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EVALUATION OF THE GODDARD RANGE AND RANGE RATE SYSTEM AT ROSMAN BY INTERCOMPARISON WITH GEOS I LONG-ARC ORBITAL SOLUTIONS

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ABSTRACT

The range measurements of the Goddard Range and Range Rate (GRARR) S-Band Tracking System at Rosman, North Carolina, have been evaluated using long-arc optical reference orbits as a standard. The optical reference orbits were determined from GEOS I flash sequence data sets and some optical passive data from five major geodetic optical tracking networks. The networks and camera types consisted of: the Smithsonian Astrophysical Observatory (SAO) — Baker-Nunn and Geodetic 36"; Goddard Space Flight Center (GSFC) Satellite Tracking and Data Acquisition Network (STADAN) and Special Optical Tracking System (SPEOPT) — Minitrack Optical Tracking System (MOTS) 40" and 24"; United States Air Force (USAF) — PC-1000; and the United States Coast and Geodetic Survey (USC&GS) — BC-4.

Thirty passes of range and range rate measurements, consisting of all GRARR passes from the GEOS I satellite during two periods in January 1966, were evaluated. The observed range measurements were compared with values calculated from the optically-determined reference orbits. For each pass, a zero-set range bias, timing error, and random error were estimated from the residual differences between the observed and calculated ranges. The GEOS I satellite carried two range and range rate transponder channels, denoted A and C. Twenty-six of the passes evaluated were from the A channel, and four were from the C channel. A summary of the zero-set and timing error estimates is presented in the following table for the two periods considered both separately and combined. These estimates are based on long-arc orbital solutions of approximately three to six days in arc length. The results are supported by several overlapping shorter-arc solutions which vary in arc length from two hours to two days.

Summary of Rosman GRARR Zero-Set Range Bias and Timing Error Estimates.

Period	Transponder Channel	Zero-Set Error (meters)		Timing Error (m.s.)	
		Mean	S.d.	Mean	S.d.
1	A C	-10.0 18.1	8.8	-2.4 -1.4	2.4
2	A	- 5.6	11.6	-1.9	5.1
1 and 2	A C	- 7.8 25.0	10.3	-2.1 -0.6	4.0

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INTRODUCTION

This report presents the results of an evaluation of the range measurements of the Goddard Range and Range Rate S-Band Tracking System at Rosman, North Carolina, based upon an analysis of GEOS I satellite data. The GEOS I satellite was launched in November 1965 by the National Aeronautics and Space Administration (NASA) as part of the National Geodetic Satellite Program. GEOS I was the first satellite to incorporate all the geodetic instrumentation systems of concern to the agencies participating in the program.

These instrumentation systems consisted of:

- Flashing lights synchronized with an on-board clock
- Doppler transmitters
- Goddard Range and Range Rate (GRARR) S-Band transponder
- Laser reflectors
- Sequential Collation of Range (SECOR) ranging transponder

The principal mean orbital elements for the GEOS I spacecraft are as follows:

Epoch:	January 2, 1966
Apogee height:	2273 kilometers
Perigee height:	1116 kilometers
Eccentricity:	.07
Inclination:	59.4 degrees
Anomalistic period:	120.3 minutes

Data sets recorded during two periods in January 1966 (December 31 to January 5, 1966, and January 11 to 17, 1966) were used in this evaluation. During these periods, all GRARR tracking of the GEOS I satellite was performed by the station at Rosman, North Carolina. Thirty passes of range measurements, consisting of all GRARR passes from the GEOS I satellite during these two periods, were evaluated by comparing these measurements with values computed from optically-determined reference orbits.

The optical tracking data consisted for this study primarily of flash sequence data* plus some passive reflected sunlight data recorded by five major geodetic optical tracking networks.† The networks and camera types consisted of: the Smithsonian Astrophysical Observatory (SAO) — Baker-Nunn and Geodetic 36"; Goddard Space Flight Center (GSFC) Satellite Tracking and Data Acquisition Network (STADAN) and Special Optical Tracking System (SPEOPT) — Minitrack Optical Tracking System (MOTS) 40" and 24"; United States Air Force (USAF) — PC-1000; and the United States Coast and Geodetic Survey (USC&GS) — BC-4.

METHOD OF EVALUATION

The range accuracy of the Goddard Range and Range Rate (GRARR) S-Band system was evaluated by comparing the actual measurements with values calculated from reference orbits that best fitted the sets of optical tracking data. Right ascension and declination measurements from camera tracking stations were used to determine the reference orbits, because they are known to be relatively free of biases and systematic errors.

The orbits used for this evaluation were estimated from the Orbit Determination Program NONAME (Reference 1). The following earth and force models were used in this evaluation:

- SAO C-5 Standard Earth‡
- SAO M-1 Gravity Model§
- Perturbations due to solar and lunar gravity§
- Perturbations due to solar radiation pressure§

Ten reference orbits were fitted to data sets from two periods in January 1966; the first period was December 31, 1965, to January 5, 1966, and the second was January 11 to January 17, 1966. Nine of the orbits were fitted to long arcs (greater than 6 revolutions) and the other orbit was fitted to a medium arc (1/4 to 6 revolutions). Several of the orbits were fitted to overlapping data sets. This was done to assess the effects that any errors in the orbital solution (i.e. due to uncertainties in solar radiation pressure, the earth's geopotential model, tracking station positions, or other sources) were having on the evaluation of the GRARR system. The majority of the

*See Appendix A for a listing of the data, Tables A1 and A2.

†A flash sequence consisted of 7 flashes each separated by 4 seconds in time, and each flash throughout a sequence was composed of 1, 2, 3, or 4 assigned lamps.

‡See Appendix D.

§See Appendix C.

observations used to determine the orbits were recorded by observing-stations in North America, and the only observations around the world were passive, i.e. camera observations of the sunlight-illuminated satellite when the beacons were not flashing. Summaries of the orbital solutions and root mean squares of fit are given in Tables 1 and 2. A complete description of the orbital solutions and data sets is given in Appendix A.

Table 1

Summary of Orbital Solutions.

Solution No.	Approximate Arc Length	Time of First Measurement	Time of Final Measurement
Period 1			
1	5-1/4 days	12/31/65 01 hr	01/05/66 06 hr
2	2-1/2 days	01/01/66 01 hr	01/03/66 08 hr
3	2-1/4 days	01/03/66 01 hr	01/05/66 06 hr
4	2 days	01/02/66 06 hr	01/04/66 06 hr
5	1 day	01/02/66 06 hr	01/03/66 08 hr
6	2 hrs	01/02/66 06 hr	01/02/66 08 hr
Period 2			
1	4 days	01/11/66 01 hr	01/15/66 05 hr
2	3 days	01/12/66 03 hr	01/15/66 05 hr
3	2 days	01/13/66 05 hr	01/15/66 05 hr
4	2 days	01/15/66 04 hr	01/17/66 05 hr

Table 2

Root Mean Squares About the Orbital Solutions.

Orbital Solution	No. of Obs.	Rms of Fit (secs. of arc)
Period 1		
1	1057	3.08
2	631	2.58
3	532	2.74
4	644	2.45
5	444	2.33
6	236	2.17
Period 2		
1	1133	3.16
2	956	2.94
3	704	2.80
4	853	2.80

EVALUATION OF THE GRARR MEASUREMENTS

The GRARR measurements normally recorded at the rate of one per second used in this evaluation have been smoothed over two-minute intervals using a sixth-order polynomial; smoothed values were computed every 32 seconds within an interval. The residual differences between the actual smoothed GRARR range measurements and the values computed from the reference orbits were used to obtain estimates of known systematic errors in the system. For the purposes of this evaluation, no observations taken when the elevation of the satellite from the station was less than 20° have been used; however, there did not appear to be any significant deterioration in the quality of the observations at these low elevations. The GRARR passes are summarized in Tables 3 and 4.

Table 3

Summary of GRARR Passes at Rosman from Period 1.

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°

*See Appendix A for a definition of transponder channels.
†Smoothed observations occurring every 32 seconds.
‡Right ascension plus declination measurements.

The following error model* was fitted to the range residuals:

$$\Delta R = \Delta B + \Delta t\,\dot{R} + F(\dot{R}) + \frac{3}{\sin E} - 9.7\,, \qquad (1)$$

*It should be noted that in this analysis only the unknown parameters ΔB and Δt were determined. The other parameters are presented since they are known corrections which should be applied to the GRARR range data as it exists in the National Space Science Data Center (NSSDC).

Table 4

Summary of GRARR Passes at Rosman from Period 2.

Pass No.	Transponder Channel	Date	Time	No. of Obs. in Pass		Max. Elevation Angle
				$R/\dot{R}$	Optical	
803	A	1/12/66	20^H	68	0	87.7°
804	A	1/12/66	22^H	22	0	33.1°
806	A	1/13/66	02^H	44	4	26.4°
807	A	1/13/66	04^H	46	91	83.7°
815	A	1/13/66	20^H	46	0	77.2°
818	A	1/14/66	02^H	42	0	30.2°
819	A	1/14/66	04^H	32	60	74.3°
827	C	1/14/66	20^H	38	0	67.6°
831	A	1/15/66	04^H	48	115	60.6°
839	A	1/15/66	20^H	44	0	58.8°
842	A	1/16/66	02^H	52	81	40.8°
843	A	1/16/66	04^H	50	68	47.9°
850	A	1/16/66	18^H	48	0	57.5°
854	A	1/17/66	02^H	50	59	48.3°
855	A	1/17/66	05^H	26	81	37.4°

where

ΔR = observed range minus calculated range,

ΔB = error in the zero-set value of the range (range bias),

Δt = an error in timing which may be due to a clock error, a Doppler-sensitive delay in the transponder, or the inverse of the velocity coefficient of the range tracking servo,

$F(\dot{R})$ = error due to the transponder delay,

E = elevation angle of the satellite,

and

9.7 = known range-measurement bias in the system at Rosman.

