-1 coefficients were used but agreement was generally poor when the reference orbits were determined using the NWL 5E-6 and APL 3.5 gravitational coefficients.

Two estimates of the coordinates for the Goddard Range and Range Rate station in Tananarive, Madagascar were obtained from independent data sets using each set of coefficients. Only the SAO M-1 set produced two estimates that were consistent; they differed by only 5 meters.

These comparisons serve to reinforce what was intuitively obvious — that for long arc geodetic work, the most complete set of gravity coefficients together with consistent station coordinates should be used.

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LIST OF ABBREVIATIONS

APL	Applied Physics Laboratory of Johns Hopkins University
GSFC	Goddard Space Flight Center
MOTS	Minitrack Optical Tracking System
NWL	Naval Weapons Laboratory
SAO	Smithsonian Astrophysical Observatory
SPEOPT	Special Optical Tracking System
STADAN	Satellite Tracking and Data Acquisition Network
USAF	United States Air Force
USC&GS	United States Coast and Geodetic Survey

GRAVITY MODEL COMPARISON
USING GEOS-I LONG ARC
ORBITAL SOLUTIONS

1.0 INTRODUCTION

This report presents results and comparisons that have been obtained from the reduction of satellite tracking data using three different sets of coefficients in the mathematical model that describes the earth's gravitational field. These comparisons were not intended as an evaluation of the coefficients but as an assessment of the effects of using the different sets in order to choose the most suitable available set of gravity coefficients and station coordinates for long arc (greater than 6 revolutions) geodetic purposes.

These results were obtained using the orbit determination program NONAME (Reference 1), and the orbital solutions were estimated from optical tracking data taken from the GEOS-I satellite. The NONAME program uses a mathematical function based on Legendre polynomials to approximate the earth's gravitational field (Appendix A). Several sets of coefficients for these polynomials have been published; three of these sets were used for this work; they are:

1. The SAO M-1 Set. Modified by the GEOS-I Resonant Harmonics ($C_{13,12}$, $C_{14,12}$, $C_{15,12}$, $S_{13,12}$, $S_{14,12}$, $S_{15,12}$) (Reference 2), (Reference 7).

2. The APL 3.5 Set (Reference 3).

3. The NWL 5E-6 Set (Reference 4).

These are presented in Table II.

For the purposes of these comparisons, the earth's semi-major axis, gravitational constant, and flattening coefficient that are consistent with each set of coefficients were used. These are summarized in Table I. The station coordinates were unchanged and were referenced to the SAO C-5 standard earth (Appendix C), since no other complete set of coordinates for the optical tracking stations was available.

The use of only the one set of station coordinates prevents these results being used as any sort of definitive evaluation of these sets of gravity coefficients. It should be noted, however, that the ellipsoids defined by the parameters in Table I are very similar; thus the station coordinates, if they are fairly

Table I

Parameters for the Earth's Ellipsoid

Parameter \ Model	SAO M-1	APL 3.5	NWL 5E-6
Gravitational Constant (km^3/sec^2)	3.986032×10^5	3.986075×10^5	3.9860542×10^5
Semi-Major Axis (km)	6378.165	6378.166	6378.165
Flattening	$\frac{1.}{298.25}$	$\frac{1.}{298.30}$	$\frac{1.}{298.25}$

Table II

Harmonic Coefficients (Normalized)

n	m	SAO M1		APL 3.5		NWL 5E-6	
		$\bar{C} \times 10^6$	$\bar{S} \times 10^6$	$\bar{C} \times 10^6$	$\bar{S} \times 10^6$	$\bar{C} \times 10^6$	$\bar{S} \times 10^6$
2	0	-484.1735		-484.198		-484.194	
2	1					0.016	0.062
2	2	2.379	-1.351	2.381	-1.198	2.446	-1.519
3	0	0.9623		1.011		0.984	
3	1	1.936	0.266	1.84	0.215	2.148	0.274
3	2	0.734	-0.538	1.219	-0.6791	0.978	-0.906
3	3	0.561	1.620	0.6609	0.9795	0.585	1.625
4	0	0.5497		0.467		0.507	
4	1	-0.572	-0.469	-0.5624	-0.4403	-0.495	-0.575
4	2	0.330	0.661	-0.4179	0.4438	0.274	0.671

Table II (Continued)

n	m	SAO M1		APL 3.5		NWL 5E-6	
		$\bar{C} \times 10^6$	$\bar{S} \times 10^6$	$\bar{C} \times 10^6$	$\bar{S} \times 10^6$	$\bar{C} \times 10^6$	$\bar{S} \times 10^6$
4	3	0.851	-0.190	0.8464	0.007062	1.030	-0.247
4	4	-0.053	0.230	-0.2106	0.1898	-0.413	0.336
5	0	0.0633		0.084		0.045	
5	1	-0.079	-0.103	0.1370	-0.1669	0.032	-0.119
5	2	0.631	-0.232	0.2684	-0.3379	0.637	-0.328
5	3	-0.520	0.007	0.09131	0.1035	-0.389	-0.124
5	4	-0.265	0.064	-0.4884	-0.260	-0.549	0.148
5	5	0.156	-0.592	-0.03358	-0.6686	0.215	-0.594
6	0	-0.1792		-0.103		-0.219	
6	1	-0.047	-0.027	-0.0002093	0.1009	-0.085	0.192
6	2	0.069	-0.366	-0.1610	-0.1555	0.129	-0.457
6	3	-0.054	0.031	0.5303	0.05111	-0.020	-0.134
6	4	-0.044	-0.518	-0.3069	-0.5087	-0.193	-0.316
6	5	-0.313	-0.458	-0.18	-0.5091	-0.093	-0.786
6	6	-0.040	-0.155	0.01434	-0.2316	-0.324	-01360
7	0	-0.0860		0.153		0.105	
7	1	0.197	0.156	0.1261	0.09355	0.331	0.083
7	2	0.364	0.163	0.4586	0.05998	0.350	-0.195
7	3	0.250	0.018	0.3938	-0.2067	0.323	0.045
7	4	-0.152	-0.102	-0.1368	0.0004798	-0.467	-0.244
7	5	0.076	0.054	-0.05682	-0.1871	0.055	0.021
7	6	-0.328	0.063	-0.4552	0.758	-0.477	-0.244
7	7	0.055	0.096	0.08840	-0.1443		

Table II (Continued)

n	m	SAO M1		APL 3.5		NWL 5E-6	
		$\overline{C} \times 10^6$	$\overline{S} \times 10^6$	$\overline{C} \times 10^6$	$\overline{S} \times 10^6$	$\overline{C} \times 10^6$	$\overline{S} \times 10^6$
8	0	0.0655		0.170			
8	1	-0.075	0.065	-0.1481	-0.04843		
8	2	0.026	0.039	0.09472	-0.03764		
8	3	-0.037	0.004	-0.05497	0.2168		
8	4	-0.212	-0.012	-0.06901	0.03761		
8	5	-0.053	0.118	0.08040	-0.002495		
8	6	-0.017	0.318	-0.02193	0.6658		
8	7	-0.0087	0.031	0.1697	-0.07009		
8	8	-0.248	0.102	-0.1457	0.09424		
9	0	0.0122		0.041			
9	1	0.117	0.012				
10	00	0.0118					
10	01	0.105	-0.126				
10	02	-0.105	-0.042				
10	03	-0.065	0.030				
10	04	-0.074	-0.111				
11	00	-0.0630		0.104			
11	01	-0.053	0.015				
12	00	0.0714		0.062			
12	01	-0.163	-0.071				
12	02	-0.103	-0.0051				
12	12	-0.031	0.0008				

Table II (Continued)

n	m	SAO M1		APL 3.5		NWL 5E-6	
		$\bar{C} \times 10^6$	$\bar{S} \times 10^6$	$\bar{C} \times 10^6$	$\bar{S} \times 10^6$	$\bar{C} \times 10^6$	$\bar{S} \times 10^6$
13	00	0.0219					
13	12	-0.06769	0.06245				
13	13	-0.059	0.077	-0.4689	0.04748	-0.03	0.11
14	00	-0.0332					
14	01	-0.015	0.0053				
14	11	0.0002	-0.0001				
14	12	0.00261	-0.02457				
14	14	-0.014	-0.003	-0.06368	-0.037		
15	09	-0.0009	-0.0018				
15	12	-0.07473	-0.01026				
15	13	-0.058	-0.046			-0.06	-0.06
15	14	0.0043	-0.0211	0.00087843	-0.0101	0.01	-0.03

accurately determined with reference to the center of mass, as the SAO C-5 coordinates are generally accepted to be, should not introduce any large differences in the results.

Several long arc analyses were completed using each set of coefficients in turn, and the results have been compared; these are discussed in some detail in Sections 3.0 - 6.0.

2.0 DESCRIPTION OF THE EARTH'S GRAVITATIONAL FIELD

The earth's geopotential can be approximated by the following mathematical model:

$$U = \frac{GM}{r} \left\{ 1 + \sum_{n=2}^{k} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^n p_n^m \left(\sin \phi\right) \left[C_{nm} \cos m\lambda + S_{nm} \sin m\lambda \right] \right\} \quad (1)$$

where

G is the universal gravitational constant,

M is the mass of the earth,

r is the geocentric satellite distance,

a is the earth's mean equatorial radius,

ϕ is the sub-satellite geocentric latitude,

λ is the sub-satellite east longitude,

p_n^m $(\sin \phi)$ are the associated Legendre polynomials of degree n and order m,

and

C_{nm}, S_{nm} are the denormalized gravitational coefficients.

The denormalized gravitational coefficients are related to the normalized coefficients ($\overline{C}_{nm}$, $\overline{S}_{nm}$) as indicated below:

$$C(n,m) = \left[(n-m)!\,(2n+1)\,K/(n+m)!\right]^{1/2} \overline{C}(n,m)$$

$$S(n,m) = \left[(n-m)!\,(2n+1)\,K/(n+m)!\right]^{1/2} \overline{S}(n,m)$$

where,

$K = 1$ when $m = 0$

$K = 2$ when $m \neq 0$

The geopotential formulated in this manner can be converted into gravitational accelerations in inertial coordinates (x, y, z) as follows:

$$\ddot{x}_{\oplus} = \frac{\partial u}{\partial r}\frac{\partial r}{\partial x} + \frac{\partial u}{\partial \phi}\frac{\partial \phi}{\partial x} + \frac{\partial u}{\partial \lambda}\frac{\partial \lambda}{\partial u},$$

where the subscript "o" denotes accelerations due to the earth's gravitational field. Similar expressions hold for $\ddot{y}_{\oplus}$ and $\ddot{z}_{\oplus}$. The NONAME program uses a model in this form to compute the accelerations due to the earth's gravitational field.

The three different sets of harmonic coefficients (normalized) and associated earth parameters used in this analysis are shown in Tables I and II. The SAO M-1 is the largest set with a total of 122 coefficients; the APL 3.5 set has 84 coefficients and the NWL 5E-6 set has 64. Of these three sets, only the SAO M-1 set has GEOS-I resonant terms (harmonics of order 12).

The SAO M-1 set was determined using optical observations from a number of satellites, and the other two sets were determined from Tranet Doppler observations, again from a number of satellites.

3.0 DIFFERENCES IN ORBITAL SOLUTIONS

Orbits were fitted to two data sets from the first week in January 1966, and the arc lengths of these orbits were 5-1/4 days and 1 day. The 5-1/4 day arc covered the period from 01 hrs. GMT on December 31, 1965 to 06 hrs., January 5, 1966, and the data set consisted of 1057 optical observations.* The 1 day arc covered the period from 06 hrs., January 2, 1966, to 08 hrs., January 3, 1966. This data was a subset of the 5-1/4 day arc data set and consisted of 444 optical observations. These data sets are summarized in Table III.

The root mean squares of the observations about the orbital solutions were computed and these are shown in Table IV. The r.m.s. values were lower for the orbits fitted using the SAO M-1 set for both arcs. The differences between the observed measurements and values computed from the orbital solutions were computed and plotted on histograms; these are shown in Figures 1-4. The right ascension residuals shown in the Figures have been multiplied by the cosine of the corresponding declination measurement to account for the degradation of the measurements recorded when the declination value was large. These Figures clearly indicate that the orbital solutions obtained with the SAO M-1 set of coefficients fit the data sets better than the other solutions. This is especially true

*Right ascension plus declination measurements.

Table III

Summary of Optical Measurements By Station

Network	Station	Camera Type	No. of Observations	
			5-1/4 Day Arc	1 Day Arc
SAO	1ORGAN	Baker-Nunn	2	
	1JUPTR	"	26	26
	1NATOL	"	8	2
	OSLONR	"	4	
	AUSBAK	"	4	
	1SHRAZ	"	2	2
	1SPAIN	"	6	
	1TOKYO	"	12	4
	1VILDO	"	2	
	1MAUIO	"	2	
	AGASSI	Geodetic 36"	10	
	Total:		78	34
SPEOPT	1COLBA	MOTS 40"	164	71
	1JUM40	"	22	16
	1BERMD	"	84	36
	1PURI0	"	14	
	1DENVR	"	70	14
	1JUM24	MOTS 24"	26	24
	Total:		380	158
STADAN	1FTMYR	MOTS 40"	82	54
	1BPOIN	"	53	
	1GFORK	"	26	9
	1MOJAV	"	25	25
	Total:		186	91
USAF	HUNTER	PC-1000	59	47
	SWANIS	"	14	14
	GRDTRK	"	7	
	ANTIGA	"	26	
	SEMMES	"	60	36
	CURACO	"	40	26
	HOMEST	"	94	24
	JUPRAF	"	17	17
	BEDFRD	"	22	
	ABERDN	"	74	
	Total:		413	164
Total of All Observations			1,057	444