This model was fitted independently to the range residuals from each pass, using the method of least squares to solve for the unknown parameters, ΔB and Δt. The estimates of these parameters are summarized in Tables 5 through 8. The random errors or the standard deviations of the residual differences about the error model fit are summarized in Tables 9 and 10.

Table 5

Summary of Rosman Zero-Set Range Bias Estimates from Period 1.
(meters)

Pass No.	Transponder Channel	Orbital Solution No.					
		1	2	3	4	5	6
652 653	A A	-16.5 - 6.1					
664 665 673	A A A	- 5.0 - 2.0 -19.1	- 8.0 2.8 -13.9				
676 677 685	A A A	2.3 0.2 -29.5	6.6 1.4 -24.2		2.7 6.0 -25.4	4.2 7.4 -20.7	5.2 4.4
688 689 697	A A A	- 3.3 -14.9 -16.0	1.0 -14.3	- 9.4 -12.6 -18.4	- 2.7 - 8.6 -11.5	- 1.0 - 7.7	
700 708 709	C C C	20.6 16.8 17.0		15.8 19.0 14.1	21.5		
712	A	- 9.5		-13.0			
Mean S.d.	A A	-10.0 8.8					
Mean	C	18.1					

Table 6

Summary of Rosman Timing Error Estimates from Period 1.
(milliseconds)

Pass No.	Transponder Channel	Orbital Solution No.					
		1	2	3	4	5	6
652 653	A A	-2.0 1.5					
664 665 673	A A A	-3.9 1.0 -3.4	-5.0 0.9 -0.6				
676 677 685	A A A	-6.3 -0.2 -3.5	-6.1 -0.4 0.4		-6.4 -0.1 -3.1	-6.9 -0.3 -0.6	-3.5 -2.3
688 689 697	A A A	-5.9 0.1 -3.0	-5.1 0.6	-4.8 1.4 -3.4	-6.6 -0.3 -3.1	-5.3 1.2	
700 708 709	C C C	-5.4 -2.3 3.4		-4.8 -2.4 2.2	-6.5		
712	A	-2.8		-2.9			
Mean S.d.	A A	-2.4 2.4					
Mean	C	-1.4					

Table 7

Summary of Rosman Zero-Set Range Bias Estimates from Period 2.
(meters)

Pass No.	Transponder Channel	Orbital Solution No.			
		1	2	3	4
803	A	8.7	10.7		
804*	A	21.4	27.3		
806	A	-14.4	- 8.6		
807	A	-14.8	-15.1	-16.9	
815	A	- 3.1	- 0.4	- 1.7	
818	A	-12.8	- 7.4	- 7.1	
819	A	10.8	9.1	6.1	
827	C	45.3	48.6	44.8	
831	A	13.5	10.5	8.1	8.8
839	A				10.5
842	A				-19.3
843	A				-13.8
850*	A				2.1
854	A				- 9.1
855	A				-18.4
Mean	A	- 5.6			
S.d.	A	11.6			

*Passes 804 and 850 were omitted from the mean value calculation since pass 804 had a maximum elevation angle of only 33°, and no optical data were available within approximately 8 hours of these passes.

Table 8

Summary of Rosman Timing Error Estimates from Period 2.
(milliseconds)

Pass No.	Transponder Channel	Orbital Solution No.			
		1	2	3	4
803	A	5.4	6.1		
804*	A	13.5	14.1		
806	A	- 8.8	- 9.2		
807	A	- 2.7	- 3.1	- 4.6	
815	A	6.4	7.4	5.9	
818	A	- 7.8	- 8.0	- 8.1	
819	A	- 1.9	- 2.0	- 2.6	
827	C	2.0	3.1	2.0	
831	A	- 3.9	- 3.2	- 2.6	- 3.3
839	A				5.8
842	A				- 6.3
843	A				0.7
850*	A				12.4
854	A				- 7.7
855	A				- 2.6
Mean	A	- 1.9			
S.d.	A	5.1			

*Passes 804 and 850 were omitted from the mean value calculation since pass 804 had a maximum elevation angle of only 33°, and no optical data were available within approximately 8 hours of these passes.

Table 9

Summary of Random Error Estimates from Period 1.
(meters)

Pass No.	Transponder Channel	Orbital Solution No.					
		1	2	3	4	5	6
652	A	3.3					
653	A	3.6					
664	A	3.2	3.1				
665	A	4.5	5.2				
673	A	2.6	2.2				
676	A	2.9	3.0		2.9	3.0	2.9
677	A	3.2	3.5		3.8	4.0	3.5
685	A	2.5	2.3		2.5	2.3	
688	A	4.5	5.2	4.1	4.7	5.3	
689	A	4.1	4.0	4.1	3.9	3.8	
697	A	3.4		3.4	3.4		
700	C	5.8		4.7	6.4		
708	C	4.5		4.9			
709	C	3.1		3.2			
712	A	6.0		4.8			
Mean	A	3.7					
Mean	C	4.5					

Table 10

Summary of Random Error Estimates from Period 2.
(meters)

Pass No.	Transponder Channel	Orbital Solution No.			
		1	2	3	4
803	A	10.7	11.7		
804	A	7.6	7.8		
806	A	3.1	3.3		
807	A	8.6	8.4	7.8	
815	A	6.3	7.1	7.0	
818	A	2.8	2.9	2.9	
819	A	6.7	6.2	5.1	
827	C	7.0	7.6	7.9	
831	A	10.5	9.8	7.9	11.6
839	A				7.3
842	A				5.3
843	A				5.5
850	A				9.2
854	A				6.5
855	A				2.2
Mean	A	6.6			

RESULTS

Rosman GRARR Zero-Set Range Bias and Timing Error Estimates

The zero-set range bias estimates for the A channel passes from period 1 had a mean value of -10.0 meters and a standard deviation of 8.8 meters, and the three C channel passes had a mean value of 18.1 meters. (See Table 11.) The A channel passes from period 2 had a mean zero-set range bias estimate of -5.6 meters and a standard deviation of 11.6 meters, and the one C channel pass had a zero-set range bias estimate of 45.3 meters. The overall mean zero-set range bias estimates were -7.8 meters with a standard deviation of 10.3 meters for the A channel passes, and 25.0 meters for the C channel passes.

Table 11

Summary of Rosman GRARR Zero-Set Range Bias and Timing Error Estimates.

Period	Transponder Channel	Zero-Set Error (meters)		Timing Error (m.s.)	
		Mean	S.d.	Mean	S.d.
1	A C	-10.0 18.1	8.8	-2.4 -1.4	2.4
2	A	- 5.6	11.6	-1.9	5.1
1 and 2	A C	- 7.8 25.0	10.3	-2.1 -0.6	4.0

The timing error estimates for some passes were larger than would be expected, and it is probable that other systematic error sources are contributing to these estimates. The A channel passes for period 1 had a mean value of -2.4 milliseconds and the C channel passes had a mean value of -1.4 milliseconds. The A channel passes for period 2 had a mean value of -1.9 milliseconds and the one C channel pass had a timing-error estimate of 2.0 milliseconds. The overall mean timing error estimate for the A channel passes was -2.1 milliseconds with a standard deviation of 4.0 milliseconds.

Comparison with Previous Results

Berbert et al. (Reference 2) analyzed GRARR range data recorded by the GRARR S-Band System and the Goddard Laser Tracking System during a side-by-side tracking experiment with the GEOS I spacecraft. The data used in this analysis were recorded primarily during the period of October-November 1966.

For this analysis the actual range measurements were compared with those calculated from short-arc orbital solutions determined from Laser range data. The Laser orbital solutions were used as a standard reference in this analysis because they can be used to detect systematic errors in both range and range rate to about 2 meters and 1 cm/sec respectively.

Berbert et al. evaluated a selected set of 10 simultaneous GRARR and Laser passes. The average zero-set range bias for the Rosman GRARR relative to the Laser was -5.3 ± 12.4 meters. The average timing difference between the Laser and the GRARR range timing was -2.1 ± 1.2 milliseconds. Zero-set range biases for three of these passes deviated greatly from the norm. A new zero-set range bias of -5.3 ± 2.5 meters was calculated when these passes were omitted.

These results are in good agreement with those obtained from the long-arc optical evaluation of the GRARR range measurements at Rosman.

CONCLUSIONS

The large volume of high-precision optical observations of GEOS I has provided the first opportunity to analyze the GRARR data recorded from the same satellite for systematic errors and biases. For this analysis, definitive long-arc optical orbital solutions determined from the GEOS I flashing lamp and passive data have provided a very accurate standard for estimating these errors.

The GRARR zero-set range bias and timing error estimates for the two satellite transponder channels, A and C, differed significantly. Twenty-six A channel passes analyzed had a mean zero-set range bias error of -7.8 meters with a standard deviation of 10.3 meters and a timing error of -2.1 milliseconds with a standard deviation of 4.0 milliseconds. Four C channel passes analyzed had a mean zero-set range bias error of 25.0 meters and a mean timing error of -0.6 milliseconds. This discrepancy can be explained in part by inaccuracies in the transponder delay curve.