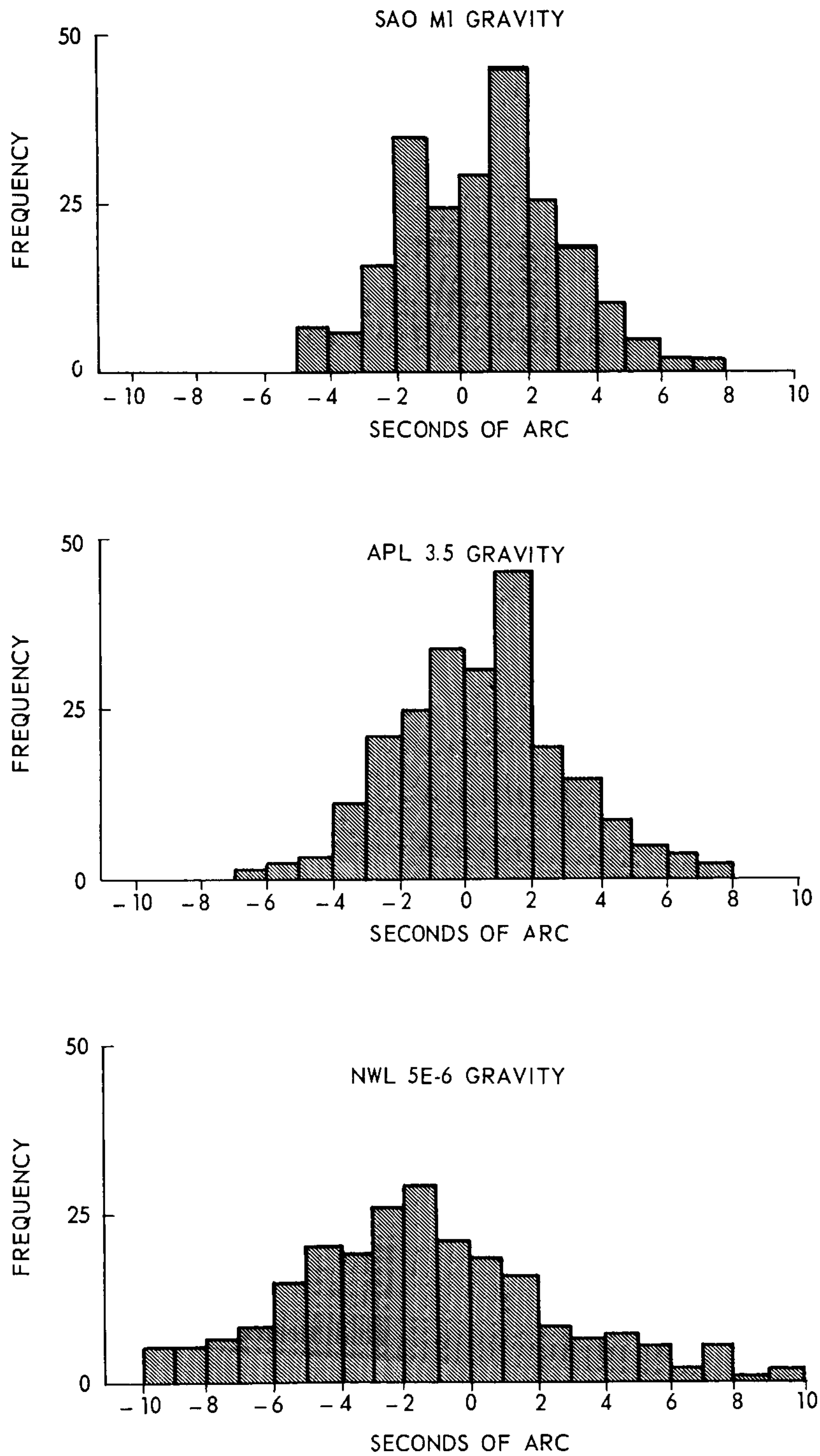


Figure 1. Right Ascension Residuals from 1 Day Arc

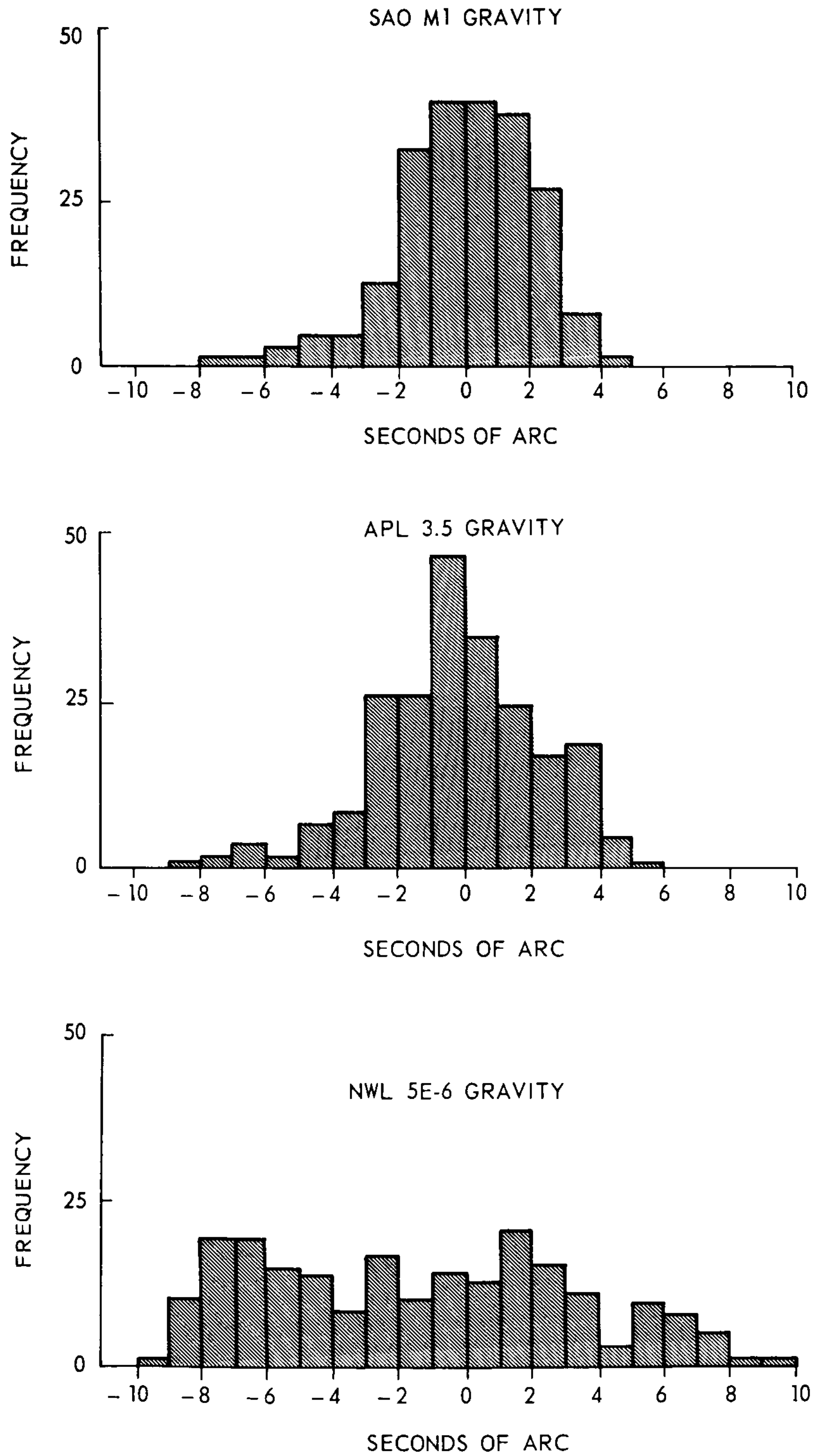


Figure 2. Declination Residuals from 1 Day Arc

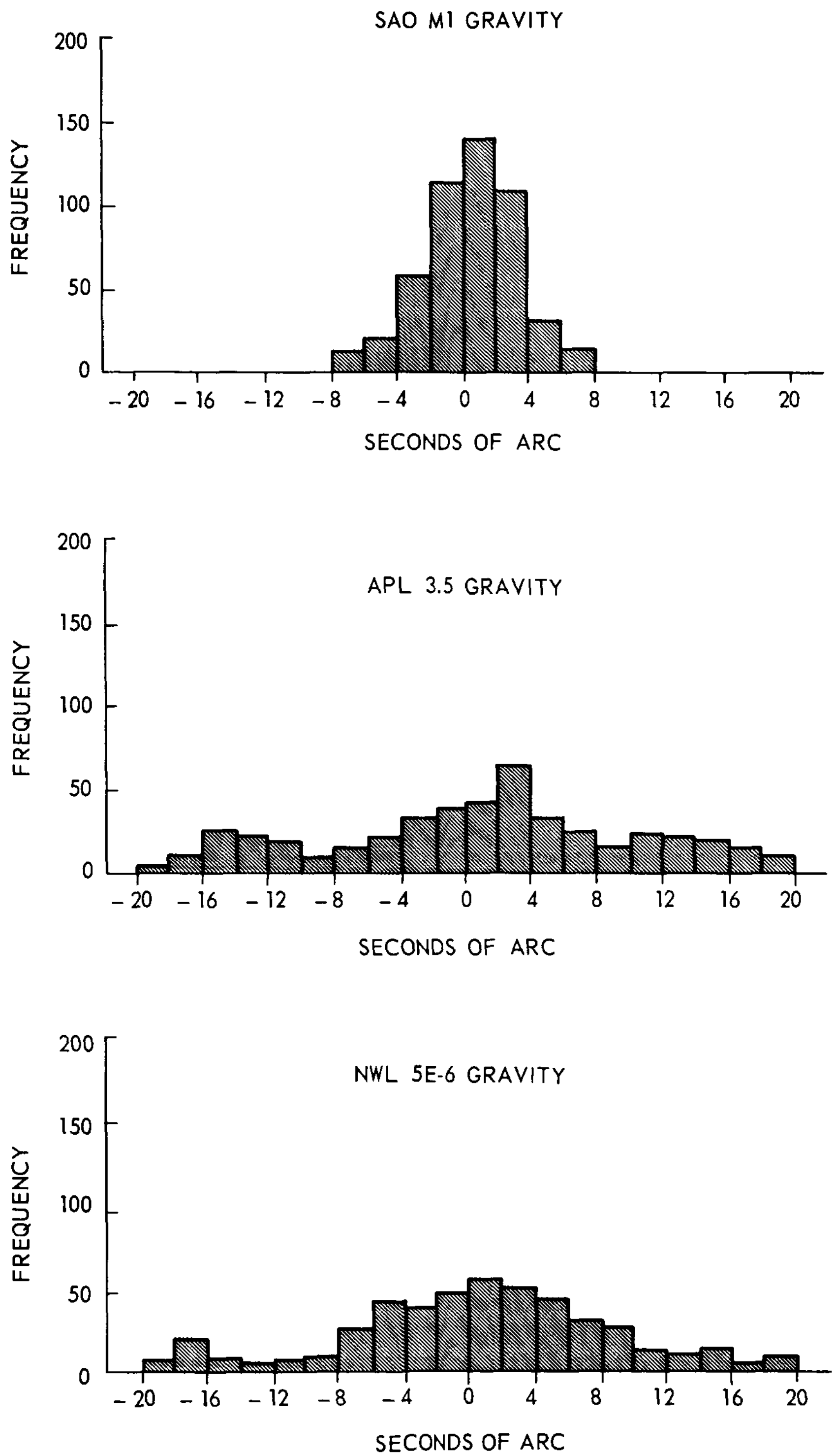


Figure 3. Right Ascension Residuals from 5 1/4 Day Arc

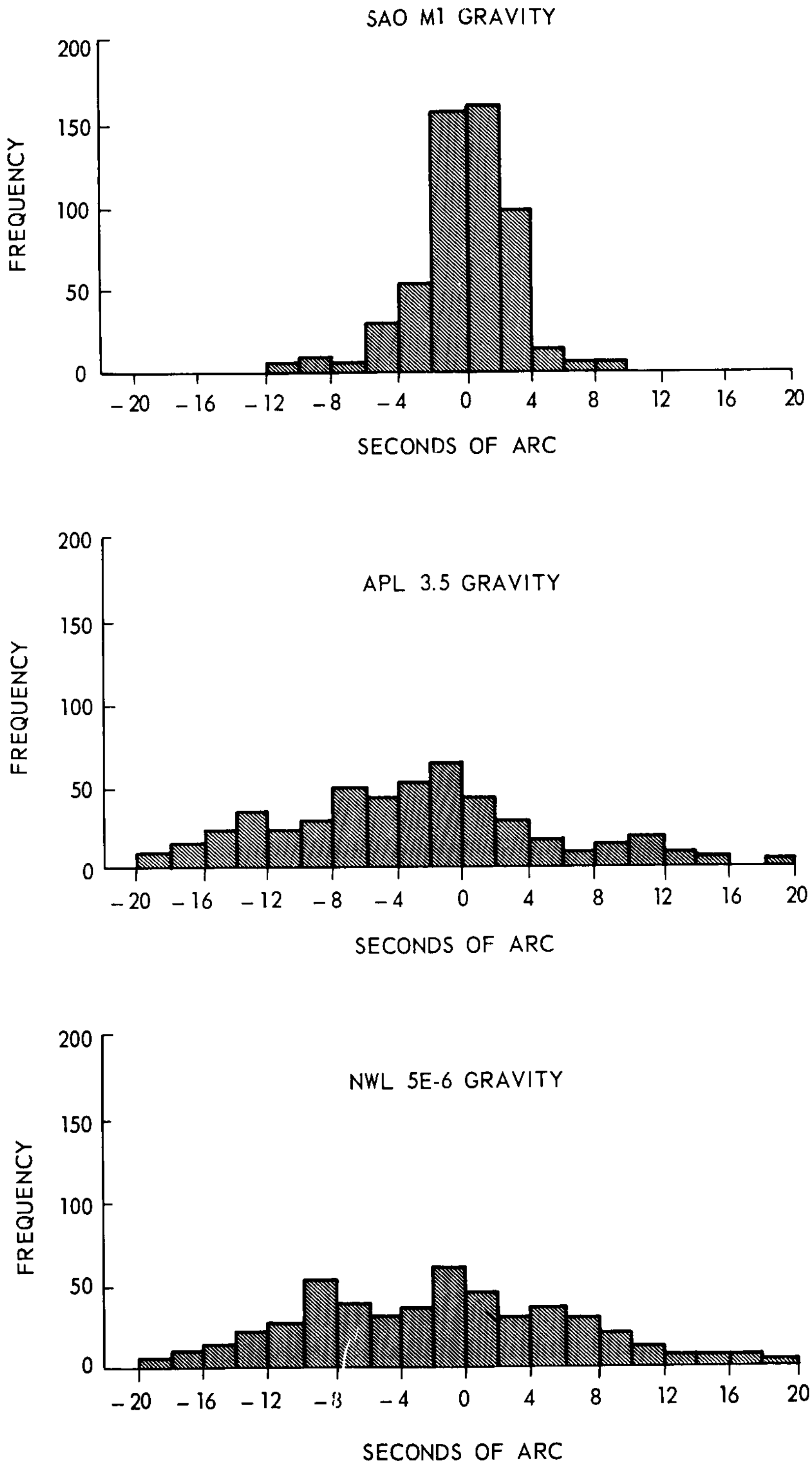


Figure 4. Declination Residuals from 5 1/4 Day Arc

Table IV

Root Mean Squares About The Orbital Solution

Arc Length	R.M.S. of Fit (Secs. of Arc)		
	SAO M-1	APL 3.5	NWL 5E-6
5-1/4 day	3.08	11.14	11.01
1 day	2.33	2.50	4.54

for the 5-1/4 day arc (Figures 3-4) where the distributions of the right ascension and declination residuals for the APL 3.5 and NWL 5E-6 solutions are obviously non normal.

4.0 TRAJECTORY DIFFERENCES

Satellite position differences were computed at five minute intervals using the orbital solution obtained from the SAO M-1 coefficients as a standard for comparing the solutions obtained for the same data set when the APL 3.5 and NWL 5E-6 gravitational coefficients were used. These position differences were resolved into along track, cross track and radial components and are shown in Figures 5-8.

The along track differences were the largest. They were as large as 400 meters for the 5-1/4 day arc and 200 meters for the 1 day arc. The cross track and radial differences were approximately the same order of magnitude and were as large as 100 meters for the 5-1/4 day arc and 50 meters for the 1 day arc. The differences have a period approximately equal to the period of the satellite (2 hrs), and, in addition, the along track differences have some other long period associated with them. The periods of the along track, cross track, and radial differences are not in phase, and in general, the minima occur where there is good data coverage; this is shown by the solid blocks in the figures.

5.0 EVALUATION OF THE ROSMAN GRARR RANGE ACCURACY

The range measurements of the Goddard Range and Range Rate (GRARR) S Band Tracking System at Rosman, North Carolina, were evaluated by comparing the actual measurements with values computed from the optical reference orbits (Reference 5). The 5-1/4 day arc and the 1 day arc discussed in Section 3.0 were

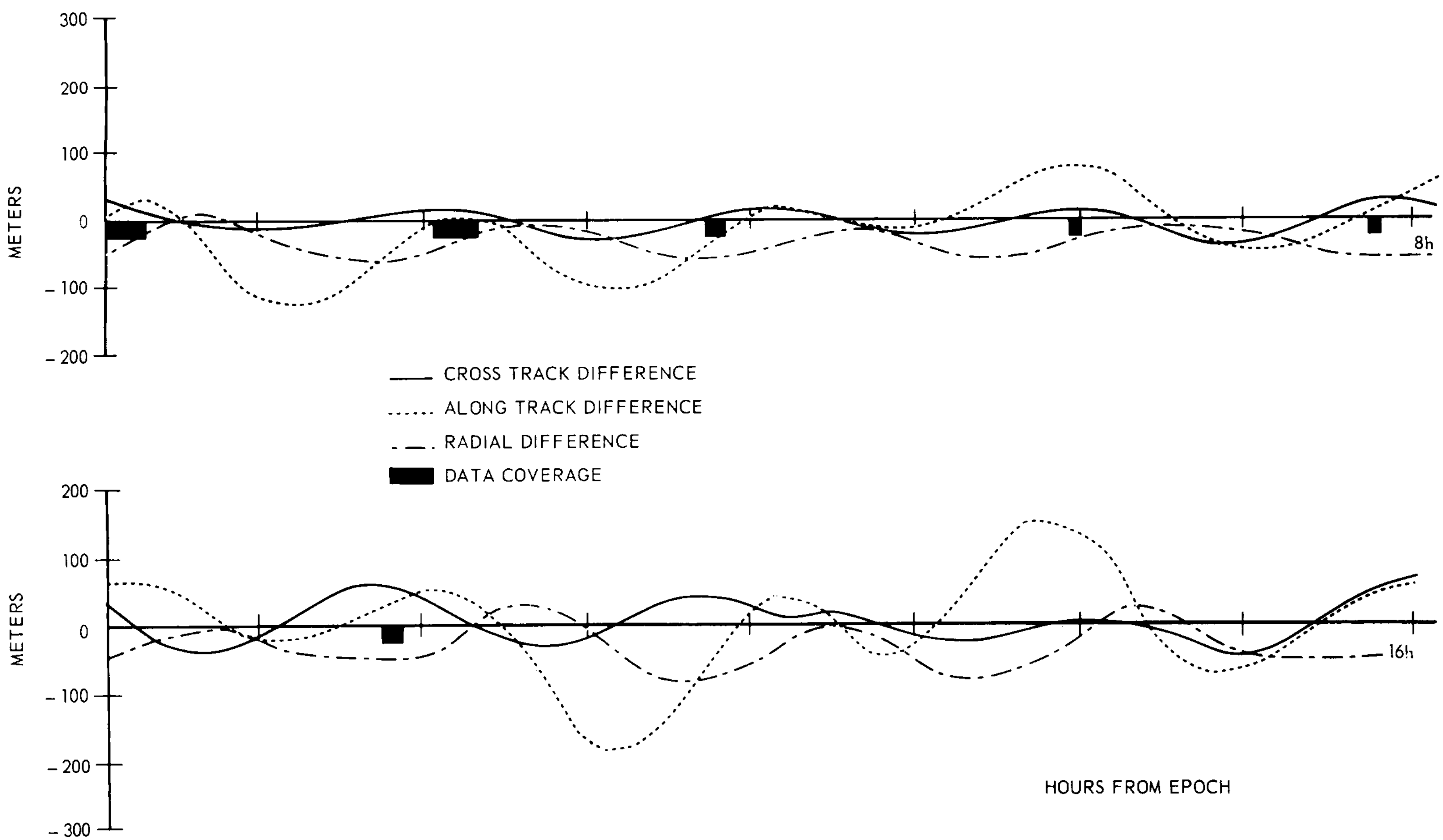


Figure 5. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 1 Day Arc

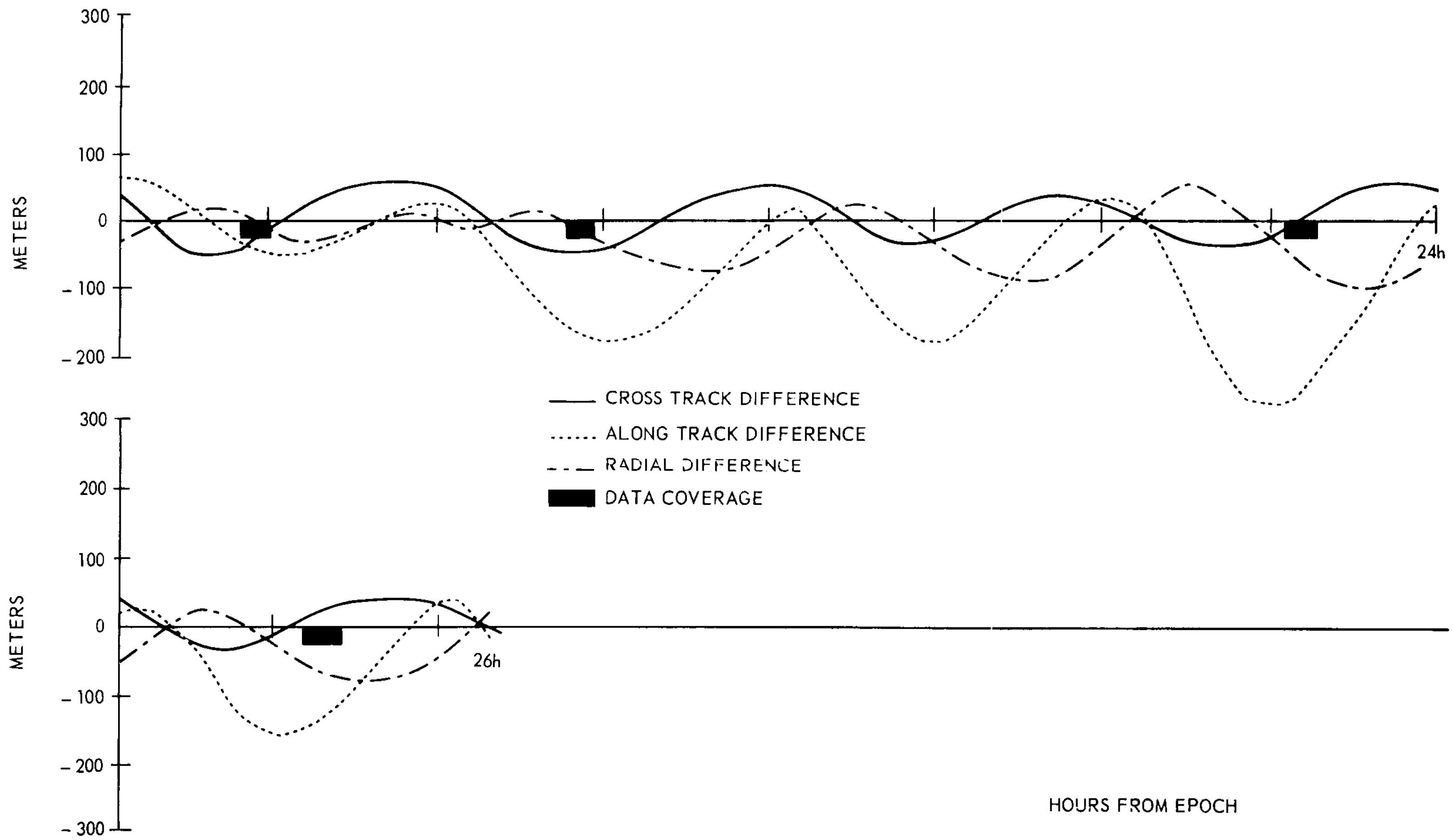


Figure 5. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 1 Day Arc (Continued)

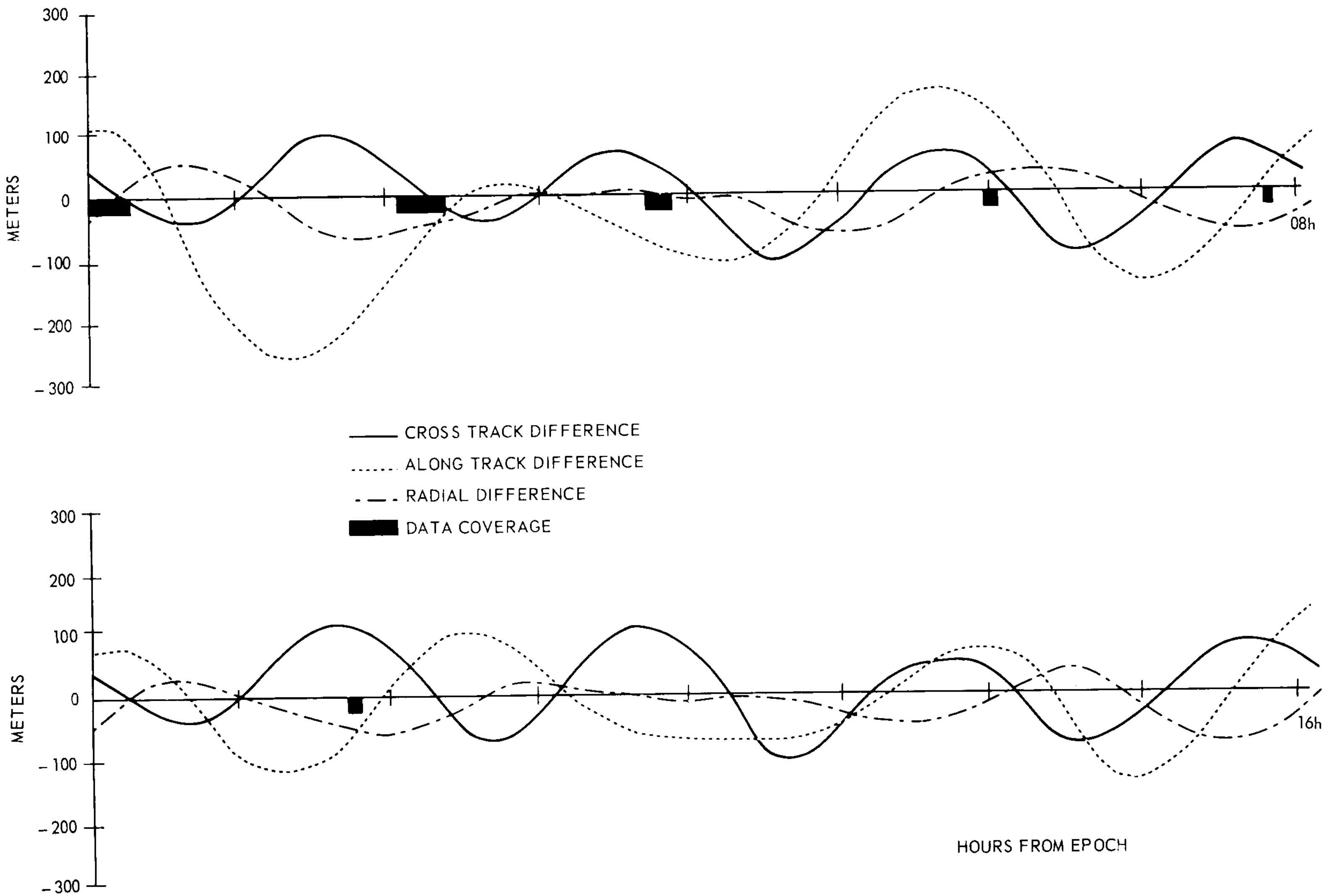


Figure 6. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 1 Day Arc

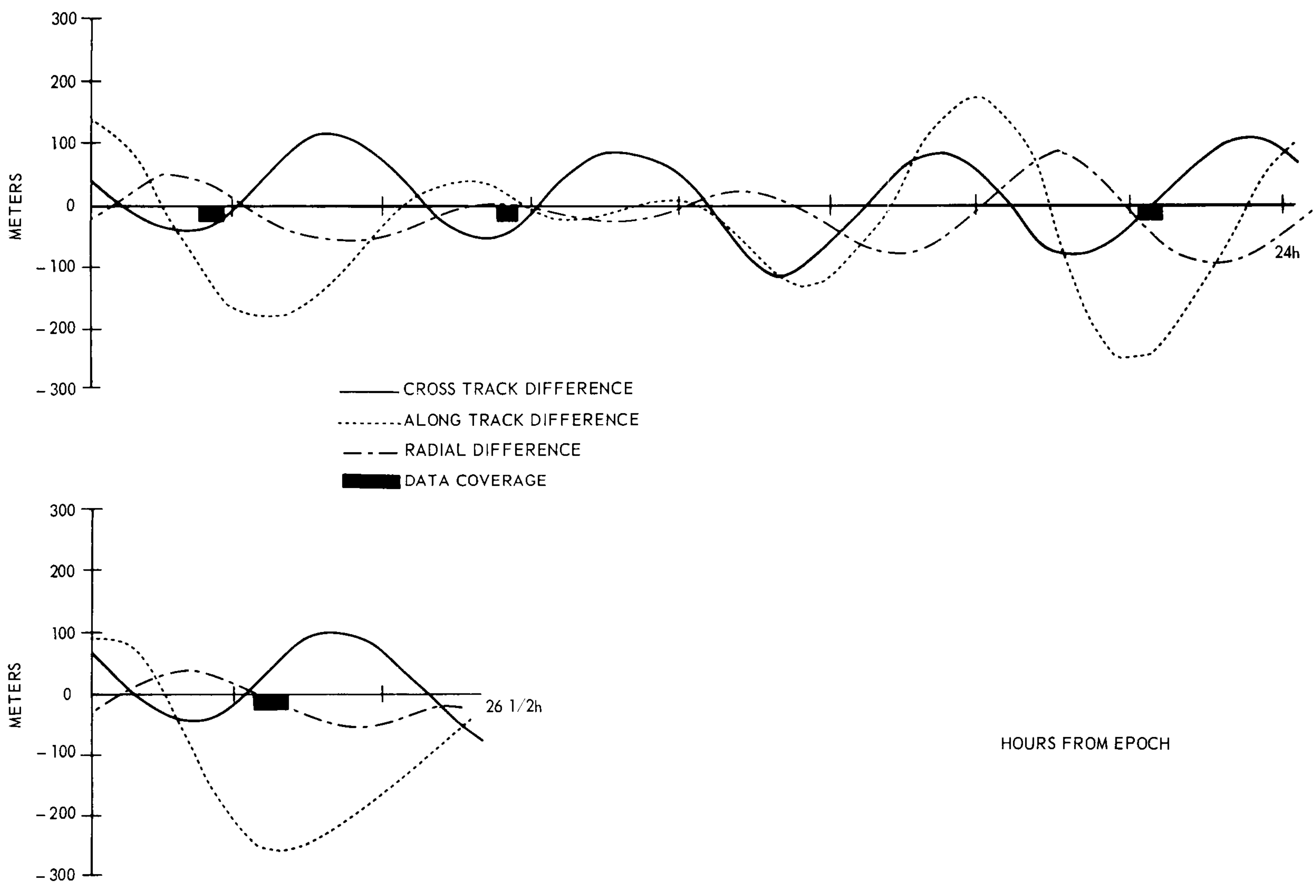


Figure 6. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 1 Day Arc (Continued)

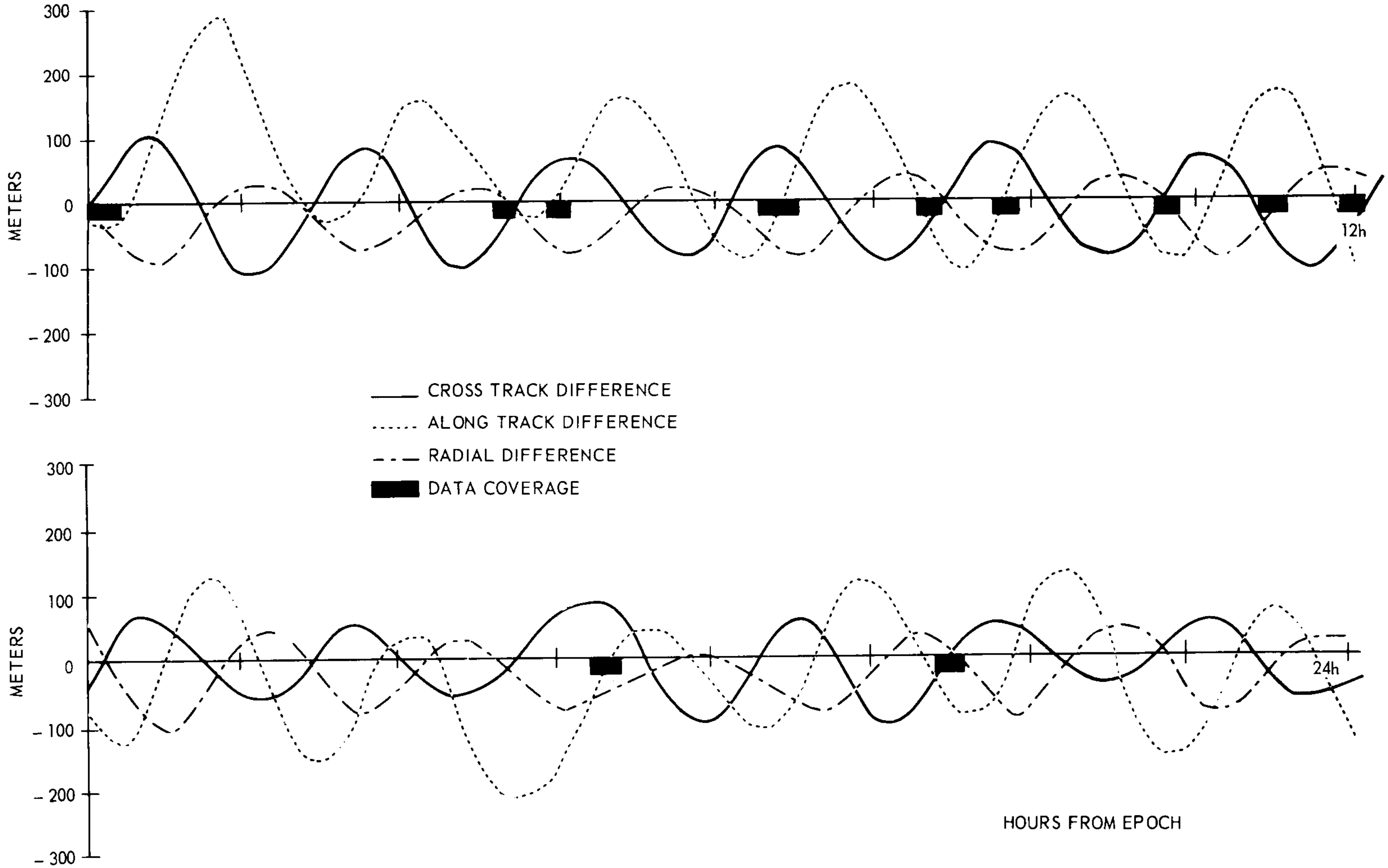


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 5 1/4 Day Arc

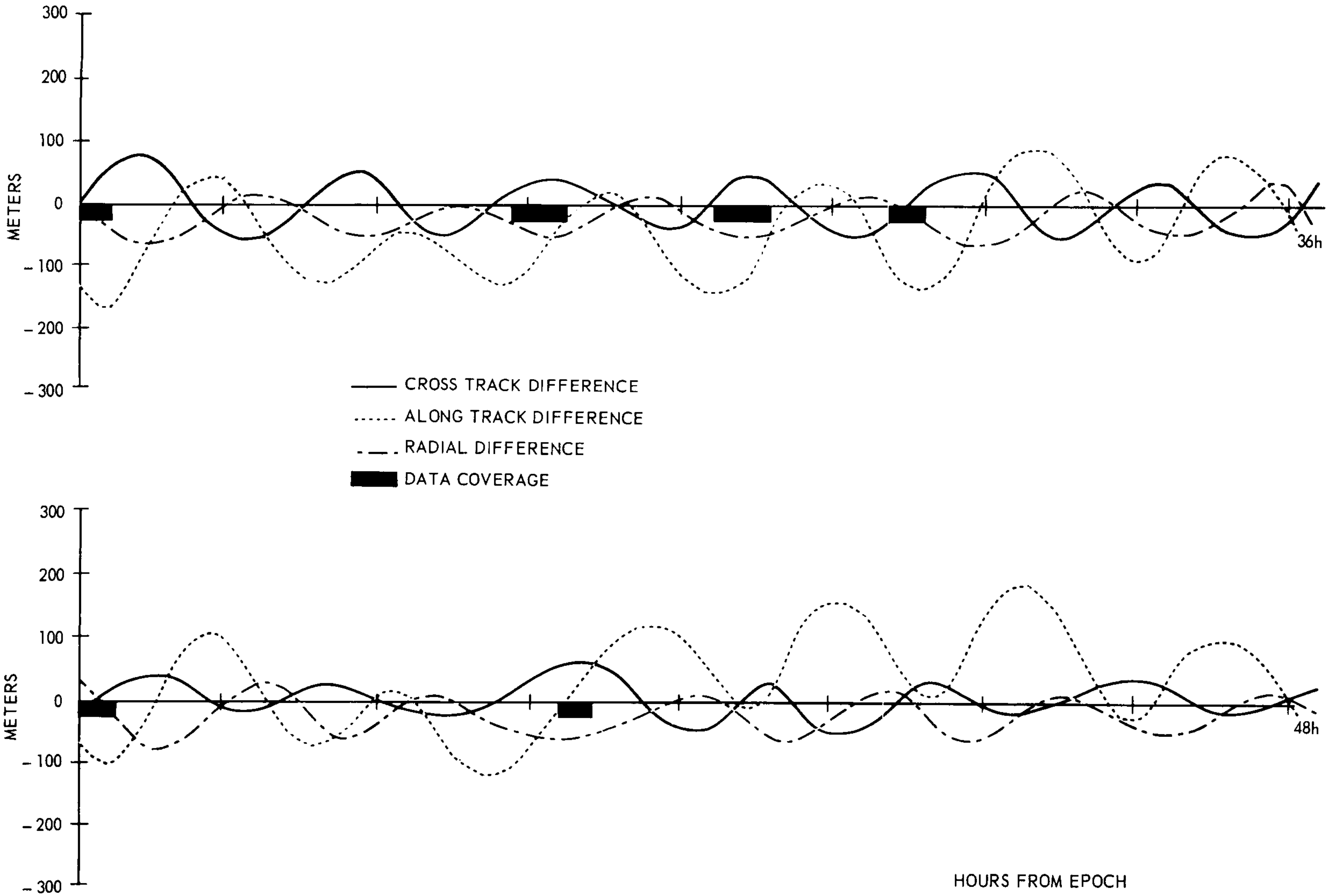


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 5 1/4 Day Arc (Continued)