A timing error of up to 2 milliseconds can possibly be attributed to the orbital solution; however, the consistent results obtained from the shorter overlapping solutions indicate that these errors are due to other sources, either the GRARR system itself, or station survey errors, etc. Further analysis and a possible expansion of the error model will be necessary before a complete explanation of these errors is possible.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, August 16, 1968
311-07-21-01-51

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2. Berbert, J. H., Maresca, P., Norris, P., and Reich, R., "Intercomparison of Collocated Laser Optical and GRARR Radio Ranging System Tracks on GEOS-A," NASA TM X-55950, September 1967.

Appendix A

Summary of Data Sets and Orbital Solutions

Optical Data

The optically-determined reference orbits that are used as standards in this report were determined from right ascension and declination measurements recorded by STADAN and SPEOPT MOTS 40" and 24" cameras, SAO Baker-Nunn and Geodetic 36" cameras, USAF PC-1000 cameras and United States Coast and Geodetic Survey BC-4 cameras. The locations of most of these cameras are shown in Figures A1 and A2. These figures serve to illustrate that the majority of the tracking stations were located in North America. Because of the station mutual visibility scheduling of the GEOS I spacecraft, flash sequences occurring over North America were observed by many tracking stations simultaneously.

Observations from two periods in January 1966 were used. The two periods were:

1. December 31, 1965, to January 5, 1966

2. January 11 to January 17, 1966

The complete data sets that were used from each period are summarized in Tables A1 and A2, and Figures A3 and A4. Tables A1 and A2 summarize the observations by network and tracking station, and Figures A3 and A4 indicate the data coverage by time.

Six overlapping orbits were estimated using subsets of data from Period 1, and four overlapping orbits were estimated using the data from Period 2. These orbital solutions are summarized in Tables A3 through A5 and Figures A5 and A6. The lengths of the arcs in these solutions range from two hours to approximately 5-1/4 days in length, and root mean squares about the orbital solutions are given in Table A6.

Details on the passes for Periods 1 and 2 are listed in Tables A7 and A8, and the passes are mapped in Figures A7 through A13.

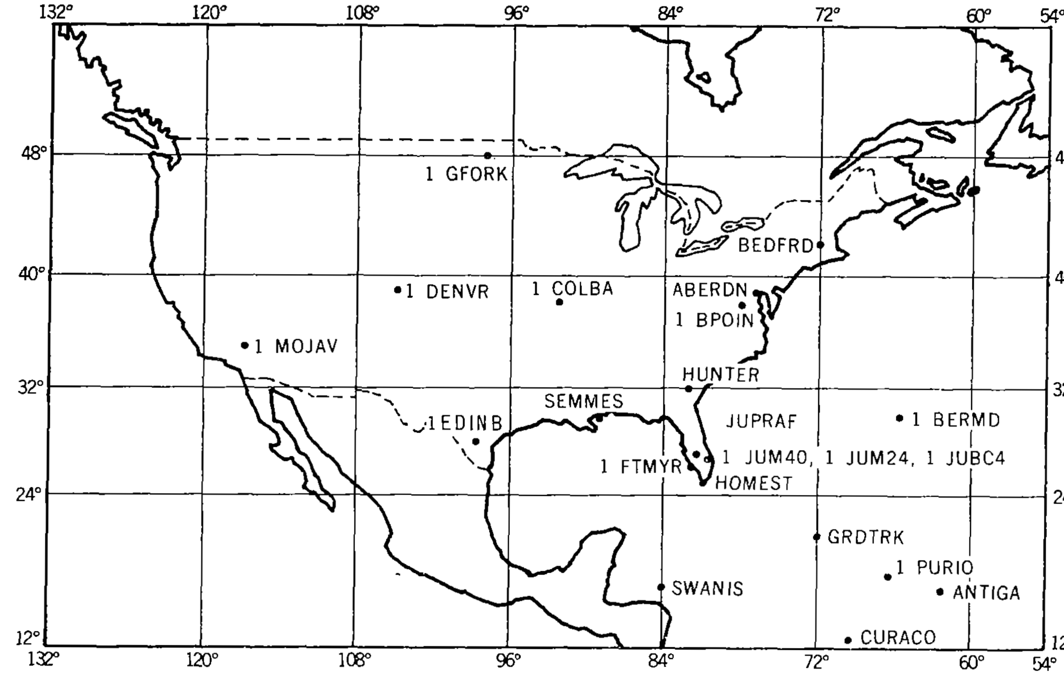


Figure A1—STADAN, SPEOPT, and USAF camera stations.

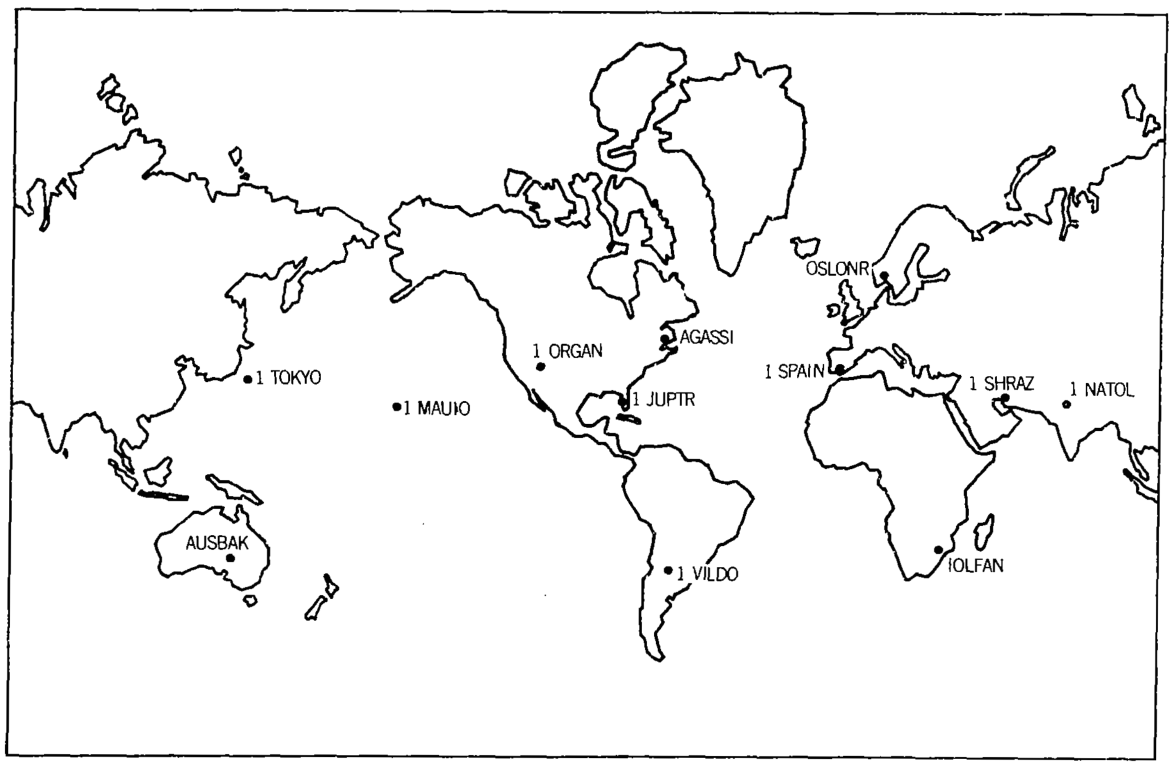


Figure A2—SAO camera stations.

Table A1

Summary of Optical Measurements by Station for Period 1

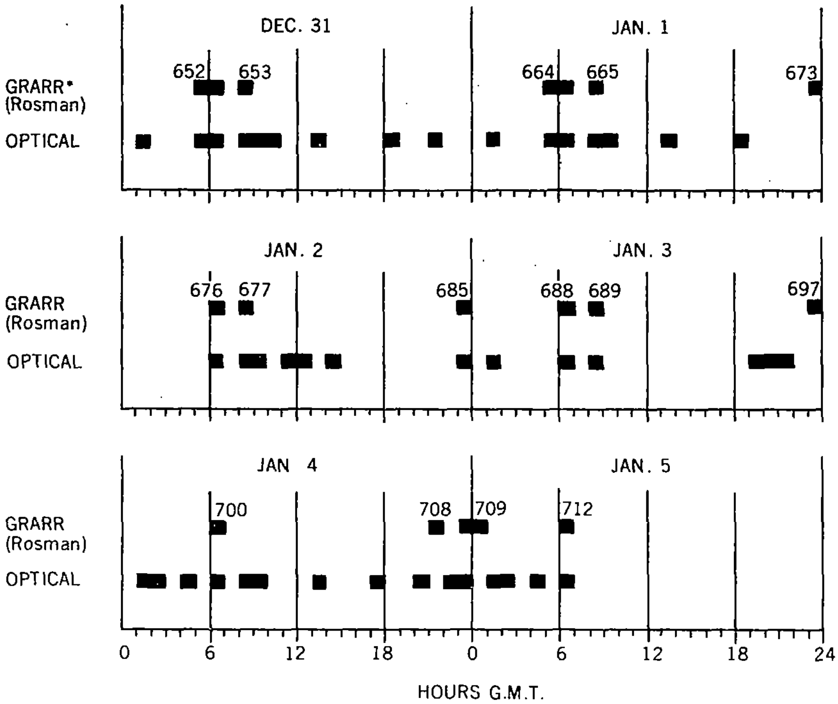
Network	Station	Camera Type	No. of Observations*	Type	No. Passes/ No. Flash Sequences
SAO	1ORGAN	Baker-Nunn	2	Passive	1/
	1NATOL	"	8	"	4/
	OSLONR	"	4	"	2/
	AUSBAK	"	4	"	2/
	1SHRAZ	"	2	"	1/
	1SPAIN	"	6	"	3/
	1TOKYO	"	12	"	6/
	1VILDO	"	2	"	1/
	1MAUIO	"	2	"	1/
	1JUPTR	"	26	Active	1/2
	AGASSI	Geodetic 36"	10	"	1/1
	TOTAL:		78		
SPEOPT	1COLBA	MOTS 40"	164	Active	8/13
	1JUM40	"	22	"	3/3
	1BERMD	"	84	"	5/7
	1PURIO	"	14	"	1/1
	1DENVR	"	70	"	4/6
	1JUM24	MOTS 24"	26	"	3/3
	TOTAL:		380		
STADAN	1FTMYR	MOTS 40"	82	Active	4/6
	1BPOIN	"	53	"	5/6
	1GFORK	"	26	"	3/3
	1MOJAV	"	25	"	2/2
	TOTAL:		186		
USAF	HUNTER	PC-1000	59	Active	5/5
	SWANIS	"	14	"	1/1
	GRDTRK	"	7	"	1/1
	ANTIGA	"	26	"	2/2
	SEMMES	"	60	"	4/5
	CURACO	"	40	"	3/3
	HOMEST	"	94	"	4/6
	JUPRAF	"	17	"	2/2
	BEDFRD	"	22	"	2/2
	ABERDN	"	74	"	6/6
	TOTAL		413		
	Total of All Observations		= 1057		21/ Passive 70/86 Active
	Total Passive Observations =		.42		91 Total Station-Passes

*Right ascension plus declination measurements.

Table A2

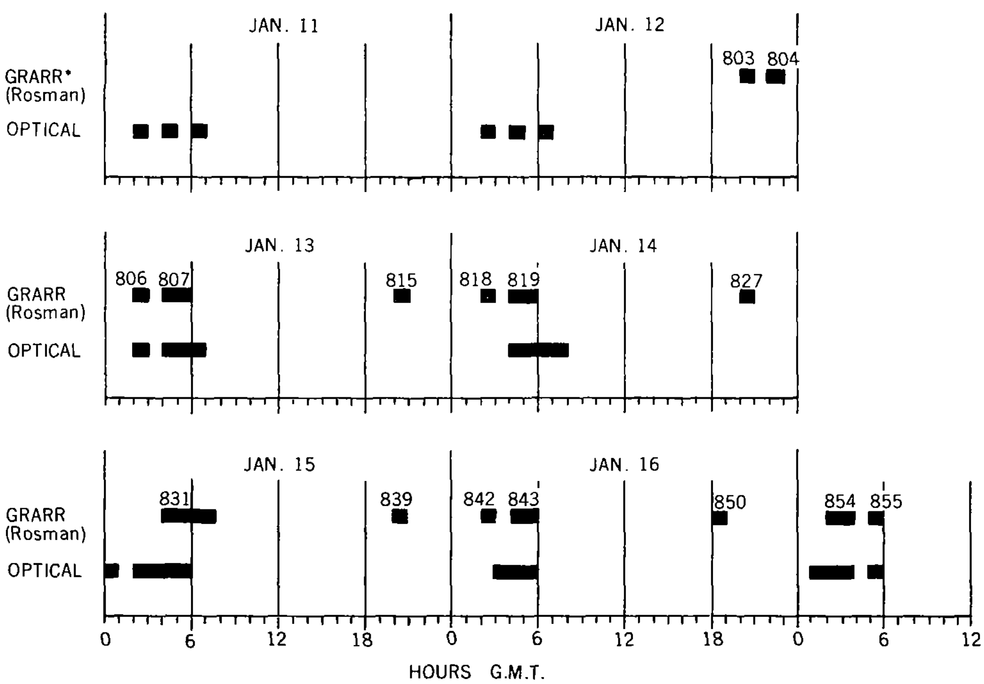
Summary of Optical Measurements by Station for Period 2.

Network	Station	Camera Type	No. of Observations	Type	No. Passes/ No. Flash Sequences
SAO	1OLFAN	Baker-Nunn	6	Passive	3/
	1TOKYO	"	4	"	2/
	1VILDO	"	8	"	4/
	AUSBAK	"	8	"	4/
	OSLONR	"	1	"	1/
	1JUPTR	"	84	Active	2/6
	AGASSI	Geodetic 36"	63	"	3/5
	TOTAL		174		
SPEOPT	1EDINB	MOTS 40"	109	Active	4/8
	1COLBA	"	92	"	3/7
	1BERMD	"	10	"	1/1
	1PURIO	"	34	"	3/3
	1GSFCP	"	40	"	3/3
	1DENVR	"	82	"	5/6
	1JUM24	MOTS F24"	62	"	5/5
	1JUM40	MOTS F40"	70	"	5/5
	1JUBC4	BC-4	65	"	4/5
	TOTAL		564		
STADAN	1BPOIN	MOTS 40"	41	Active	4/4
	1FTMYR	"	168	"	7/12
	1MOJAV	"	87	"	5/7
	1COLEG	"	30	"	3/3
	1GFORK	"	74	"	4/6
	1ROSMA	"	34	"	2/3
	TOTAL		434		
USAF	ANTIGA	PC-1000	52	Active	4/4
	BEDFRD	"	85	"	7/7
	SEMMES	"	60	"	5/5
	GRDTRK	"	74	"	6/6
	CURACO	"	21	"	2/2
	TRNDAD	"	21	"	2/2
	HUNTER	"	12	"	1/1
	JUPRAF	"	73	"	6/8
	ABERDN	"	74	"	6/6
	HOMEST	"	108	"	6/8
	TOTAL		580		
US C&GS	TIMINS	BC-4	14	Active	1/1
	Total of All Observations = 1766 Total Passive Observations = 27				14/ Passive 109/139 Active 123 Total Station-Passes



* The GRARR data coverage is presented in terms of orbit number.

Figure A3—Summary of data coverage for Period 1.



* The GRARR data coverage is presented in terms of orbit number.

Figure A4—Summary of data coverage for Period 2.

Table A3

Summary of Orbital Solutions.

Period 1			
Solution No.	Approximate Arc Length	Time of First Measurement	Time of Final Measurement
1	5-1/4 days	12/31/65 01 hr	01/05/66 06 hr
2	2-1/2 days	01/01/66 01 hr	01/03/66 08 hr
3	2-1/4 days	01/03/66 01 hr	01/05/66 06 hr
4	2 days	01/02/66 06 hr	01/04/66 06 hr
5	1 day	01/02/66 06 hr	01/03/66 08 hr
6	2 hrs	01/02/66 06 hr	01/02/66 08 hr
Period 2			
1	4 days	01/11/66 01 hr	01/15/66 05 hr
2	3 days	01/12/66 03 hr	01/15/66 05 hr
3	2 days	01/13/66 05 hr	01/15/66 05 hr
4	2 days	01/15/66 04 hr	01/17/66 05 hr

Table A4

Subsets of Optical Measurements Used in Orbital Solutions for Period 1.

Network	Station	No. of Observations*				
		Arc 2	Arc 3	Arc 4	Arc 5	Arc 6
SAO	1ORGAN		2			
	1JUPTR	26		26	26	26
	1NATOL	4	2	2	2	
	OSLONR		4			
	AUSBAK	2				
	1SHRAZ	2		2	2	
	1SPAIN		4	4		
	1TOKYO	6	2	4	4	
	1VILDO		2			
	AGASSI		10			
	TOTAL	40	26	38	34	26
SPEOPT	1COLBA	71	164	136	71	
	1JUM40	16		16	16	16
	1BERMD	64	40	50	36	10
	1PURIO		14			
	1DENVR	42	14	28	14	14
	1JUM24	21		21	21	21
	TOTAL	214	232	251	158	61
STADAN	1FTMYR	82	42	54	54	12
	1BPOIN		46	26		
	1GFORK	26	9	9	9	
	1MOJAV	25		25	25	25
	TOTAL	133	97	114	88	37
USAF	HUNTER	59	14	47	47	23
	SWANIS	14	14	14	14	
	GRDTRK		7	7		
	ANTIGA	12	14	14		
	SEMMES	50		36	36	36
	CURACO	26	28	40	26	12
	HOMEST	66	28	38	24	24
	JUPRAF	17		17	17	17
	BEDFRD		22	14		
	ABERDN		50	14		
	TOTAL	244	177	241	164	112
Total of All Observations		631	532	644	444	236

*For Arc 1, refer to Table A1.

Table A5

Subsets of Optical Measurements Used in Orbital Solutions for Period 2.