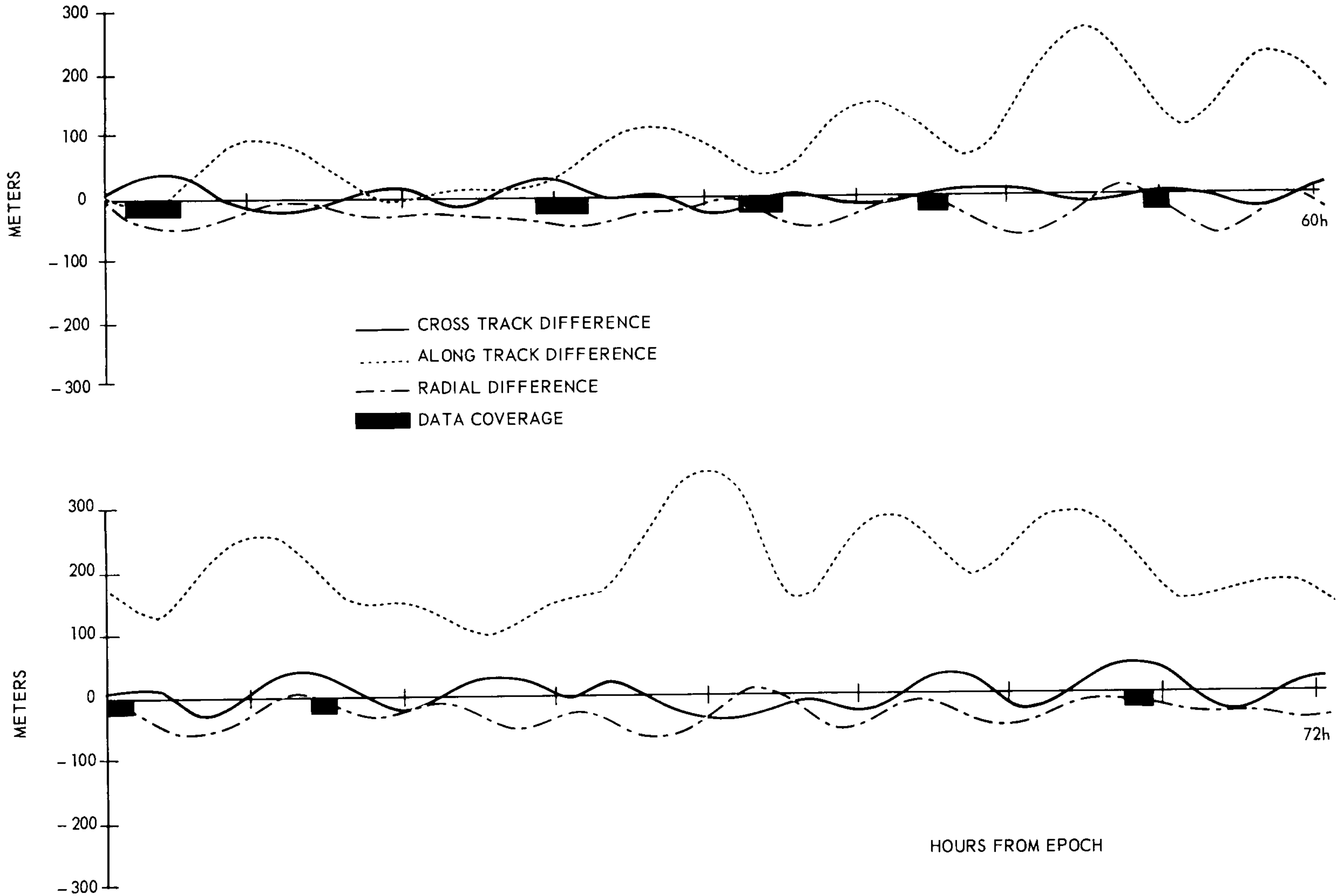


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 5 1/4 Day Arc (Continued)

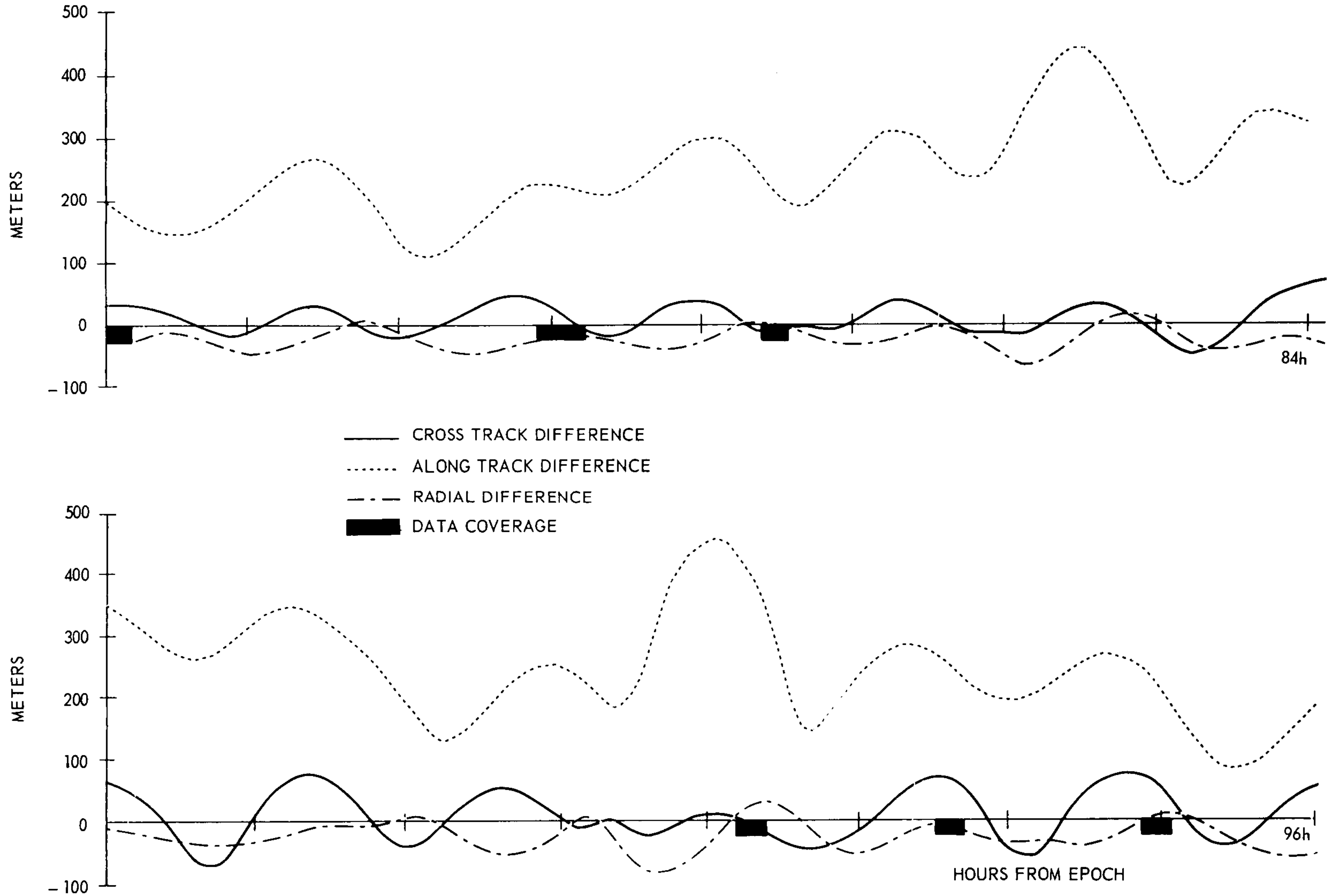


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 5 1/4 Day Arc (Continued)

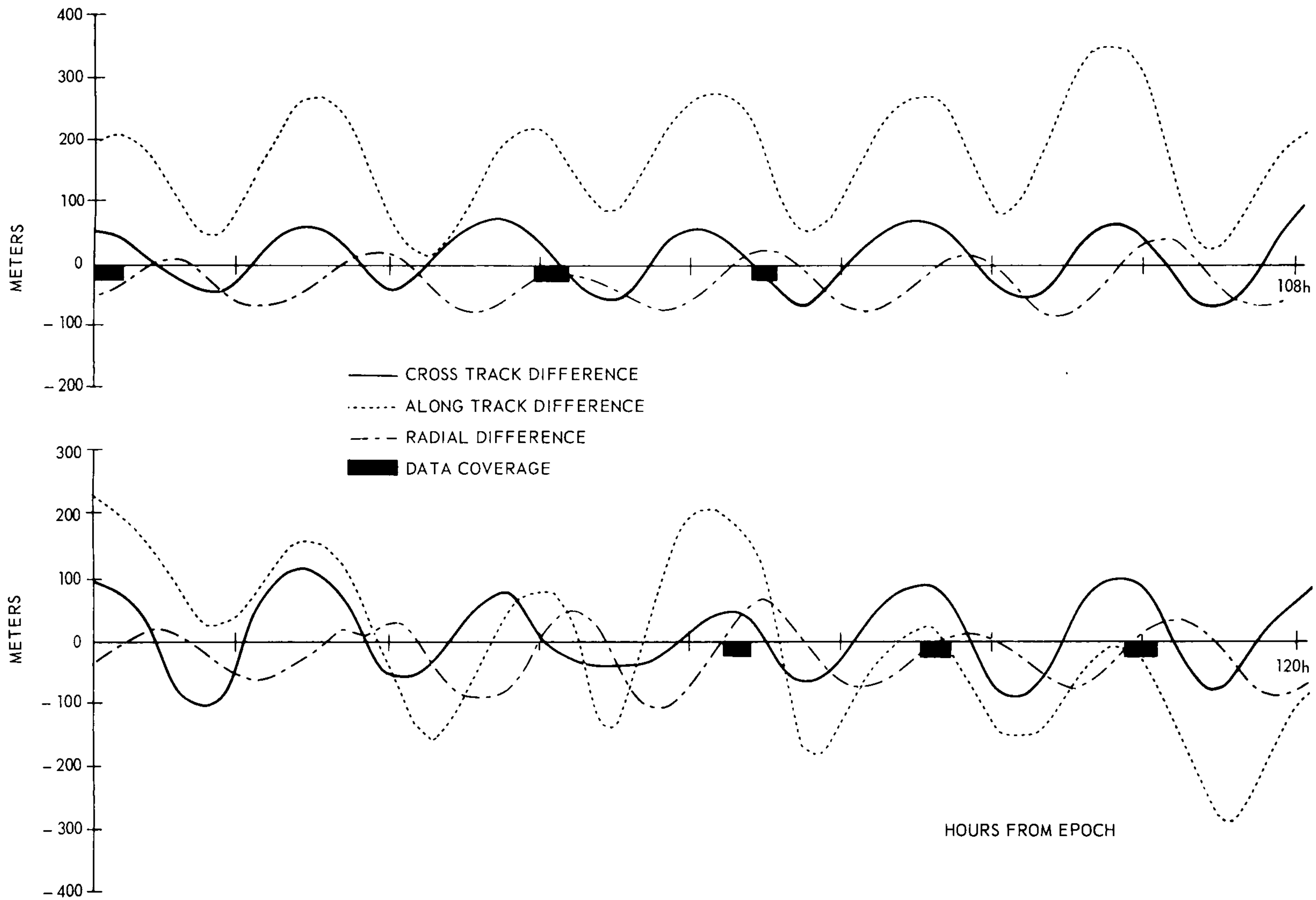


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 5 1/4 Day Arc (Continued)

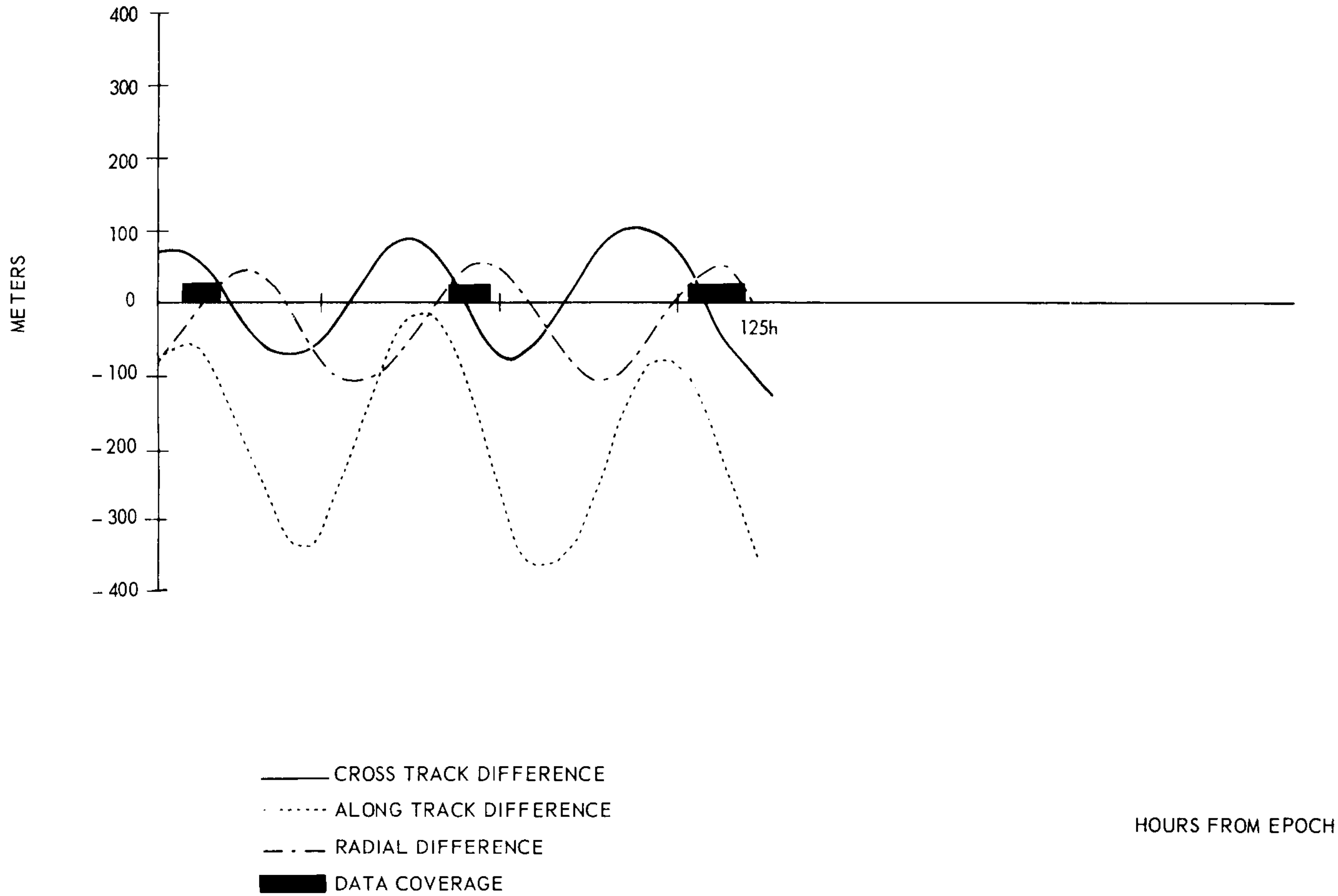


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 5 1/4 Day Arc (Continued)