Network	Station	No. of Observations			
		Arc 1	Arc 2	Arc 3	Arc 4
SAO	1OLFAN	6	4		
	1TOKYO	4	2	2	
	1JUPTR				84
	1VILDO	8	6	6	2
	AUSBAK	6	4	4	2
	AGASSI	63	46	12	12
	OSLONR				1
	TOTAL	87	62	24	101
SPEOPT	1EDINB	72	48	20	65
	1COLBA	92	92	92	38
	1BERMD				10
	1PURIO	20	14	14	14
	1GSFCP	40	40	26	
	1DENVR	56	56	56	26
	1JUM24	22	22	22	54
	1JUM40	28	28	28	56
	1JUBC4	38	38	38	41
	TOTAL	368	338	296	304
STADAN	1BPOIN	37	37	18	8
	1FTMYR	103	103	75	78
	1MOJAV	52	52	52	42
	1COLEG	17	17	17	13
	1GFORK	40	14	14	34
	1ROSMA	22			12
	TOTAL	271	223	176	187
USAF	ANTIGA	38	38	24	24
	BEDFRD	58	58	26	27
	SEMMES	50	26		10
	GRDTRK	46	34	34	38
	CURACO	21	21	21	10
	TRNDAD	11	11		10
	HUNTER	12			
	JUPRAF	38	38	38	53
	ABERDN	68	42	14	20
	HOMEST	51	51	51	69
	TOTAL	393	319	208	261
USC&GS	TIMINS	14	14		
Total of All Observations		1133	956	704	853

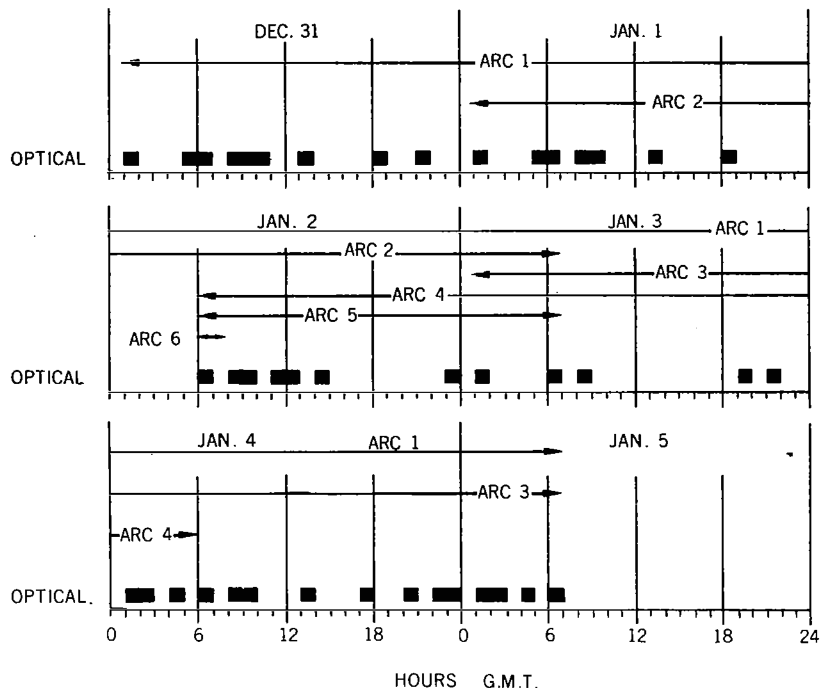


Figure A5—Summary of orbital solutions for Period 1.

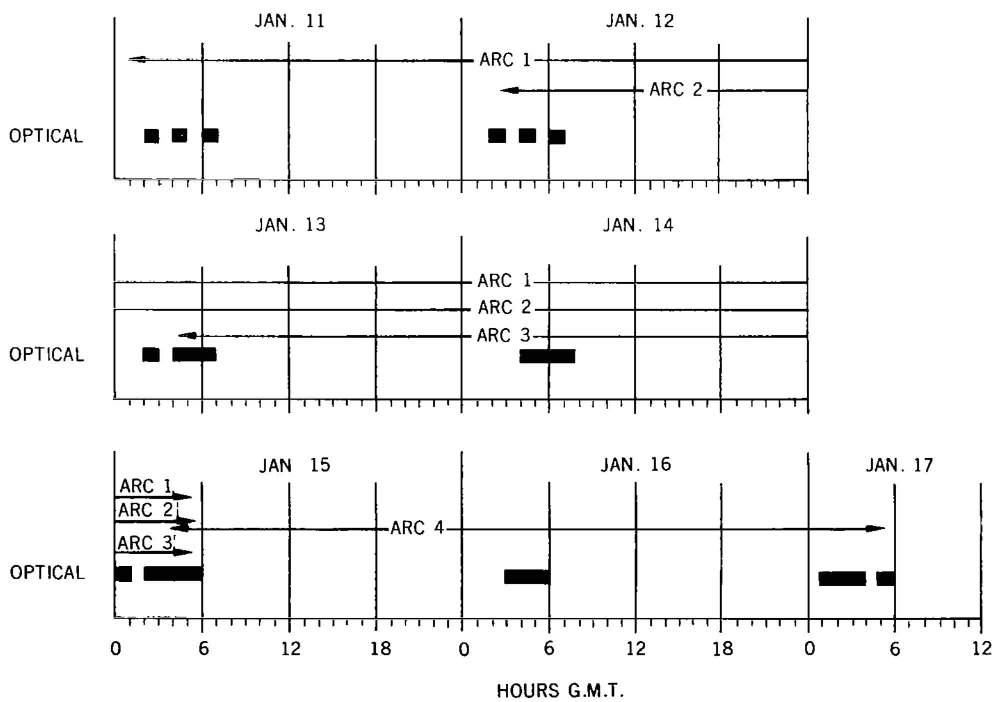


Figure A6—Summary of orbital solutions for Period 2.

Table A6

Root Mean Squares About the Orbital Solutions.

Period 1		
Orbital Solution	No. of Obs.	Rms of Fit (secs. of arc)
1	1057	3.08
2	631	2.58
3	532	2.74
4	644	2.45
5	444	2.33
6	236	2.17
Period 2		
1	1133	3.16
2	956	2.94
3	704	2.80
4	853	2.80

Table A7

Summary of GRARR Passes at ROSRAN from Period 1.

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°

Table A8

Summary of GRARR Passes at ROSRAN from Period 2.

Pass No.	Transponder Channel	Date	Time	No. of Obs. in Pass		Max. Elevation Angle
				$R/\dot{R}$	Optical	
803	A	1/12/66	20^H	68	0	87.7°
804	A	1/12/66	22^H	22	0	33.1°
806	A	1/13/66	02^H	44	4	26.4°
807	A	1/13/66	04^H	46	91	83.7°
815	A	1/13/66	20^H	46	0	77.2°
818	A	1/14/66	02^H	42	0	30.2°
819	A	1/14/66	04^H	32	60	74.3°
827	C	1/14/66	20^H	38	0	67.6°
831	A	1/15/66	04^H	48	115	60.6°
839	A	1/15/66	20^H	44	0	58.8°
842	A	1/16/66	02^H	52	81	40.8°
843	A	1/16/66	04^H	50	68	47.9°
850	A	1/16/66	18^H	48	0	57.5°
854	A	1/17/66	02^H	50	59	48.3°
855	A	1/17/66	05^H	26	81	37.4°

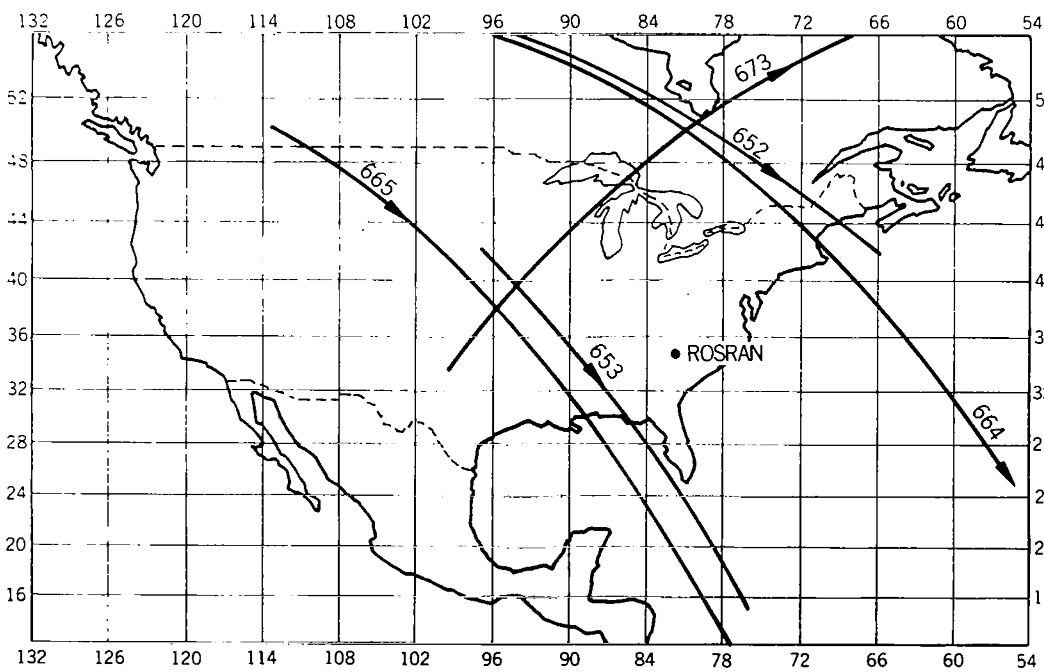


Figure A7—GRARR passes, December 31, 1965, and January 1, 1966.

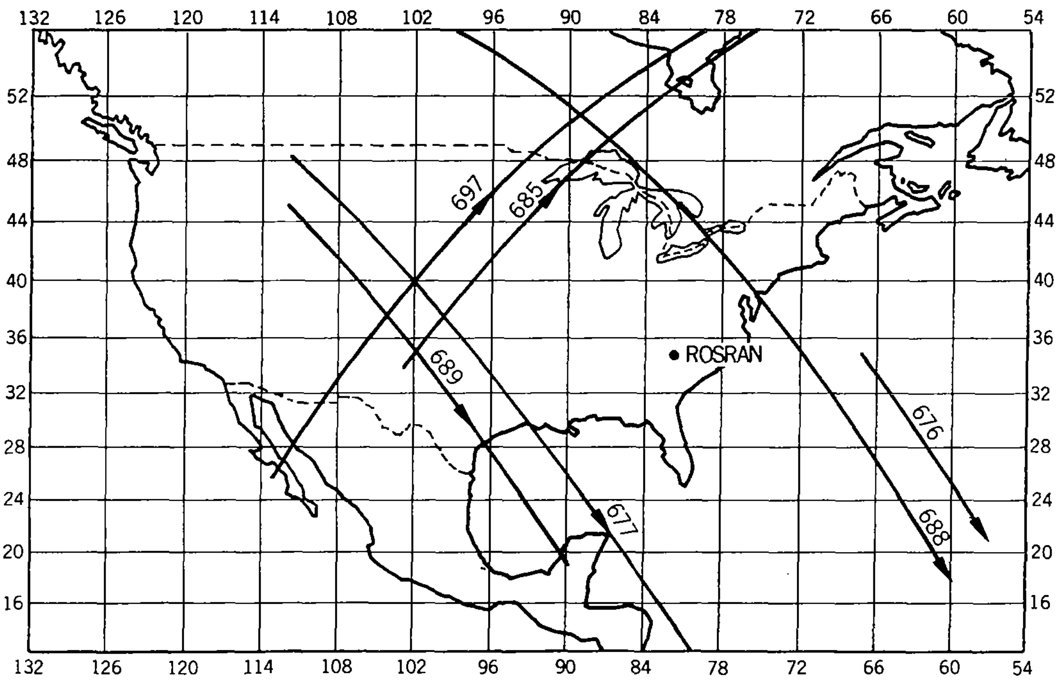


Figure A8—GRARR passes, January 2 and 3, 1966.

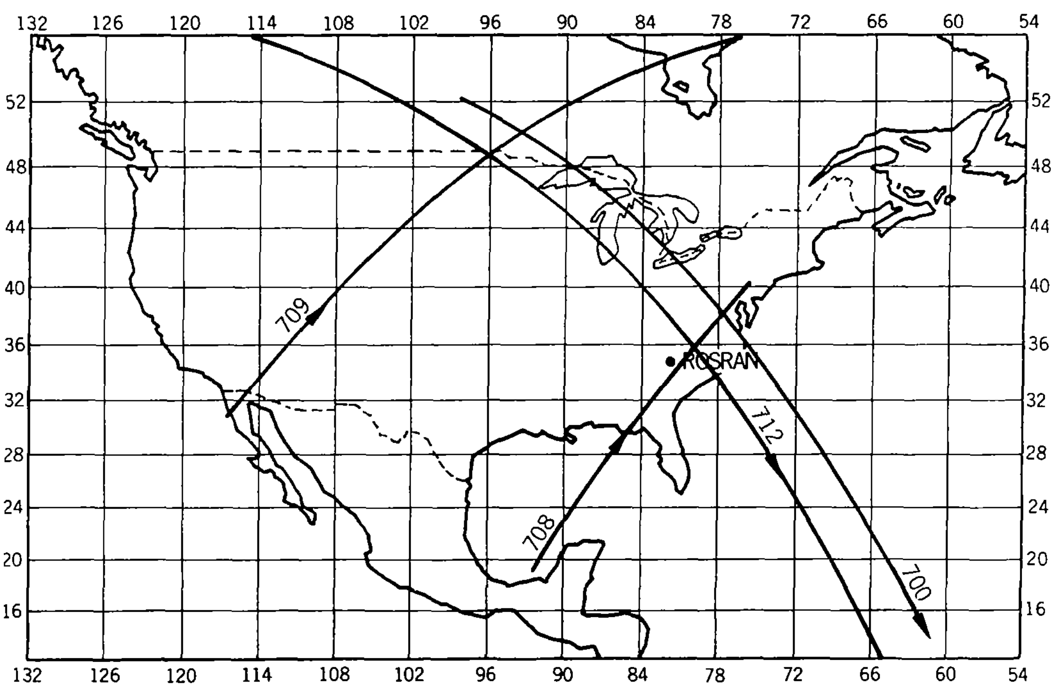


Figure A9—GRARR passes, January 4 and 5, 1966.

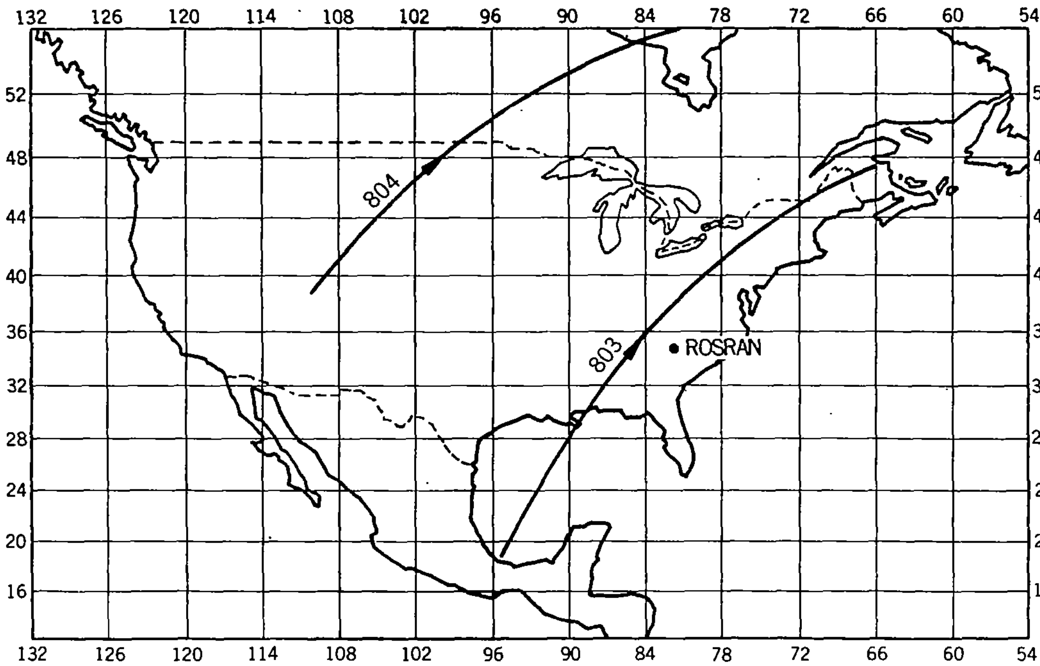


Figure A10—GRARR passes, January 11 and 12, 1966.

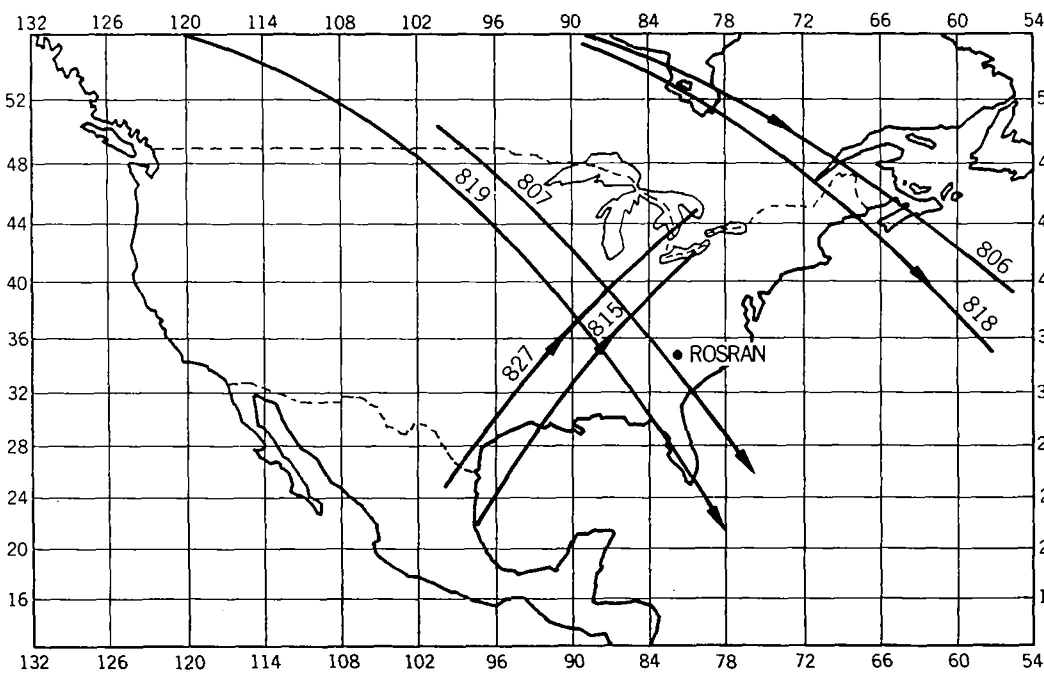


Figure A11—GRARR passes, January 13 and 14, 1966.