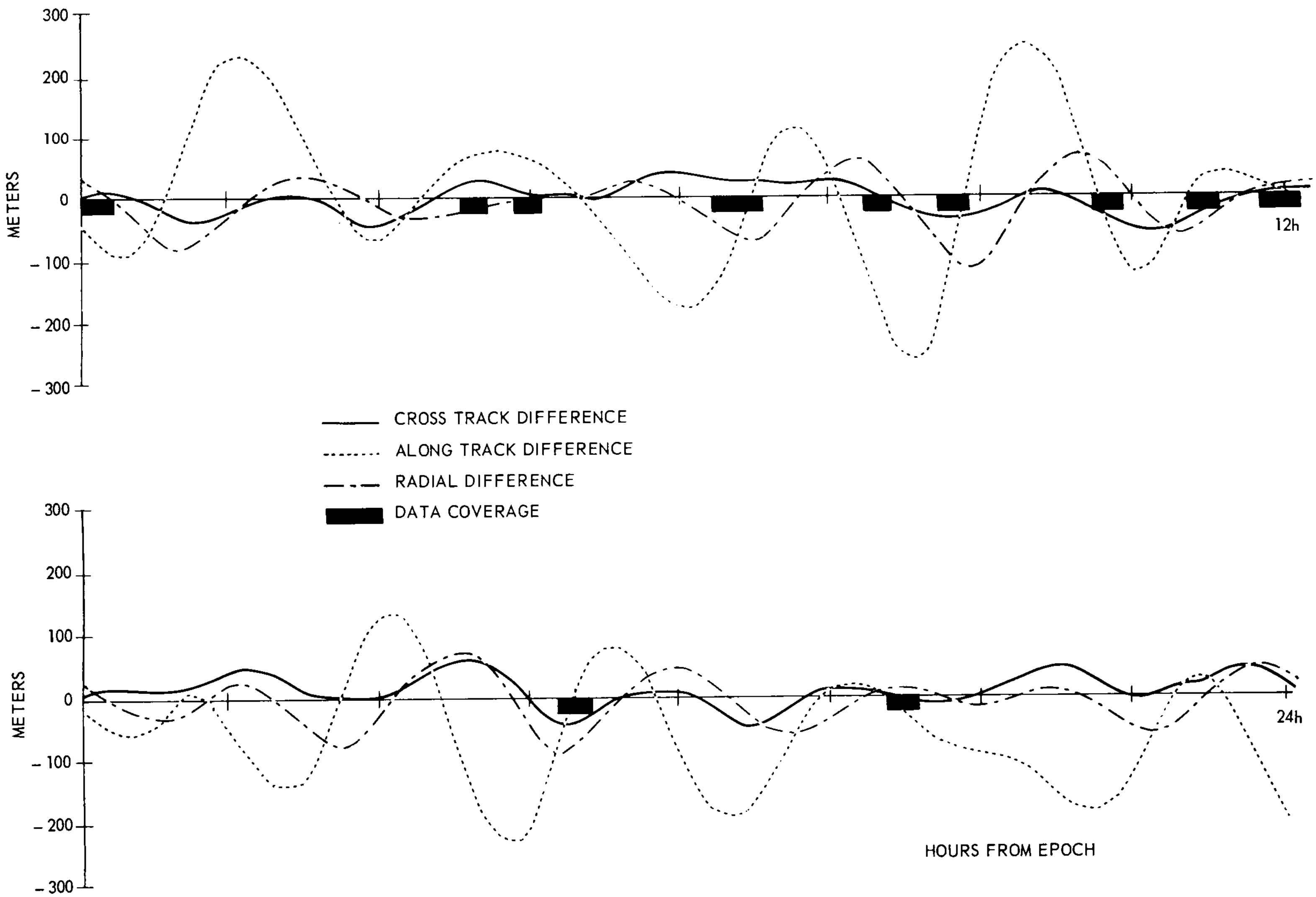


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 5 1/4 Day Arc

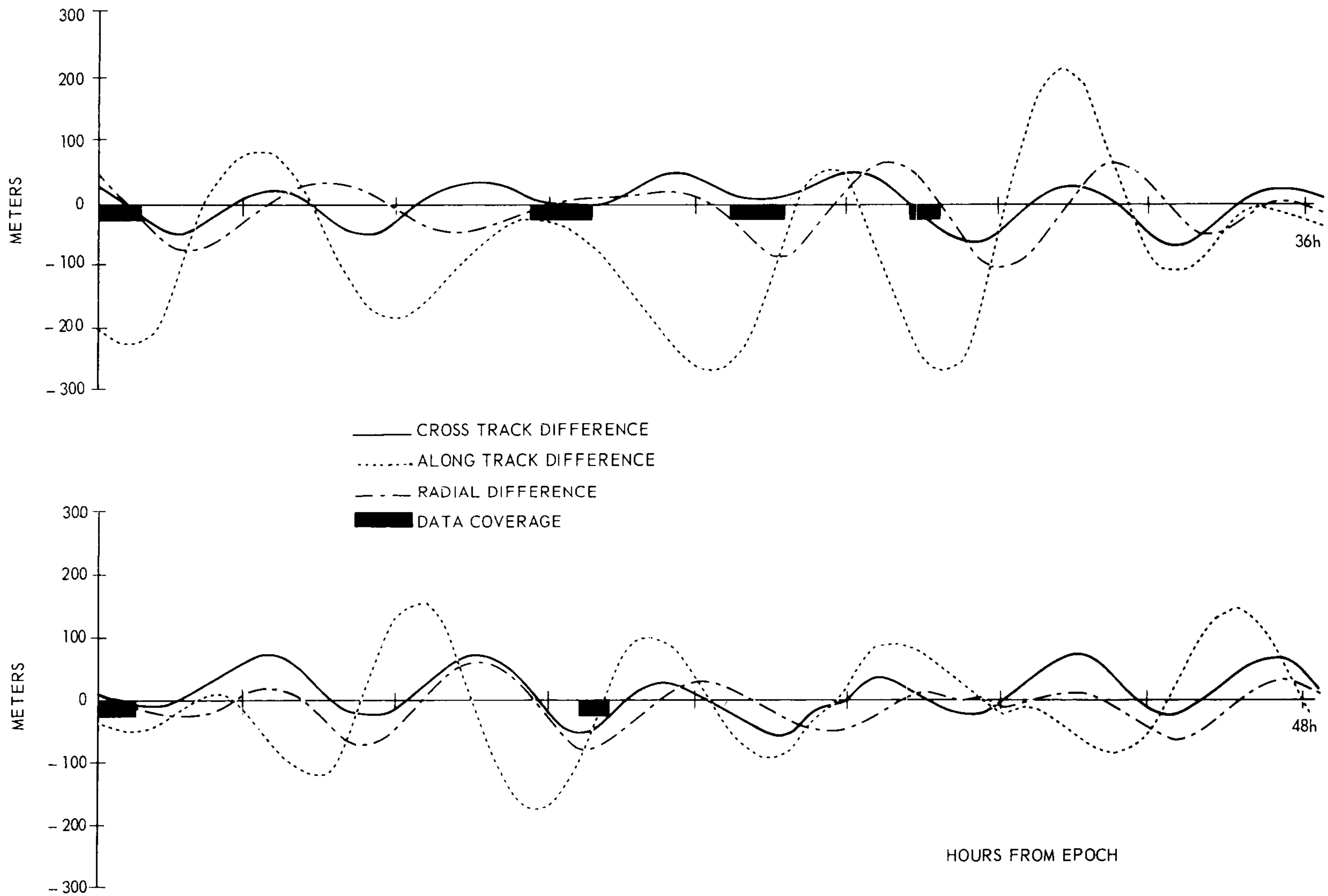


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 5 1/4 Day Arc (Continued)

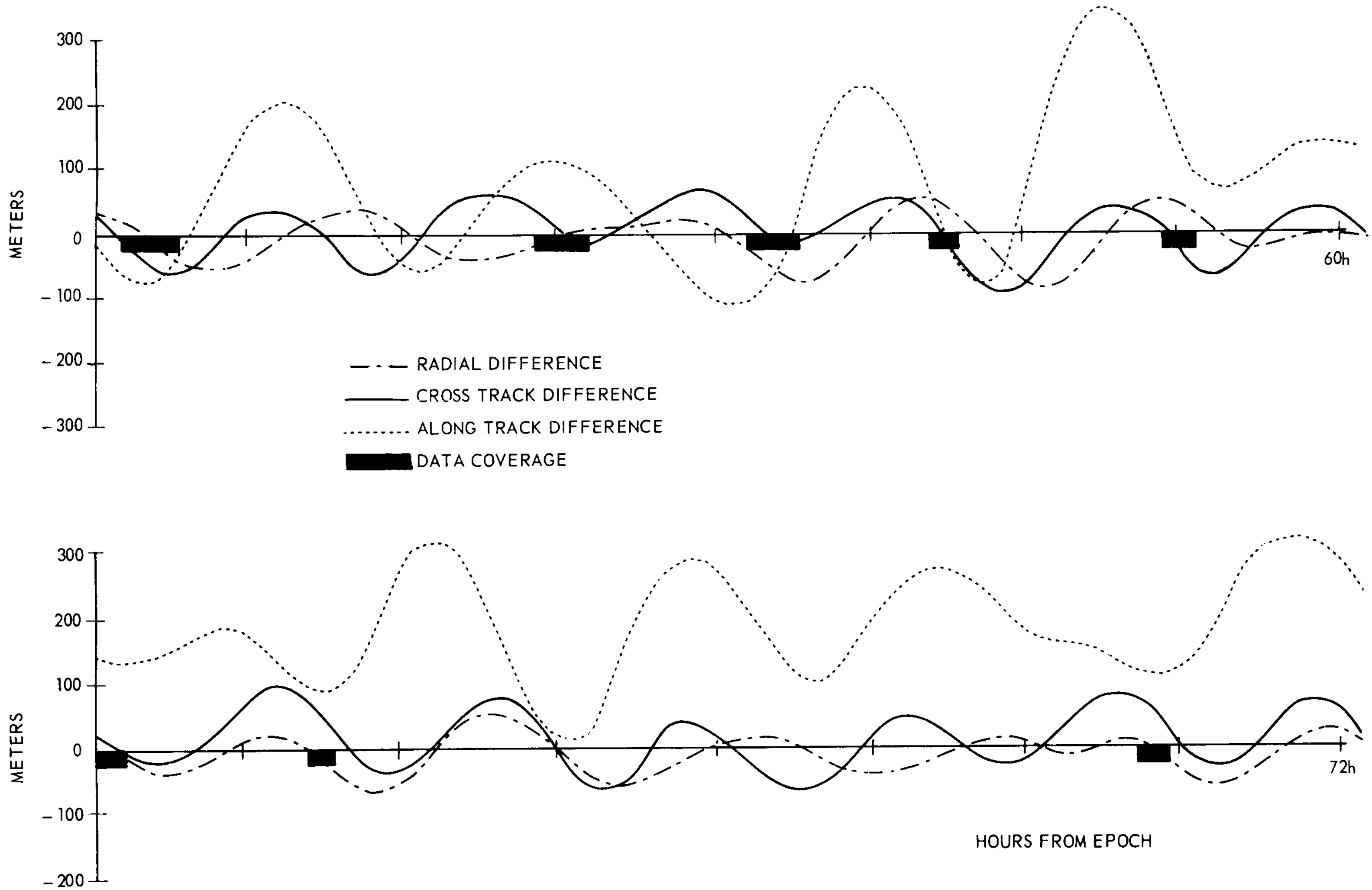


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 5 1/4 Day Arc (Continued)

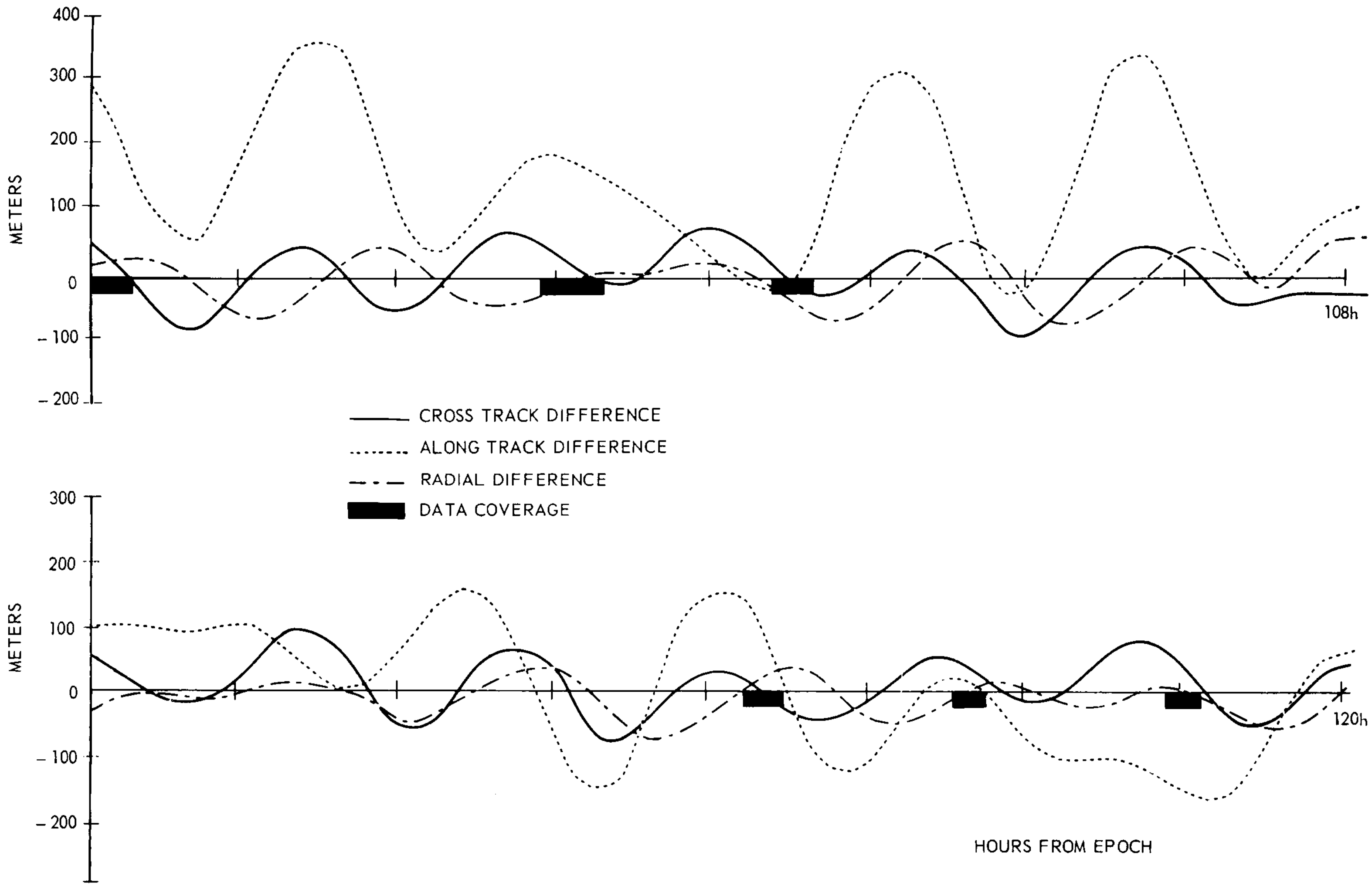


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 5 1/4 Day Arc (Continued)

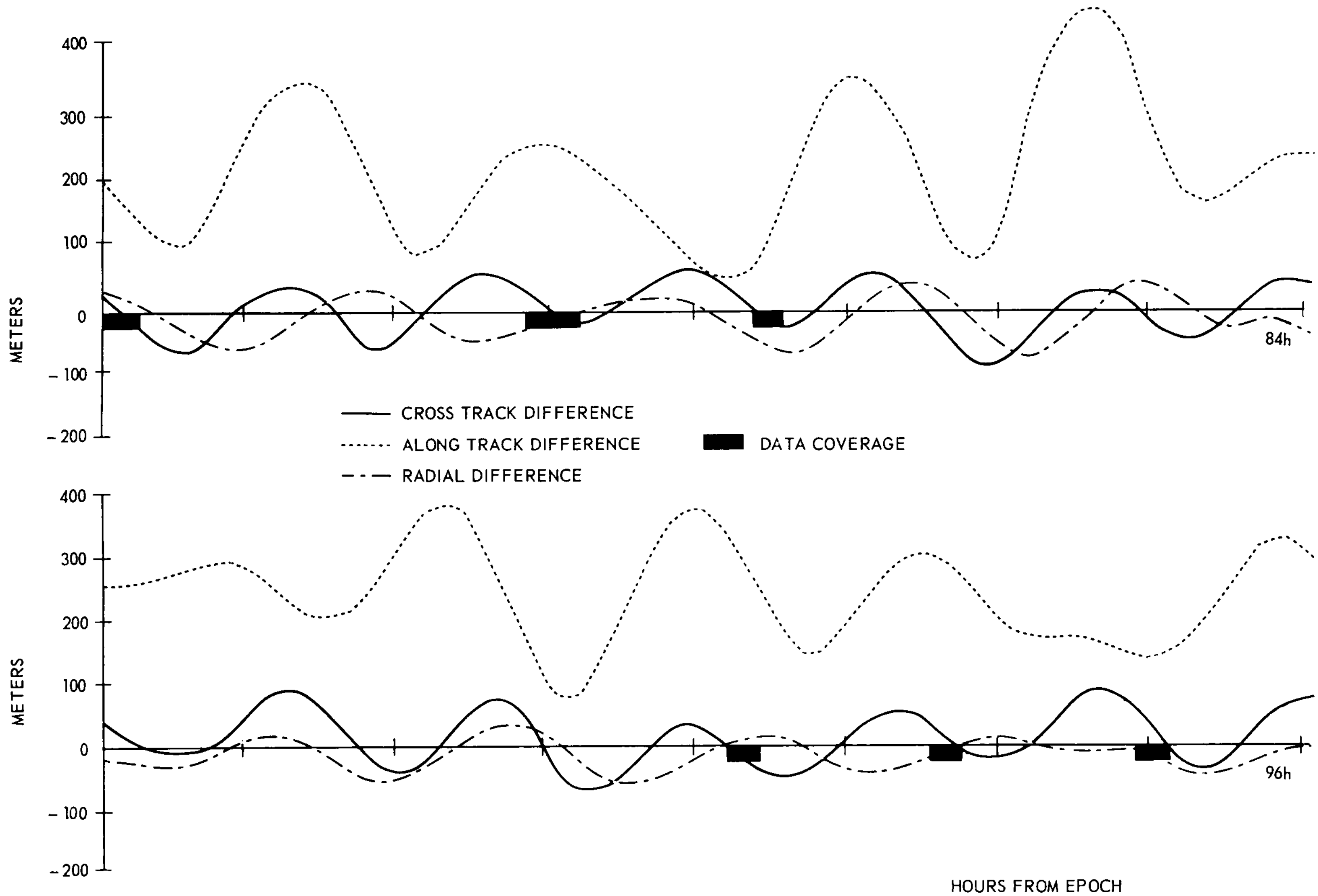


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 5 1/4 Day Arc (Continued)

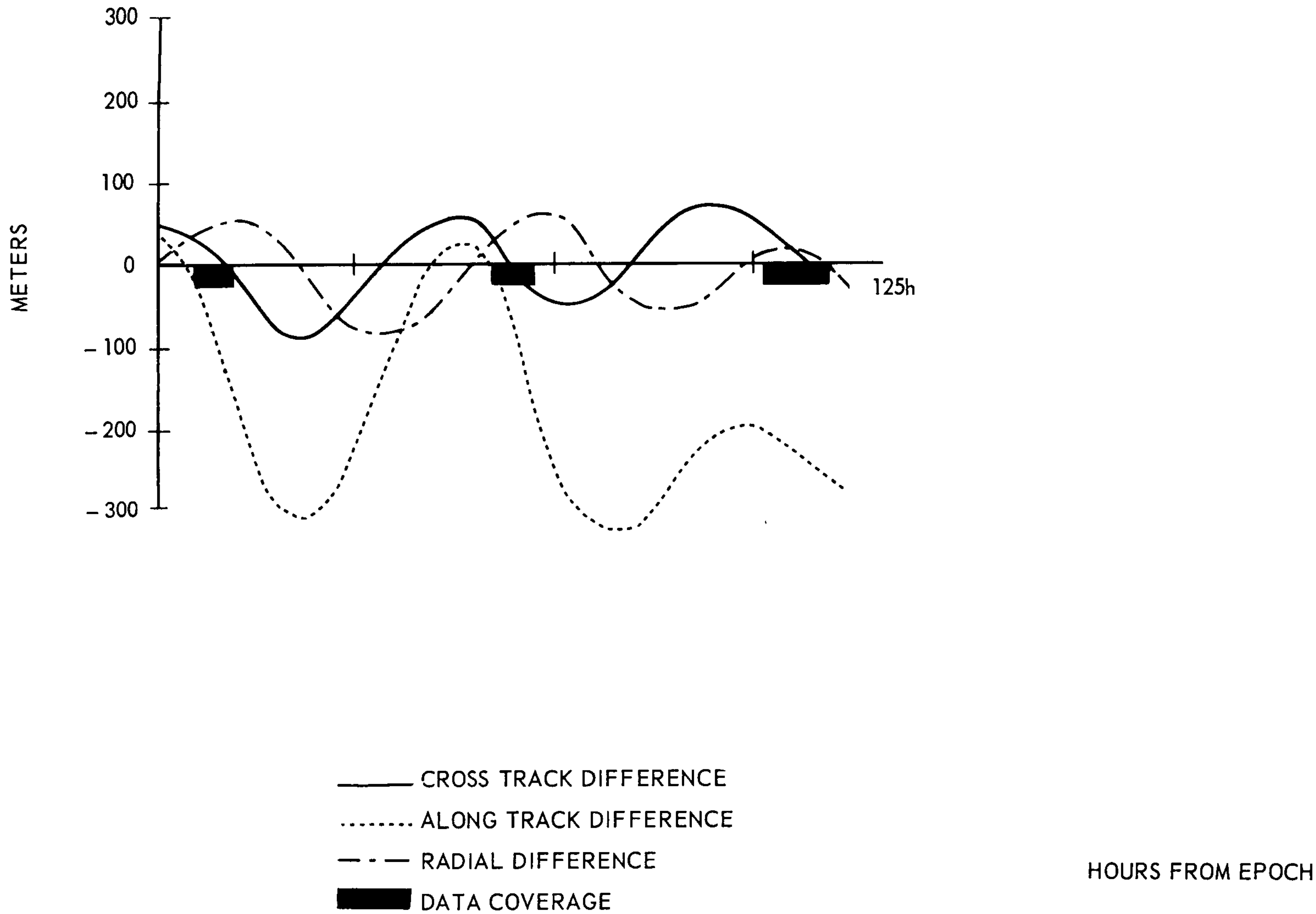


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 5 1/4 Day Arc (Continued)

used as the reference orbits. A summary of the station pass times, simultaneous optical coverage and maximum elevation angles for 15 GRARR passes recorded at Rosman during the 5-1/4 day optical arc is presented in Table V. It should be noted that a large percentage of the optical data used in the determination of the reference orbital solutions was recorded by tracking stations located on or near

Table V

Summary of GRARR Passes At Rosman Occurring During The 5-1/4 Day Optical Orbital Arc

Pass No.	Transponder Channel*	Date	Time	No. of Obs. in Pass		Max. Elevation Angle
				$R/\dot{R}$	Optical	
652	A	12/31/65	06^H	18	18	31.3°
653	A	12/31/65	08^H	28	30	65.4°
664	A	1/1/66	06^H	28	78	36.6°
665	A	1/1/66	08^H	32	95	51.8°
673	A	1/1/66	23^H	34	0	53.5°
676	A	1/2/66	06^H	32	106	43.3°
677	A	1/2/66	08^H	28	138	40.2°
685	A	1/2/66	23^H	34	10	46.5°
688	A	1/3/66	06^H	30	101	52.2°
689	A	1/3/66	08^H	14	79	30.1°
697	A	1/3/66	23^H	44	0	40.8°
700	C	1/4/66	06^H	36	100	62.7°
708	C	1/4/66	21^H	48	0	84.2°
709	C	1/4/66	23^H	42	14	35.8°
712	A	1/5/66	06^H	36	66	76.6°

*The GEOS-I GRARR transponder contained two channels denoted A and C which received signals at 2271.9328 MHz and 2270.1328 MHz respectively.

the North American Continent (Table III) and also most of the Rosman GRARR passes had simultaneous optical data coverage.

For each GRARR pass over Rosman, zero set range bias errors, timing errors, and random errors were estimated from the residual differences between the observed and calculated ranges; these are summarized in Tables VI-VIII. The 12 A channel passes had a mean zero set error of -10 meters with a standard deviation of 8.8 meters, and a timing error of -2.4 milliseconds with a standard deviation of 2.4 milliseconds when compared with the orbital solution determined with the SAO M-1 gravitational coefficients; a mean zero set error of -33.7 meters with a standard deviation of 21.0 meters, and a timing error of -0.8 milliseconds with a standard deviation of 9.8 milliseconds when compared with the orbital solution determined with the NWL 5E-6 coefficients; and a mean zero set error of -34.6 meters with a standard deviation of 30.7 meters, and a timing error of 3.1 milliseconds with a standard deviation of 22.1 milliseconds when compared with orbital solution determined with the APL 3.5 coefficients. As indicated by the standard deviations associated with these errors, the estimates obtained from the orbital solutions fitted using the SAO M-1 set of coefficients were significantly less variable than those obtained using the other two sets. In addition, the estimates obtained from the shorter overlapping 1 day arc were only consistent with the 5-1/4 day arc estimates when the orbital solutions were obtained with the SAO M-1 set of coefficients.

6.0 ESTIMATION OF COORDINATES FOR THE GRARR MADGAR SITE

Two independent estimates of the coordinates of the GRARR site in Tananarive, Madagascar (MADGAR) were obtained using each set of coefficients (Reference 6). One estimate was obtained from optical flash sequence data recorded by the MOTS 40" camera (1 TANAN) during July 1966 and the other from range measurements taken at MADGAR during November 1965. The data sets used for these estimations are shown in Tables IX and X.

The two sets of coordinates estimated using the SAO M-1 coefficients were very consistent, within 5 meters of each other; whereas the estimates obtained using the other two sets of coefficients were not at all consistent. These estimates are shown in Table XI and Figure 9.

Table VI

Summary of Rosman Zero-Set Range Bias Error Estimates

(meters)

Pass No.	Transponder Channel	SAO M1		NWL 5E-6		APL 3.5	
		No. 1*	No.2	No. 1	No. 2	No. 1	No. 2
652	A	-16.5		-26.5		-98.8	
653	A	- 6.1		-45.9		-35.9	
664	A	- 5.0		-18.0		-74.1	
665	A	- 2.0		-39.4		-16.3	
673	A	-19.1		-44.7		-15.8	
676	A	2.3	4.2	8.1	6.6	-25.8	-24.6
677	A	0.2	7.4	-51.8	- 23.6	-20.2	3.8
685	A	-29.5	-20.7	-60.0	-112.5	-46.7	-79.0
688	A	- 3.3	- 1.0	8.4	- 7.9	- 2.2	- 1.7
689	A	-14.9	- 7.7	-71.2	- 35.8	-38.7	- 7.7
697	A	-16.0		-49.4		-52.8	
700	C	20.6		25.4		36.5	
708	C	16.8		10.5		7.9	
709	C	17.0		-17.7		-33.7	
712	A	- 9.5		-14.5		11.8	
Mean	A	-10.0		-33.7		-34.6	
Std. dev.	A	8.8		21.0		30.7	
Mean	C	18.1		6.1		3.6	

*No. 1 and No. 2 refer to the 5¼ day and 1 day orbital arcs described in Section 3.0.

Table VII

Summary of Rosman Timing Error Estimates

(milliseconds)

Pass No.	Transponder Channel	SAO	M1	NWL	5E-6	APL	3.5
		No. 1	No. 2	No. 1	No. 2	No. 1	No. 2
652	A	-2.0		6.1		- 7.7	
653	A	1.5		-11.1		- 4.3	
664	A	-3.9		- 9.9		-22.7	
665	A	1.0		-23.7		-16.9	
673	A	-3.4		-17.4		- 6.5	
676	A	-6.3	-6.9	10.0	12.9	- 0.9	-1.2
677	A	-0.2	-0.3	- 5.0	- 7.3	3.4	0.1
685	A	-3.5	-0.6	14.2	-12.2	31.3	1.5
688	A	-5.0	-5.3	31.4	10.7	25.1	0.7
689	A	0.1	1.2	13.2	12.5	25.6	-1.5
697	A	-3.0		19.6		38.9	
700	C	-5.4		18.1		18.9	
708	C	-2.3		3.3		2.7	
709	C	3.4		-18.9		5.5	
712	A	-2.8		-36.4		-28.2	
Mean	A	-2.4		- 0.8		3.1	
Std. dev.	A	2.4		9.8		22.1	
Mean	C	-1.4		0.8		9.0	

Table VIII

Summary of Random Error Estimates

(meters)

Pass No.	Transponder Channel	SAO M1		NWL 5E-6		APL 3.5	
		No. 1	No. 2	No. 1	No. 2	No. 1	No. 2
652	A	3.3		3.5		6.0	
653	A	3.6		10.5		7.3	
664	A	3.2		3.6		6.1	
665	A	4.5		12.0		3.6	
673	A	2.6		4.7		3.1	
676	A	2.9	3.0	3.9	5.3	5.0	3.8
677	A	3.2	4.0	10.4	4.7	2.8	5.3
685	A	2.5	2.3	3.5	10.5	2.6	5.2
688	A	4.5	5.0	8.3	10.3	7.0	8.2
689	A	4.1	3.8	7.4	5.0	3.9	3.9
697	A	3.4		3.5		3.8	
700	C	5.8		10.8		16.8	
708	C	4.5		3.9		5.3	
709	C	3.1		4.4		3.6	
712	A	6.0		8.0		22.7	
Mean	A	3.7		6.6		6.2	
Mean	C	4.5		6.4		8.6	

Table IX

Summary of Optical Data by Station
For July 9, 10, and 11, 1966

Station	No. of Measurements	
	Right Ascension	Declination
1TANAN	14	14
1ROSMA	7	7
1COLBA	14	14
1BPOIN	14	14
1DENVR	20	20
1JOBUR	14	14
1ORGAN	91	91
1OLFAN	28	28
1SPAIN	21	21
1QUIPA	28	28
1CURAC	28	28
1JUPTR	35	35
1VILDO	7	7
AUSBAK	14	14
1MAUIO	28	28
EDWAFB	2	2
Total	365	365

Table X

Summary of Optical and GRARR Data By Station
For November 28 and 29, 1965

Station	No. of Measurements	
	Right Ascension	Declination
1ORGAN	59	59
1OLFAN	1	1
1SPAIN	1	1
1QUIPA	2	2
1CURAC	96	96
1JUPTR	127	127
1VILDO	1	1
Total	287	287
	Range	
MADGAR	24	

Table XI

Estimated Coordinates for Madgar

SAO M1 Gravity Model

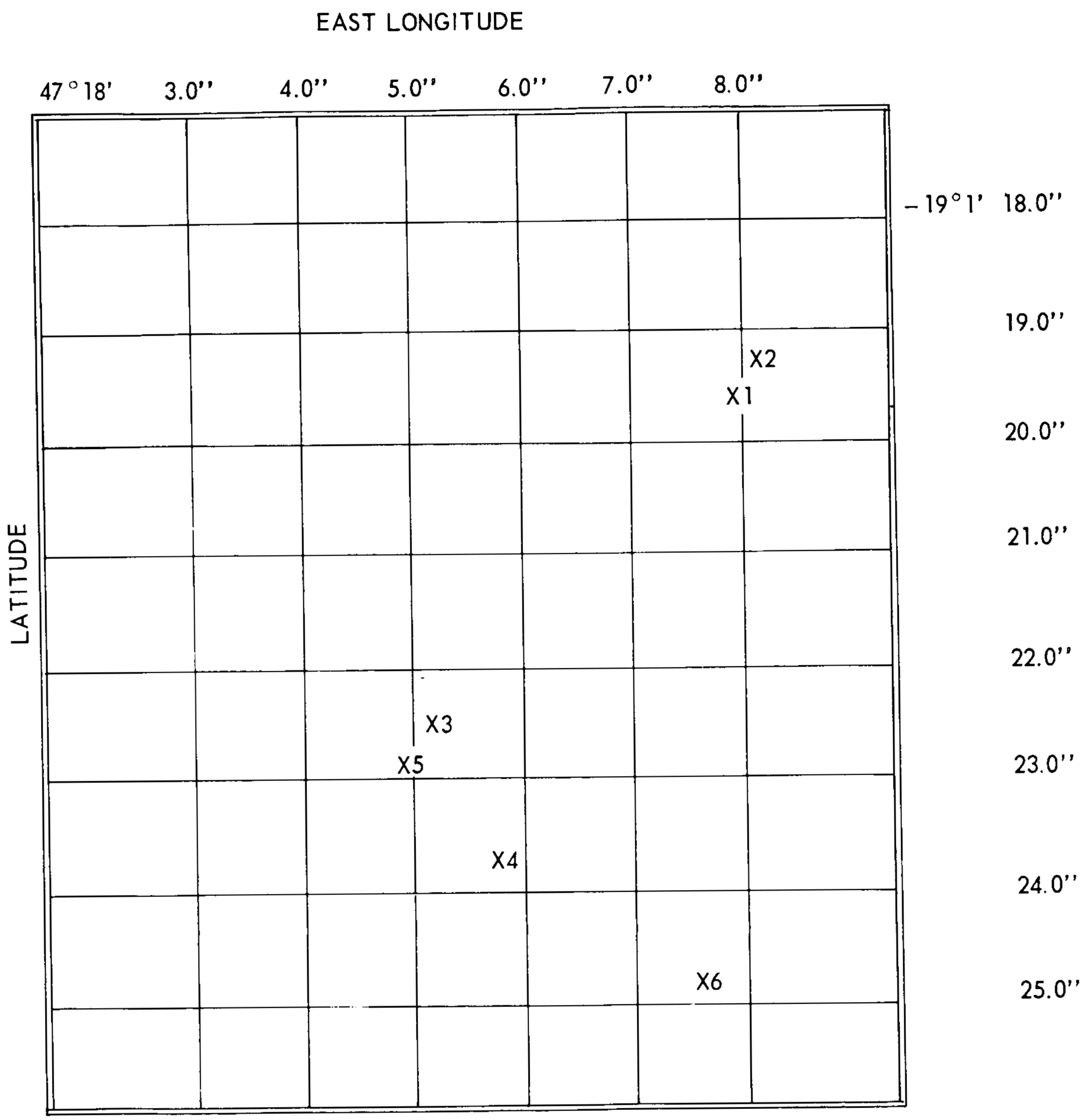
	Latitude	E. Longitude	Spheroid Height
Optical Estimate	-19° 1' 19.5"	47° 18' 7.9"	1380.0 meters
GRARR Estimate	-19° 1' 19.4"	47° 18' 8.0"	1382.6 meters
Difference	0.1"	-0.1"	-2.6 meters

APL 3.5 Gravity Model

	Latitude	E. Longitude	Spheroid Height
Optical Estimate	-19° 1' 22.6"	47° 18' 5.1"	1454.5 meters
GRARR Estimate	-19° 1' 23.7"	47° 18' 5.7"	1443.1 meters
Difference	-1.1"	-0.6"	11.4 meters

NWL 5E-6 Gravity Model

	Latitude	E. Longitude	Spheroid Height
Optical Estimate	-19° 1' 22.9"	47° 18' 4.8"	1458.0 meters
GRARR Estimate	-19° 1' 24.9"	47° 18' 7.5"	1467.4 meters
Difference	-2.0"	-2.7"	10.6 meters



1 OPTICAL ESTIMATE – SAO M1 GRAVITY
2 GRARR ESTIMATE – SAO M1 GRAVITY
3 OPTICAL ESTIMATE – APL 3.5 GRAVITY
4 GRARR ESTIMATE – APL 3.5 GRAVITY
5 OPTICAL ESTIMATE – NWL 5E-6 GRAVITY
6 GRARR ESTIMATE – NWL 5E-6 GRAVITY

Figure 9. Estimated Coordinates for MADGAR

7.0 REFERENCES

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APPENDIX A

FORCE MODELS USED IN THE NONAME ORBIT DETERMINATION SYSTEM

APPENDIX A

FORCE MODELS USED IN THE NONAME ORBIT DETERMINATION SYSTEM

1.1 FORCE MODELS

The data reduction program in its present form incorporates four force models. These are:

1. The earth gravitational field

2. The solar and lunar gravitational perturbations

3. Solar radiation pressure

4. Atmospheric drag

The program is designed such that the gravitational coefficients and pertinent physical characteristics of satellites, such as reflectivity, cross-sectional area mass, and drag coefficient can be simply changed through card input or block data statement.

1.2 THE EARTH'S GRAVITATIONAL FIELD

The formulation of the geopotential used is:

$$u = \frac{GM}{r}\left\{1 + \sum_{n=2}^{k} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^n p_n^m (\sin \phi) \left[C_{nm} \cos m\lambda + S_{nm} \sin m\lambda\right]\right\} \quad \text{(A-1)}$$

where

G is the universal gravitational constant

M is the mass of the earth

r is the geocentric satellite distance

a is the earth's mean equatorial radius

ϕ is the sub-satellite geocentric latitude

λ is the sub-satellite east longitude

$P_n^m(\sin\phi)$ is the associated spherical harmonic of degree n and order m.

The design of the potential function requires that denormalized gravitational coefficients $C_{n,m}$ and $S_{n,m}$ be used. The program is presently capable of accepting coefficients up to (20,20) or any sub-set of these.

The transformation of the geopotential in earth-fixed coordinates (r, ϕ, λ) to gravitational accelerations in inertial coordinates (x, y, z) is accomplished as follows:

$$\ddot{x}_{\oplus} = \frac{\partial u}{\partial r}\frac{\partial r}{\partial x} + \frac{\partial u}{\partial \phi}\frac{\partial \phi}{\partial x} + \frac{\partial u}{\partial \lambda}\frac{\partial \lambda}{\partial x}; \quad \ddot{y}_{\oplus}, \quad \ddot{z}_{\oplus} \qquad \text{(A-2)}$$

where the subscript "$\oplus$" denotes accelerations due to the earth's field.

1.3 SOLAR AND LUNAR GRAVITATIONAL PERTURBATIONS

The perturbations caused by a third body, e.g., the sun or moon, on a satellite orbit are treated by defining a disturbing function R (Reference 1) which can be treated as the potential function U. For the solar perturbation $R_{\odot}$ takes the form

$$R_{\odot} = \frac{GMm_{\odot}}{r_{\odot}}\left[\left(1 - \frac{2r}{r_{\odot}}S + \frac{r^2}{r_{\odot}^2}\right)^{-1/2} - \frac{rs}{r_{\odot}}\right] \qquad \text{(A-3)}$$

where

$S = \cos(\vec{r}, \vec{r}_{\odot})$

$m_{\odot}$ is the mass of the sun in earth masses

$\vec{r}_{\odot}$ is the geocentric position vector of the sun

$r_{\odot}$ is the geocentric distance to the sun r is the geocentric distance to the satellite

$\vec{r}$ is the geocentric position vector of the satellite

G is the universal gravitational constant

M is the mass of the earth

The acceleration of the satellite due to the sun is then

$$\ddot{x}_{\odot} = \frac{\partial R_{\odot}}{\partial r}\frac{\partial r}{\partial x} + \frac{\partial R_{\odot}}{\partial \phi}\frac{\partial \phi}{\partial x} + \frac{\partial R_{\odot}}{\partial \lambda}\frac{\partial \lambda}{\partial x}; \; \ddot{y}_{\odot}; \; \ddot{z}_{\odot} \qquad \text{(A-4)}$$

where ϕ and λ are the latitude and longitude of the satellite respectively. The lunar perturbations are found from Equation (A-3) by substituting the lunar mass and distance for those of the sun.