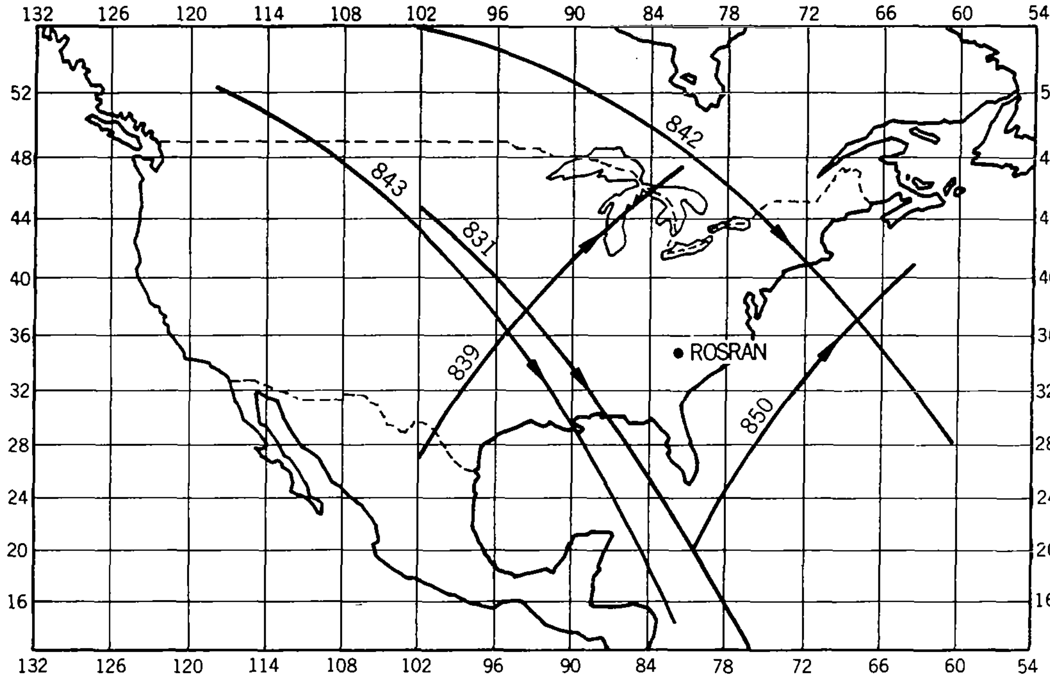


Figure A12—GRARR passes, January 15 and 16, 1966.

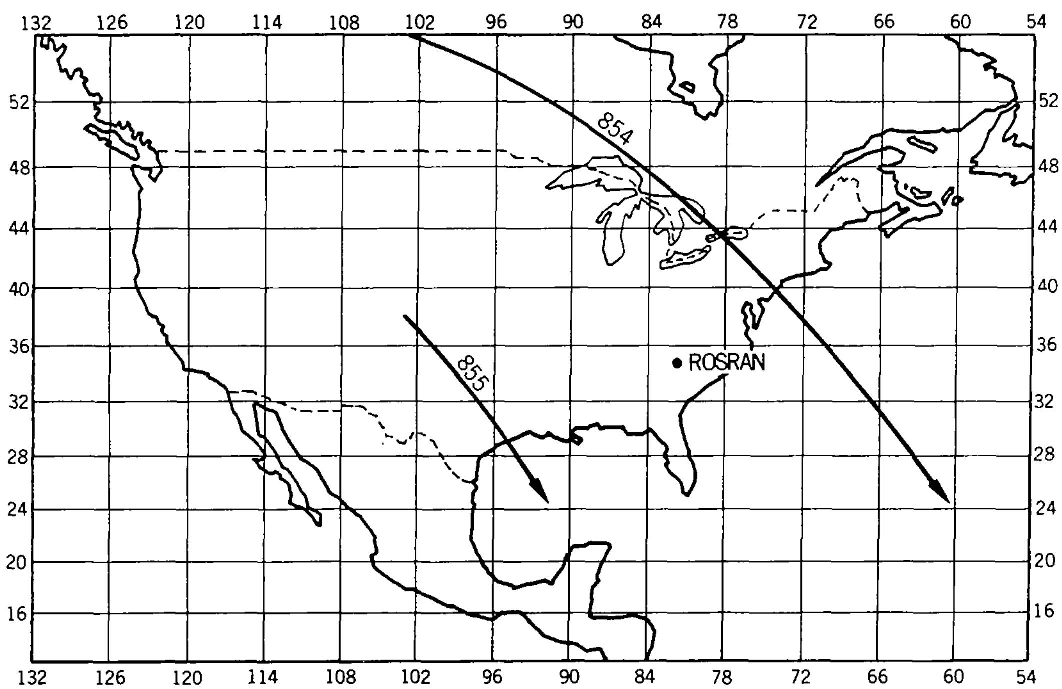


Figure A13—GRARR passes, January 17, 1966.

GRARR Data

The Goddard Range and Range Rate (GRARR) Tracking System* was designed as a high-precision tracking system able to accurately determine the range and radial velocity of a spacecraft by measuring phase shift and Doppler. Each station uses an S-band and a VHF system. Only the S-band system was used in this evaluation. For use with the S-band system, a 3-channel ranging transponder may be installed in the spacecraft. The GEOS I satellite transponder contained two channels, referred to as the A and C channels, which received signals at 2271.9328 MHz and 2270.1328 MHz respectively.

Range and range rate measurements for the GEOS I spacecraft were made and recorded at the rate of one per second. The GRARR observations used in this evaluation had been smoothed using a sixth-order polynomial smoothing program. The data were smoothed over two-minute periods, and smoothed values were calculated at 32-second intervals within these periods.

The GRARR passes evaluated in this report are summarized in Tables A7 and A8. These tables indicate the date and time of each pass, number of GRARR observations, number of simultaneous optical observations, maximum elevation of pass, and the satellite transponder channel. The geometry of these passes is represented in Figures A7 through A13.

*Kronmiller, G. C., Jr., and Baghdady, E. J., "The Goddard Range and Range Rate Tracking System: Concept, Design, and Performance," NASA TM X-55382, October 1965.

Appendix B

Preprocessing of Optical Observations

Preprocessing of Optical Data

The first step in the processing of optical observations (and one usually performed by the observing source) consists of developing a plate or film and identifying thereon 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 both of satellite images and of 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 corrections 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 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,* 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 millisecond, 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 necessary only to precess from that epoch to the dates of the observations. 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 epoch of the observation.

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

*"GEOS-A Clock Calibration," Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Md., 1966.

Nutation

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

$$Y = NX , \tag{B1}$$

where

$$Y = \begin{bmatrix} \cos\delta_m & \cos\alpha_m \\ \cos\delta_m & \sin\alpha_m \\ \sin\delta_m & \end{bmatrix} , \tag{B2}$$

$$X = \begin{bmatrix} \cos\delta_T & \cos\alpha_T \\ \cos\delta_T & \sin\alpha_T \\ \sin\delta_T & \end{bmatrix} , \tag{B3}$$

$$N = \begin{bmatrix} 1 & +\Delta\psi\cos\epsilon_m & +\Delta\psi\sin\epsilon_m \\ -\Delta\psi\cos\epsilon_m & 1 & +\Delta\epsilon \\ -\Delta\psi\sin\epsilon_m & -\Delta\epsilon & 1 \end{bmatrix} , \tag{B4}$$

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, and

$\Delta\epsilon$ = nutation in obliquity.

The inverse transformation is simply:

$$X = N^{-1} Y = N^T Y . \tag{B5}$$

Precession

The transformation from the mean equator and equinox of 1950.0 to the mean equator and equinox of an arbitrary epoch t1 is

$$Y = PX , \tag{B6}$$

where

$$Y = \begin{bmatrix} \cos\delta_{t1} & \cos\alpha_{t1} \\ \cos\delta_{t1} & \sin\alpha_{t1} \\ \sin\delta_{t1} & \end{bmatrix}, \tag{B7}$$

$$X = \begin{bmatrix} \cos\delta_{1950.0} & \cos\alpha_{1950.0} \\ \cos\delta_{1950.0} & \sin\alpha_{1950.0} \\ \sin\delta_{1950.0} & \end{bmatrix}, \tag{B8}$$

and

$$P = \begin{bmatrix} (\cos z \cos\theta \cos\zeta - \sin z \sin\zeta) & (-\cos z \cos\theta \sin\zeta - \sin z \cos\zeta) & (-\cos z \sin\theta) \\ (\sin z \cos\theta \cos\zeta + \cos z \sin\zeta) & (-\sin z \cos\theta \sin\zeta + \cos z \cos\zeta) & (-\sin z \sin\theta) \\ (\sin\theta \cos\zeta) & (-\sin\theta \sin\zeta) & (\cos\theta) \end{bmatrix}. \tag{B9}$$

The inverse transformation is

$$X = P^{-1} Y = P^{T} Y . \tag{B10}$$

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

Appendix C

Force Models used in the NONAME Orbit Determination Program

Force Models

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

1. The earth's 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.

The Earth's Gravitational Field

The formulation of the geopotential used is:

$$U = \frac{GM}{r}\left[1 + \sum_{n=2}^{k}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n} P_n^m(\sin\phi)\left(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right)\right] \tag{C1}$$

where

G = the universal gravitational constant,

M = the mass of the earth,

r = the geocentric satellite distance,

a = the earth's mean equatorial radius,

ϕ = the sub-satellite geocentric latitude,

λ = the sub-satellite east longitude measured from Greenwich,

$P_n^m(\sin\phi)$ = 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 subset of these.

The SAO M-1 earth gravitational model (Reference C1) modified by the GEOS I resonant harmonics ($\bar{C}_{13,12}$, $\bar{S}_{13,12}$, $\bar{C}_{14,12}$, $\bar{S}_{14,12}$, $\bar{C}_{15,12}$, $\bar{S}_{15,12}$) (Reference C2) is listed in Table C1. These coefficients have been used extensively in the NONAME orbit determination program for the reduction of GEOS I optical and electronic data. The same data sets have been reduced using various other gravity models. An intercomparison of the results can be found in Reference C3.