The lunar and solar ephemerides are computed internal to the program. These positions are computed at ten equal intervals over each five day period and least squares fit to a fourth order polynomial in time about the midpoint of the five day period. The positions of these bodies are then determined at each data point by evaluating the polynomial at the observation time.

1.4 SOLAR RADIATION PRESSURE

The acceleration acting on a satellite due to solar radiation pressure is formulated as follows (Reference 2).

$$\ddot{x}_{RAD} = -\frac{AP_{\odot}}{m}\gamma\nu L_x; \; \ddot{y}_{RAD}; \; \ddot{z}_{RAD} \qquad \text{(A-5)}$$

where

L is the inertial unit vector from the geocenter to the sun and whose components are L_x, L_y, L_z

A is the cross sectional area of the satellite

m is the satellite mass

γ is a factor depending on the reflective characteristics of the satellite.

ν is the eclipse factor such that:

$$\nu = \begin{cases} 0 \text{ when satellite is in earth's shadow} \\ 1 \text{ when satellite is illuminated by the sun} \end{cases}$$

$P_\odot$ is the solar radiation pressure in the vicinity of the earth,

$$4.5 \times 10^{-6} \frac{\text{Newton}}{\text{m}^2}$$

At present, it is assumed that the satellite is specularly reflecting with reflectivity, ρ, and thus

$$\gamma = (1 + \rho). \qquad \text{(A-6)}$$

The vector $\hat{L}$ and the eclipse factor are determined from the solar ephemeris subroutine previously described, the satellite ephemeris, and involve the approximation of a cylindrical earth shadow.

1.5 ATMOSPHERIC DRAG

The atmospheric decelerations are computed as follows:

$$\ddot{x}_{DRAG} = \frac{\rho C_D A v v_x}{2m}; \ \ddot{y}_{DRAG}, \ \ddot{z}_{DRAG} \qquad \text{(A-7)}$$

where

ρ is the ambient atmospheric density

C_D is the satellite drag coefficient

A is the projected area of the satellite on a plane perpendicular to direction of motion

m is the satellite mass.

The velocity vector $\vec{\nu}$ given in inertial coordinates by

$$\vec{\nu} = \nu_x \hat{i} + \nu_y \hat{j} + \nu_z \hat{k} \tag{A-8}$$

can be chosen to be either the velocity relative to the atmosphere which implies that the atmosphere rotates with the earth or the inertial velocity which assumes that the atmosphere is static. Presently, the former assumption is made.

The density, ρ, is computed from the 1962 U.S. Standard Atmosphere.

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APPENDIX B

PREPROCESSING OF OPTICAL OBSERVATIONS

APPENDIX B

PREPROCESSING OF OPTICAL OBSERVATIONS

2.1 PREPROCESSING OF OPTICAL DATA

The first step in the processing of optical observations is usually performed by the observing source. This consists of developing a plate or film, identifying the image or images of the satellite and the images of several reference stars whose right ascensions and declinations are well known. The initial measurements of both satellite images and reference stars consist of linear rectangular coordinates. From the knowledge of the spherical coordinates of the reference stars, the right ascensions and declinations of the satellite images may be calculated. These coordinates as received by the preprocessor may be referred to the mean equator and equinox of date, true equator and equinox of date, or mean equator and equinox of some standard epoch.

Preprocessing includes, for example in the case of the GEOS-I SAO Baker-Nunn data, updating the observations from a mean equinox and equator of 1950.0 to the true equinox and equator of date through the luni-solar precession and nutation effects, the correction for planetary aberration, and the transformation of the A-S (SAO atomic time) time tag to UTC time. It is necessary to know UT1 time when the angle between Aries and the Mean Greenwich Meridian is required. UT1 time is then calculated on the basis of the differences (UT1-UTC) as published by the U.S. Naval Observatory. In the case of active flash data, where the time is recoverable to better than 100 microseconds through the use of APL published corrections to the satellite on-board clock (Reference 1), the time tag is shifted to correspond to the center of the photographic flashing light image. This latter adjustment corresponds to a shift of 0.5 milliseconds which is equivalent to approximately 4.0 meters of satellite position.

Currently, the preprocessor transforms all right ascensions and declinations to the true equator and equinox of the epoch of the observations being processed. If the observations were originally referred to the mean equator and equinox of a particular epoch, it is only necessary to precess from that epoch to the dates of the observation. However, if they were referred to the true equator and equinox of a particular epoch, it is necessary first to transform them to the mean equator and equinox of that same epoch and then precess to the epochs of the observations.

Finally, a transformation must be made from the mean equator and equinox of the epoch of the observation to the true equator and equinox of the epoch of the observation.

2.2 NUTATION

The transformations from the true equator and equinox of date to the mean equator and equinox of date is

$$Y = NX \qquad \text{(B-1)}$$

where

$$Y = \begin{bmatrix} \cos\delta_m \cos\alpha_m \\ \cos\delta_m \sin\alpha_m \\ \sin\delta_m \end{bmatrix} \qquad \text{(B-2)}$$

$$X = \begin{bmatrix} \cos\delta_T \cos\alpha_T \\ \cos\delta_T \sin\alpha_T \\ \sin\delta_T \end{bmatrix} \qquad \text{(B-3)}$$

$$N = \begin{bmatrix} 1 & +\Delta\psi \cos\epsilon_m & +\Delta\psi \sin\epsilon_m \\ -\Delta\psi \cos\epsilon_m & 1 & +\Delta\epsilon \\ -\Delta\psi \sin\epsilon_m & -\Delta\epsilon & 1 \end{bmatrix} \qquad \text{(B-4)}$$

where

α_m, δ_m = right ascension and declination referred to mean equator and equinox of date

α_T, δ_T = right ascension and declination referred to true equator and equinox of date

ϵ_m = mean obliquity of date

$\Delta\psi$ = nutation in longitude

$\Delta\epsilon$ = nutation in obliquity.

The inverse transformation is simply:

$$X = N^{-1} Y = N^T Y \qquad \text{(B-5)}$$

2.3 PRECESSION

The transformation from the mean equator and equinox of 1950.0 to the mean equator and equinox of an arbitrary epoch t 1 is

$$Y = PX \qquad \text{(B-6)}$$

where

$$Y = \begin{bmatrix} \cos \delta_{t1} & \cos \alpha_{t1} \\ \cos \delta_{t1} & \sin \alpha_{t1} \\ \sin \delta_{t1} & \end{bmatrix} \qquad \text{(B-7)}$$

$$X = \begin{bmatrix} \cos \delta_{1950.0} & \cos \alpha_{1950.0} \\ \cos \delta_{1950.0} & \sin \alpha_{1950.0} \\ \sin \delta_{1950.0} & \end{bmatrix} \qquad \text{(B-8)}$$

$$P = \begin{bmatrix} (\cos z \cos\theta \cos\zeta - \sin z \sin\zeta) & (-\cos z \cos\theta \sin\zeta - \sin z \cos\zeta) & (-\cos z \sin\theta) \\ (\sin z \cos\theta \cos\zeta + \cos z \sin\zeta) & (-\sin z \cos\theta \sin\zeta + \cos z \cos\zeta) & (-\sin z \sin\theta) \\ (\sin\theta \cos\zeta) & (-\sin\theta \sin\zeta) & (\cos\theta) \end{bmatrix} \quad \text{(B-9)}$$

The inverse transformation is

$$X = P^{-1} Y = P^{T} Y \quad \text{(B-10)}$$

Since the expression for z, θ, ζ are tied to 1950.0 as an epoch, the precession between 2 different epochs, neither of which is 1950.0, must be performed in two steps, using 1950.0 as an intermediary epoch.

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APPENDIX C

TRACKING STATION COORDINATES

APPENDIX C

TRACKING STATION COORDINATES

1.0 DATUM PARAMETERS AND STATION COORDINATES

For the purpose of long arc satellite data reduction and intercomparison, all GEOS-I participating tracking stations have been transformed to a common datum. The common datum selected is the SAO Standard Earth C-5 Model (Reference 1) in which the Baker-Nunn station positions are used as the controlling stations for all other stations to be transformed. The semi-major axis and flattening coefficient for the SAO C-5 Earth Model are 6378165 meters and 298.25 respectively. Descriptions and formulations to effect the transformations from major and isolated datums are presented in Reference 2. The transformation of local datum station coordinates to a common center of mass reference system is important to be performed since the datum shifts are quite large. For example, on the North American datum the center of mass shift to the C-5 Standard Earth is approximately 250 meters. The center of mass coordinates of the SAO C-5 Baker-Nunn stations are assessed by SAO to have approximately 20 meter accuracy.

In order to effect any transformation, the parameters of the original datums must be known as well as the geodetic latitude, longitude and height. Table I provides a listing of the original datums and their parameters on which the stations were originally surveyed. Tables II to XI list alternately the original surveyed ellipsoidal positions and the SAO C-5 ellipsoidal positions for over 100 GEOS-I tracking stations that have been used in the long arc intercomparison effort. These tables contain symbols designating the source of original station coordinates. The symbols are defined in Section 2.0 with a list of source information. The C-5 positions for 1TANAN and MADGAR (Reference 3) have been derived by the station estimation technique contained in the Orbit Determination Program NONAME. Tables XII to XXI provide a listing of the proper station names from which the six letter designations have been derived.

Table I

Parameters of Original Datums

Datum Name	Semi-Major Axis (meters)	1/f
North American (N.A.)	6378206.4	294.9787
European	6378388.0	297.0
Tokyo	6377397.2	299.1528
Argentina	6378388.0	297.0
Mercury	6378166.0	298.3
Madagascar	6378388.0	297.0
Australian Nat'l.	6378160.0	298.25
Old Hawaiian	6378206.4	294.9787
Indian	6377276.3	300.8017
Arc (Cape)	6378249.1	293.4663
1966 Canton Astro	6378388.0	297.0
Johnston Island 1961	6378388.0	297.0
Midway Astro 1961	6378388.0	297.0
Navy Iben Astro 1947	6378206.4	294.9787
Provisional DOS	6378388.0	297.0
Astro 1962, 65 Allen Sodano Lt.	6378388.0	297.0
1966 SECOR ASTRO	6378388.0	297.0
Viti Levu 1916	6378249.1	293.4663
CORREGO ALEGRE	6378206.4	294.9787
USGS 1962 ASTRO	6378206.4	294.9787
BERNE	6377397.2	299.1528

Table II

SAO — Optical — Source A

Source	Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
	1ORGAN	9001	32°25'24".56	253°26'51".17	1649	N.A.
			32 25 24.70	253 26 48.29	1610	C-5
	1OLFAN	9002	-25 57 33.85	28 14 53.91	1562	Arc (Cape)
			-25 57 37.67	28 14 51.45	1560	C-5
	WOOMER	9003	-31 06 07.26	136 46 58.70	185	Australian
			-31 06 04.14	136 47 01.93	158	C-5
	1SPAIN	9004	36 27 51.24	353 47 41.47	7	European
			36 27 46.68	353 47 36.55	56	C-5
	1TOKYO	9005	35 40 11.08	139 32 28.22	58	Tokyo
			35 40 23.03	139 32 16.42	84	C-5
	1NATOL	9006	29 21 38.90	79 27 25.61	1847	European
			29 21 34.38	79 27 27.05	1855	C-5
	1QUIPA	9007	-16 28 05.09	288 30 22.84	2600	N.A.
			-16 27 58.04	288 30 24.02	2479	C-5
	1SHRAZ	9008	29 38 17.96	52 31 11.80	1578	European
			29 38 13.59	52 31 11.20	1561	C-5
	1CURAC	9009	12 05 21.55	291 09 42.55	23	N.A.
			12 05 24.93	291 09 43.97	-33	C-5
	1JUPTR	9010	27 01 13.00	279 53 12.92	26	N.A.
			27 01 14.23	279 53 12.95	-36	C-5
	1VILDO	9011	-31 56 36.53	294 53 39.82	598	Argentinean
			-31 56 36.35	294 53 36.11	636	C-5
	1MAUIO	9012	20 42 37.49	203 44 24.11	3027	Old Hawaiian
			20 42 25.66	203 44 33.23	3027	C-5

Table II (Continued)

Source	Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
A	AUSBAK	9023	-31°23'30".82	136°52'39".02	164	Australian
			-31 23 27.69	136 52 42.23	137	C-5
A	OSLONR	9426	60 12 40.38	10 45 08.74	585	European
			60 12 38.88	10 45 02.26	573	C-5
I	NATALB*	9029	-05 55 50.00	324 50 18.00	112	N.A.
			-05 55 43.49	324 50 21.30	45	C-5
D	AGASSI*	9050	42 30 20.97	288 26 28.71	193	N.A.
			42 30 20.51	288 26 29.79	138	C-5
I	COLDLK*	9424	54 44 38.02	249 57 25.85	597	N.A.
			54 44 37.26	249 57 21.90	548	C-5
I	EDWAFB*	9425	34 57 50.68	242 05 11.39	784	N.A.
			34 57 50.17	242 05 07.80	754	C-5
I	RIGLAT*	9428	56 56 54.00	24 03 42.00	5	European
			56 56 52.37	24 03 37.49	-15	C-5
I	POTDAM*	9429	52 22 55.00	13 04 01.00	111	European
			52 22 52.33	13 03 55.80	106	C-5
I	ZVENIG*	9430	55 41 37.70	36 46 03.00	145	European
			55 41 36.17	36 46 00.17	114	C-5

*These SAO station positions were derived by using the weighting scheme described in Reference 2, Section 2.

Table III

STADAN — Optical — Source B

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
1BPOIN	1021	38°25'49".63	282°54'48".23	5	N.A.
		38 25 49.44	282 54 48.65	-50	C-5
1FTMYR	1022	26 32 51.89	278 08 03.93	19	N.A.
		26 32 53.08	278 08 03.80	-42	C-5
1OOMER	1024	-31 23 30.07	136 52 11.05	152	Australian
		-31 23 26.96	136 52 14.25	148	C-5
1QUITO	1025	-0 37 28.00	281 25 14.81	3649	N.A.
		-0 37 22.63	281 25 15.23	3554	C-5
1LIMAP	1026	-11 46 44.43	282 50 58.23	155	N.A.
		-11 46 37.56	282 50 58.86	34	C-5
1SATAG	1028	-33 09 07.66	289 19 51.35	922	N.A.
		-33 08 58.76	289 19 52.59	705	C-5
1MOJAV	1030	35 19 48.09	243 06 02.73	905	N.A.
		35 19 47.57	243 05 59.18	874	C-5
1JOBUR	1031	-25 52 58.86	27 42 27.93	1530	ARC (Cape)
		-25 53 02.70	27 42 25.41	1546	C-5
1NEWFL	1032	47 44 29.74	307 16 43.37	104	N.A.
		47 44 28.73	307 16 46.67	58	C-5
1COLEG	1033	64 52 19.72	212 09 47.17	162	N.A.
		64 52 17.78	212 09 37.29	139	C-5
1GFORK	1034	48 01 21.40	262 59 21.56	253	N.A.
		48 01 20.81	262 59 19.55	200	C-5
1WNKFL	1035	51 26 44.12	359 18 14.62	62	European
		51 26 40.67	359 18 08.35	76	C-5

Table III (Continued)

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
1ROSMA	1042	35°12'06".93	277°07'41".01	914	N.A.
		35 12 07.03	277 07 40.81	857	C-5
1TANAN	1043	-19 00 27.09	47 18 00.46	1377	Tananarive
		-19 00 33.26	47 17 58.89	1355	C-5

Table IV

STADAN — R/$\dot{R}$ — Source B

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
CARVON	1152	-24°54'14".85	113°42'55".05	38	Australian
		-24 54 12.29	113 42 58.54	10	C-5
ROSRAN	1126	35 11 45.05	277 07 26.23	880	N.A.
		35 11 45.15	277 07 26.02	823	C-5
MADGAR	1122	-19 01 13.32	47 18 09.45	1403	Tananarive
		-19 01 19.41	47 18 07.96	1382	C-5

Table V

NAVY TRANET — Doppler — Source C

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
LASHAM	2006	51°11'10."62	358°58'30."51	182	European
		51 11 07.12	358 58 24.25	196	C-5
SANHES	2008	-23 13 01.74	314 07 50.59	608*	Correga Alegre
		-23 13 01.74	314 07 50.59	608	C-5
PHILIP	2011	14 58 57.79	120 04 25.98	8	Tokyo
		14 59 16.42	120 04 21.61	-70	C-5
SMTHFD	2012	-34 40 31.31	138 39 12.39	39	Australian
		-34 40 28.16	138 39 15.66	31	C-5
MISAWA	2013	40 43 04.63	141 20 04.69	-10	Tokyo
		40 43 14.63	141 19 51.45	38	C-5
ANCHOR	2014	61 17 01.98	210 10 37.46	61	N.A.
		61 16 59.60	210 10 28.60	44	C-5
TAFUNA	2017	-14 19 50.19	189 17 13.96	6*	USGS 1962 Astro
		-14 19 50.19	189 17 13.96	6	C-5
THULEG	2018	76 32 18.62	291 13 46.72	43	N.A.
		76 32 20.72	291 13 51.07	-7	C-5
MCMRDO	2019	-77 50 51.00	166 40 25.00	-43	Mercury
		-77 50 50.58	166 40 35.02	-29	C-5
WAHIWA	2100	21 31 26.86	202 00 00.63	380	Old Hawaiian
		21 31 14.95	202 00 09.83	368	C-5
LACRES	2103	32 16 43.75	253 14 48.25	1201	N.A.
		32 16 43.91	253 14 45.34	1162	C-5

*MSL

Table V (Continued)

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
LASHM2	2106	51°11'12".32	358°58'30".21	187	European
		51 11 08.82	358 58 23.95	201	C-5
APLMND	2111	39 09 47.83	283 06 11.07	146	N.A.
		39 09 47.60	283 06 11.52	90	C-5
PRETOR	2115	-25 56 46.09	28 20 53.00	1417	European
		-25 56 49.97	28 20 50.67	1595	C-5
SHEMYA	2739	52 43 01.52	174 06 51.43	44	N.A.
		52 42 56.52	174 06 44.17	89	C-5
BELTSV	2742	39 01 39.46	283 10 27.25	50	N.A.
		39 01 39.23	283 10 27.72	-5	C-5
STNVIL	2745	33 25 31.57	269 09 10.70	44	N.A.
		33 25 31.76	269 09 09.66	-10	C-5

Table VI

AIR FORCE — Optical — Source I

Source	Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
	ANTIGA	3106	17°08'51".68	298°12'37".41	7	N.A.
			17 08 53.88	298 12 39.19	-42	C-5
E	GRNVLE	3333	33 28 48.97	268 59 49.17	45	N.A.
			33 28 49.15	268 59 48.12	-9	C-5
	GRVILL	3334	33 25 31.95	269 05 11.35	43	N.A.
			33 25 32.14	269 05 10.30	-10	C-5
	USAFAC	3400	39 00 22.44	255 07 01.01	2191	N.A.
			39 00 21.99	255 06 58.32	2147	C-5
E	BEDFRD	3401	42 27 17.53	288 43 35.03	88	N.A.
			42 27 17.06	288 43 36.14	33	C-5
E	SEMMES	3402	30 46 49.35	271 44 52.37	79	N.A.
			30 46 49.85	271 44 51.64	23	C-5
	SWANIS	3404	17 24 16.57	276 03 29.87	83	N.A.
			17 24 18.90	276 03 29.71	18	C-5
	GRDTRK	3405	21 25 47.05	288 51 14.03	7	N.A.
			21 25 48.69	288 51 15.03	-48	C-5
	CURACO	3406	12 05 22.11	291 09 43.76	23	N.A.
			12 05 25.49	291 09 45.16	-34	C-5
	TRNDAD	3407	10 44 32.78	298 23 23.67	269	N.A.
			10 44 36.16	298 23 25.43	210	C-5
	GRANFK	3451	47 56 38.63	262 37 11.21	296	N.A.
			47 56 38.03	262 37 09.15	242	C-5
	TWINOK	3452	36 07 25.69	262 47 04.48	312	N.A.
			36 07 25.58	262 47 02.68	262	C-5

Table VI (Continued)

Source	Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
	ROTHGR	3453	51°25'00".00	9°30'06".00	351	European
			51 24 57.05	9 30 00.58	352	C-5
	ATHNGR	3463	37 53 30.00	23 44 30.00	16	European
			37 53 26.07	23 44 26.73	23	C-5
	TORRSP	3464	40 29 18.53	356 34 41.24	588	European
			40 29 14.10	356 34 36.06	635	C-5
	CHOFUJ	3465	35 39 57.00	139 32 12.00	49	Tokyo
			35 40 08.96	139 32 00.19	75	C-5
	KINDLY	3471	32 22 57.30	295 19 00.46	26	N.A.
			32 22 57.41	295 19 02.09	-23	C-5
E	HUNTER	3648	32 00 05.87	278 50 46.36	17	N.A.
			32 00 06.32	278 50 46.32	-40	C-5
	JUPRAF	3649	27 01 14.80	279 53 13.72	26	N.A.
			27 01 16.02	279 53 13.72	-37	C-5
E	ABERDN	3657	39 28 18.97	283 55 44.56	4	N.A.
			39 28 18.71	283 55 45.10	-51	C-5
E	HOMEST	3861	25 30 24.69	279 36 42.69	18	N.A.
			25 30 26.02	279 36 42.70	-44	C-5
	CHYWYN	3902	41 07 59.20	255 08 02.65	1890	N.A.
			41 07 58.61	255 07 59.94	1845	C-5

Table VII

ARMY MAP SERVICE — SECOR — Source H

Source	Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
G	HERNDN	5001	38°59'37."69	282°40'16."68	119	N.A.
			38 59 37.47	282 40 17.08	64	C-5
I	CUBCAL	5200	32 48 00.00	242 52 00.00	101	N.A.
			32 47 59.74	242 51 56.55	71	C-5
I	LARSON	5201	47 11 00.00	240 40 00.00	354	N.A.
			47 10 58.76	240 39 55.68	319	C-5
I	WRGTON	5202	43 39 00.00	264 25 00.00	481	N.A.
			43 38 59.49	264 24 58.27	428	C-5
G	GREENV	5333	33 25 32.34	269 05 10.78	43	N.A.
			33 25 32.53	269 05 09.73	-10	C-5
	TRUKIS	5401	7 27 39.30	151 50 31.28	5*	Navy Iben Astro 1947
			7 27 39.30	151 50 31.28	5	C-5
	SWALLO	5402	-10 18 21.42	166 17 56.79	9*	1966 SECOR Astro
			-10 18 21.42	166 17 56.79	9	C-5
	KUSAIE	5403	5 17 44.43	163 01 29.88	7*	Astro 1962, 65, Allen Sodano Lt
			5 17 44.43	163 01 29.88	7	C-5
	GIZZOO	5404	-8 05 40.58	156 49 24.82	49*	Provisional DOS
			-8 05 40.58	156 49 24.82	49	C-5

*MSL

Table VII (Continued)

Source	Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
	TARAWA	5405	1°21'42".13	172°55'47".26	7*	1966 SECOR Astro
			1 21 42.13	172 55 47 26	7	C-5
	NANDIS	5406	-17 45 31.01	177 27 02.83	17*	Viti Levu 1916
			-17 45 31.01	177 27 02.83	17	C-5
	CANTON	5407	-2 46 28.90	188 16 43.47	6*	1966 Canton Astro
			-2 46 28.90	188 16 43.47	6	C-5
	JONSTN	5408	16 43 51.68	190 28 41.55	6*	Johnston Island 1961
			16 43 51.68	190 28 41.55	6	C-5
	MIDWAY	5410	28 12 32.06	182 37 49.53	6	Midway Astro 1961
			28 12 32.06	182 37 49.53	6	C-5
	MAUIHI	5411	20 49 37.00	203 31 52.77	32	Old Hawaiian
			20 49 25.14	203 32 01.88	31	C-5
G	FTWART	5648	31 55 18.41	278 26 00.26	29	N.A.
			31 55 18.86	278 26 00.18	-27	C-5
G	HNTAFB	5649	32 00 04.04	278 50 43.17	27	N.A.
			32 00 04.49	278 50 43.13	-30	C-5
G	HOMEFL	5861	25 29 21.18	279 37 39.35	18	N.A.
			25 29 22.51	279 37 39.37	-44	C-5

*MSL

Table VIII

USC&GS — Optical — Source F

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
BELTVL	6002	39°01'39".03	283°10'26".94	45	N.A.
		39 01 38.80	283 10 27.40	-10	C-5
ASTRMD	6100	39 01 39.72	283 10 27.83	45	N.A.
		39 01 39.49	283 10 28.29	-10	C-5
TIMINS	6113	48 33 56.17	278 37 44.54	290	N.A.
		48 33 55.70	278 37 44.49	232	C-5

Table IX

SPEOPT — Optical — Source B

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
1UNDAK	7034	48°01'21".40	262°59'21".56	255	N.A.
		48 01 20.81	262 59 19.55	201	C-5
1EDINB	7036	26 22 45.44	261 40 09.03	67	N.A.
		26 22 46.35	261 40 07.34	15	C-5
1COLBA	7037	38 53 36.07	267 47 42.12	271	N.A.
		38 53 35.81	267 47 40.85	218	C-5
1BERMD	7039	32 21 48.83	295 20 32.56	21	N.A.
		32 21 48.94	295 20 34.18	-28	C-5
1PURIO	7040	18 15 26.22	294 00 22.17	58	N.A.
		18 15 28.30	294 00 23.63	5	C-5

Table IX (Continued)

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
1GSFCP	7043	39°01'15".01	283°10'19".93	54	N.A.
		39 01 14.78	283 10 20.39	-1	C-5
1CKVLE	7044	38 22 12.50	274 21 16.81	187	N.A.
		38 22 12.33	274 21 16.28	131	C-5
1DENVR	7045	39 38 48.03	255 23 41.19	1796	N.A.
		39 38 47.54	255 23 38.52	1751	C-5
1JUM24	7071	27 01 12.77	279 53 12.31	25	N.A.
		27 01 14.00	279 53 12.30	-38	C-5
1JUM40	7072	27 01 13.17	279 53 12.49	25	N.A.
		27 01 14.39	279 53 12.49	-38	C-5
1JUPC1	7073	27 01 13.11	279 53 12.72	22	N.A.
		27 01 14.33	279 53 12.72	-41	C-5
1JUBC4	7074	27 01 13.33	279 53 12.76	25	N.A.
		27 01 14.55	279 53 12.76	-38	C-5
1SUDBR	7075	46 27 20.99	279 03 10.35	281	N.A.
		46 27 20.52	279 03 10.35	224	C-5
1JAMAC	7076	18 04 31.98	283 11 26.52	485	N.A.
		18 04 34.20	283 11 27.03	423	C-5

Table X

SPEOPT — Laser — Source B

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
ROSLAS	7051	35°11'46".60	277°07'26".23	879	N.A.
		35 11 46.70	277 07 26.02	822	C-5
GODLAS	7050	39 01 13.68	283 10 18.05	55	N.A.
		39 01 13.45	283 10 18.51	0	C-5

Table XI

INTERNATIONAL — Optical — Source I

Source	Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
	DELFTH	8009	52°00'09".24	4°22'21".23	23	European
			52 00 06.12	4 22 15.30	28	C-5
	MALVRN	8011	52 08 39.12	358 01 59.49	111	European
			52 08 35.68	358 01 53.03	125	C-5
D	ZIMWLD	8010	46 52 41.77	7 27 57.56	898	BERNE
			46 52 36.73	7 27 52.54	907	C-5

Table XII

SAO — optical

Name	Station No.	Location
1ORGAN	9001	Organ Pass, New Mexico
1OLFAN	9002	Olifantsfontein, South Africa
1OOMER	9003	Woomera, Australia
1SPAIN	9004	San Fernando, Spain
1TOKYO	9005	Tokyo, Japan
1NATOL	9006	Naini Tal, India
1QUIPA	9007	Arequipa, Peru
1SHRAZ	9008	Shiraz, Iran
1CURAC	9009	Curacao, Lesser Antilles
1JUPTR	9010	Jupiter, Florida
1VILDO	9011	Villa Dolores, Argentina
1MAUIO	9012	Maui, Hawaii
OSLONR	9426	Oslo, Norway
AUSBAK	9023	Woomera, Australia
NATALB	9029	Natal, Brazil
AGASSI	9050	Cambridge, Massachusetts
COLDLK	9424	Cold Lake, Alberta
EDWAFB	9425	Edwards AFB, California
RIGLAT	9428	Riga, Latvia
POTDAM	9429	Potsdam, Germany
ZVENIG	9430	Zvenigorod, Russia

Table XIII

STADAN — Optical

Name	Station No.	Location
1BPOIN	1021	Blossom Point, Maryland
1FTMYR	1022	Fort Myers, Florida
1OOMER	1024	Woomera, Australia
1QUITO	1025	Quito, Ecuador
1LIMAP	1026	Lima, Peru
1SATAG	1028	Santiago, Chile
1MOJAV	1030	Mojave, California
1JOBUR	1031	Johannesburg, Union of South Africa
1NEWFL	1032	St. John's, Newfoundland
1COLEG	1033	College, Alaska
1GFORK	1034	East Grand Forks, Minnesota
1WNKFL	1035	Winkfield, England
1ROSMA	1042	Rosman, North Carolina
1TANAN	1043	Tananarive, Madagascar

Table XIV

STADAN — $R/\dot{R}$

Name	Station No.	Location
CARVON	1152	Carnarvon, Australia
ROSMAN	1126	Rosman, North Carolina
MADGAR	1122	Tananarive, Madagascar

Table XV

NAVY TRANET — Doppler

Name	Station No.	Location
LASHAM	2006	Lasham, England
SANHES	2008	Sao Jose dos Campos, Brazil
PHILIP	2011	San Miquel, Philippines
SMTHFD	2012	Smithfield, Australia
MISAWA	2013	Misawa, Japan
ANCHOR	2014	Anchorage, Alaska
TAFUNA	2017	Tafuna, American Samoa
THULEG	2018	Thule, Greenland
MCMRDO	2019	McMurdo Sound, Antarctica
WAHIWA	2100	South Point, Hawaii
LACRES	2103	Las Cruces, New Mexico
LASHM2	2106	Lasham, England
APLMND	2111	APL Howard County, Maryland
PRETOR	2115	Pretoria, Union of South Africa
SHEMYA	2739	Shemya Island, Alaska
BELTSV	2742	Beltsville, Maryland
STNVIL	2745	Stoneville, Mississippi

Table XVI

AIR FORCE — Optical

Name	Station No.	Location
ANTIGA	3106	Antigua Island, Lesser Antilles
GRNVLE	3333	Stoneville, Mississippi
GRVILL	3334	Stoneville, Mississippi
USAFAC	3400	Colorado Springs, Colorado
BEDFRD	3401	L. G. Hanscom Field, Massachusetts
SEMMES	3402	Semmes Island, Georgia
SWANIS	3404	Swan Island, Caribbean Sea
GRDTRK	3405	Grand Turk, Caicos Islands
CURACO	3406	Curacao, Lesser Antilles
TRNDAD	3407	Trinidad Island
GRANFK	3451	Grand Forks, North Dakota
TWINOK	3452	Twin Oaks, Oklahoma
ROTHGR	3453	Rothwesten, West Germany
ATHNGR	3463	Athens, Greece
TORRSP	3464	Torrejon de Ardoz, Spain
CHOFUJ	3465	Chofu, Japan
KINDLY	3471	Kindly AFB, Bermuda
HUNTER	3648	Hunter AFB, Georgia
JUPRAF	3649	Jupiter, Florida
ABERDN	3657	Aberdeen, Maryland
HOMEST	3861	Homestead AFB, Florida
CHYWYN	3902	Cheyenne, Wyoming

Table XVII

ARMY MAP SERVICE — Secor

Name	Station No.	Location
HERNDN	5001	Herndon, Virginia
CUBCAL	5200	San Diego, California
LARSON	5201	Moses Lake, Washington
WRGTON	5202	Worthington, Minnesota
GREENV	5333	Greenville, Mississippi
TRUKIS	5401	Truk Island, Caroline Islands
SWALLO	5402	Swallow Island, Santa Cruz Islands
KUSAIE	5403	Kusaie Islands, Caroline Island
GIZZOO	5404	Gizzoo, Gonzongo, Solomon Islands
TARAWA	5405	Tarawa, Gilbert Islands
NANDIS	5406	Nandi, Vitilevu, Fiji Islands
CANTON	5407	Canton Island, Phoenix Islands
JONSTN	5408	Johnston Island, Pacific Ocean
MIDWAY	5410	Eastern Island, Midway Islands
MAUIHI	5411	Maui, Hawaii
FTWART	5648	Fort Stewart, Georgia
HNTAFB	5649	Hunter AFB, Georgia
HOMEFL	5861	Homestead AFB, Florida

Table XVIII

USC & GS — Optical

Name	Station No.	Location
BELTVL	6002	Beltsville, Maryland
ASTRMD	6100	Beltsville, Maryland
TIMINS	6113	Timmins, Ontario

Table XIX

SPEOPT — Optical

Name	Station No.	Location
1UNDAK	7034	Univ. North Dakota, Grand Forks, North Dakota
1EDINB	7036	Edinburg, Texas
1COLBA	7037	Columbia, Missouri
1BERMD	7039	Bermuda Island
1PURIO	7040	San Juan, Puerto Rico
1GSFCP	7043	GSFC, Greenbelt, Maryland
1CKVLE	7044	Clarksville, Indiana
1DENVR	7045	Denver, Colorado
1JUM24	7071	Jupiter, Florida
1JUM40	7072	Jupiter, Florida
1JUPC1	7073	Jupiter, Florida
1JUBC4	7074	Jupiter, Florida
1SUDBR	7075	Sudbury, Ontario
1JAMAC	7076	Jamaica, B. W. I.

Table XX

SPEOPT — Laser

Name	Station No.	Location
ROSLAS	7051	Rosman, North Carolina
GODLAS	7050	GSFC, Greenbelt, Maryland

Table XXI

INTERNATIONAL — Optical

Name	Station No.	Location
DELFTH	8009	Delft, Holland
MALVRN	8011	Malvern, England
ZIMWLD	8010	Berne, Switzerland

2.0 SOURCES

The following sources were used to obtain the original datum positions:

Symbol	Source
A	Geodetic Parameters for a Standard Earth Obtained from Baker-Nunn Observations; September 1966; Smithsonian Astrophysical Observatory.
B	Goddard Directory of Tracking Station Locations; August 1966; Goddard Space Flight Center.
C	NWL-8 Geodetic Parameters Based on Doppler Satellite Observations; July 1967; R. Anderle and S. Smith, Naval Weapons Laboratory.

Since the above official documents did not contain all those positions that were to be transformed, it was necessary to contact other sources for the positions of the remaining stations. These sources are:

Symbol	Source
D	Private communication with personnel at SAO; K. Haramundanis; E. Miller; A. Girnius.
E	Private communication with 1381 Geodetic Survey Squadron, USAF; S. Tischler.
F	Private communication with personnel at USC&GS; B. Stevens.
G	Private communication with personnel at U.S. Army Engineers Topographic Laboratories; L. Gambino.
H	Private communication with NASA Space Science Data Center; J. Johns; D. Tidwell.
I	General Station Data Sheet — GEOS-A-Project Manager NASA Headquarters.

REFERENCES

1. Lundquist, C. A., Veis, G., "Geodetic Parameters for a 1966 Smithsonian Institution Standard Earth," Smithsonian Astrophysical Observatory Special Report 200, Vol. 1, 1966.

2. Lerch, F. J., Marsh, J. G., D'Aria, M. D., Brooks, R. L. "Geos I Tracking Station Positions on the SAO Standard Earth (C-5)", GSFC Document X-552-68-70.

3. Lerch, F. J., Doll, C. E., Moss, S. J., O'Neill, B., "The Determination and Comparison of the GRARR MADGAR Site Location," GSFC Document X-552-67-540, October 1967.