Table C1

SAO M-1 Harmonic Coefficients (Normalized).

n	m	$\bar{C} \times 10^6$	$\bar{S} \times 10^6$	n	m	$\bar{C} \times 10^6$	$\bar{S} \times 10^6$
2	0	-484.1735		8	2	0.026	0.039
2	1			8	3	-0.037	0.004
2	2	2.379	-1.351	8	4	-0.212	-0.012
3	0	0.9623		8	5	-0.053	0.118
3	1	1.936	0.266	8	6	-0.017	0.318
3	2	0.734	-0.538	8	7	-0.0087	0.031
3	3	0.561	1.620	8	8	-0.248	0.102
4	0	0.5497		9	0	0.0122	
4	1	-0.572	-0.469	9	1	0.117	0.012
4	2	0.330	0.661	9	2	-0.0040	0.035
4	3	0.851	-0.190	10	00	0.0118	
4	4	-0.053	0.230	10	01	0.105	-0.126
5	0	0.0633		10	02	-0.105	-0.042
5	1	-0.079	-0.103	10	03	-0.065	0.030
5	2	0.631	-0.232	10	04	-0.074	-0.111
5	3	-0.520	0.007	11	00	-0.0630	
5	4	-0.265	0.064	11	01	-0.053	0.015
5	5	0.156	-0.592	12	00	0.0714	
6	0	-0.1792		12	01	-0.163	-0.071
6	1	-0.047	-0.027	12	02	-0.103	-0.0051
6	2	0.069	-0.366	12	12	-0.031	0.0008
6	3	-0.054	0.031	13	00	0.0219	
6	4	-0.044	-0.518	13	12	-0.06769	0.06245
6	5	-0.313	-0.458	13	13	-0.059	0.077
6	6	-0.040	-0.155	14	00	-0.0332	
7	0	0.0860		14	01	-0.015	0.0053
7	1	0.197	0.156	14	11	0.0002	-0.0001
7	2	0.364	0.163	14	12	0.00261	-0.02457
7	3	0.250	0.018	14	14	-0.014	-0.003
7	4	-0.152	-0.102	15	09	-0.0009	-0.0018
7	5	0.076	0.054	15	12	-0.07473	-0.01026
7	6	-0.209	0.063	15	13	-0.058	-0.046
7	7	0.055	0.096	15	14	0.0043	-0.0211
8	0	0.0655					
8	1	-0.075	0.065				

The normalized coefficients ($\bar{C}_{n,m}$, $\bar{S}_{n,m}$) are related to the denormalized coefficients ($C_{n,m}$, $S_{n,m}$) as indicated below:

$$\left.\begin{aligned} C(n,m) &= \left[(n-m)!\,(2n+1)k/(n+m)!\right]^{1/2}\bar{C}(n,m) \\ S(n,m) &= \left[(n-m)!\,(2n+1)k/(n+m)!\right]^{1/2}\bar{S}(n,m) \end{aligned}\right\}; \qquad \text{(C2)}$$

$$k = 1 \text{ when } m = 0\,,$$

$$k = 2 \text{ when } m \neq 0\,.$$

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:

$$\ddot{x}_{\oplus} = \frac{\partial u}{\partial r}\frac{\partial r}{\partial x} + \frac{\partial u}{\partial \phi}\frac{\partial \phi}{\partial x} + \frac{\partial u}{\partial \lambda}\frac{\partial \lambda}{\partial x}\,; \qquad \text{(C3)}$$

similarly for

$$\ddot{y}_{\oplus},\ \ddot{z}_{\oplus}\,,$$

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

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 C4) which can be treated as the potential function U. For the solar perturbation, $R_{\odot}$ takes the form

$$R_{\odot} = \frac{GMm_{\odot}}{r_{\odot}}\left[\left(1 - \frac{2r}{r_{\odot}}S + \frac{r^2}{r_{\odot}^2}\right)^{-1/2} - \frac{rS}{r_{\odot}}\right], \qquad \text{(C4)}$$

where

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

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

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

$r_{\odot}$ = the geocentric distance to the sun,

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

r = the geocentric distance to the satellite,

G = the universal gravitational constant, and

M = the mass of the earth.

The acceleration of the satellite due to the sun is then

$$\ddot{x}_{\odot} = \frac{\partial R_{\odot}}{\partial r}\frac{\partial r}{\partial x} + \frac{\partial R_{\odot}}{\partial \lambda}\frac{\partial \lambda}{\partial x} + \frac{\partial R_{\odot}}{\partial \phi}\frac{\partial \phi}{\partial x} ; \tag{C5}$$

similarly for

$$\ddot{y}_{\odot}, \ddot{z}_{\odot} ,$$

where ϕ and λ are the latitude and longitude of the satellite respectively. The lunar perturbations are found from Equation C4 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 are least-squares-fitted 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.

Solar Radiation Pressure

The acceleration acting on a satellite due to solar radiation pressure is formulated as follows (Reference C5)

$$\ddot{x}_{RAD} = -\frac{AP_{\odot}}{m}\gamma\nu L_x ; \tag{C6}$$

similarly for

$$\ddot{y}_{RAD}, \ddot{z}_{RAD} ,$$

where

$\hat{L}$ = the inertial unit vector from the geocenter to the sun and has components L_x, L_y, L_z,

A = the cross-sectional area of the satellite,

m = the satellite mass,

γ = a factor depending on the reflective characteristics of the satellite,

ν = the eclipse factor such that:

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

$P_{\odot}$ = the solar radiation pressure in the vicinity of the earth,

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

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

$$\gamma = (1 + \rho) . \tag{C7}$$

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

Atmospheric Drag

The atmospheric decelerations are computed as follows:

$$\ddot{x}_{DRAG} = \frac{\rho C_D A v v_x}{2m} ;$$

similarly for

$$\ddot{y}_{DRAG}, \ddot{z}_{DRAG} , \tag{C8}$$

where

ρ = the ambient atmospheric density,

C_D = the satellite drag coefficient,

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

m = the satellite mass.

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

$$\vec{v} = v_x \hat{i} + v_y \hat{j} + v_z \hat{k} , \tag{C9}$$

can be chosen to be either the velocity relative to the atmosphere, an assumption which implies that the atmosphere rotates with the earth; or the inertial velocity, an assumption which implies 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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2. Kõhnlein, W., "The Earth's Gravitational Field as Derived from a Combination of Satellite Data with Gravity Anomalies," prepared for XIV General Assembly, International Union of Geodesy and Geophysics, International Association of Geodesy, October 1967.

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Appendix D

Tracking Station Coordinates

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 D1), in which the Baker-Nunn station positions are used as the controlling stations for all other stations to be transformed. The semimajor 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 D2. The transformation of local datum station coordinates to a common center-of-mass reference system is important to perform, 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 as having 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 D1 provides a listing of the original datums and their parameters on which the stations were originally surveyed.

Tables D2 through D11 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 under "Sources" (p. 48), with a list of source information. The C-5 positions for 1TANAN and MADGAR (Reference D3) have been derived by the station estimation technique contained in the Orbit Determination Program NONAME. Tables D12 through D21 provide a listing of the proper station names from which the six-letter designations have been derived.

Table D1

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
Argentinean	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 D2

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	162	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 17.90	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
	AUSBAK	9023	-31 23 30.82	136 52 39.02	141	Australian
			-31 23 27.69	136 52 42.23	137	C-5
	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

*Unless "Source" is specified otherwise.
†These SAO station positions were derived by using the weighting scheme described in Reference 2 (in its second section, "Coordinate Transformation").

Table D3

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
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 D4

STADAN — R/Ṙ — Source B.

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
MADGAR	1122	-19°01'13"32	47°18'09"45	1403	Tananarive
		-19 01 19.41	47 18 07.96	1382	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
CARVON	1152	-24 54 14.86	113 42 55.06	38	Australian
		-24 54 12.29	113 42 58.54	10	C-5

Table D5

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*	Corrego 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
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 47.59	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

*MSL.

Table D6

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
	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

*Unless "Source" is specified otherwise.

Table D7

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
	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 28.99	188 16 43.47	6†	1966 Canton ASTRO
			- 2 46 28.99	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

*Unless "Source" is specified otherwise.
†MSL.

Table D8

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 D9

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
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 D10

SPEOPT — Laser — Source B.

Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
GODLAS	7050	39°01'13".68	283°10'18".05	55	N.A.
		39 01 13.45	283 10 18.51	0	C-5
ROSLAS	7051	35 11 46.60	277 07 26.23	879	N.A.
		35 11 46.70	277 07 26.02	822	C-5

Table D11

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
D	ZIMWLD	8010	46 52 41.77	7 27 57.56	903	Berne
			46 52 36.73	7 27 52.54	907	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

*Unless "Source" is specified otherwise.

Table D12

SAO — Optical.

Name	Station No.	Location
1ORGAN	9001	Organ Pass, New Mexico
1OLFAN	9002	Olifantsfontein, South Africa
WOOMER	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 D13

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 D14

STADAN — RIR.

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

Table D15

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 D16

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	Kindley 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 D17

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 Island, Caroline Islands
GIZZOO	5404	Gizzoo, Gonzongo, Solomon Islands
TARAWA	5405	Tarawa, Gilbert Islands
NANDIS	5406	Nandi, Viti Levu, 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 D18

USC&GS — Optical.

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

Table D19

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 D20

SPEOPT — Laser.

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

Table D21

International — Optical.

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

Sources

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

Symbol	Source
A	Geodetic Parameters for a 1966 Smithsonian Institution Standard Earth (Reference D1, below).
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, B. 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., and Veis, G., "Geodetic Parameters for a 1966 Smithsonian Institution Standard Earth," Smithsonian Astrophysical Observatory Special Report No. 200, Vol. 1, 1966.

2. Lerch, F. J., Marsh, J. G., D'Aria, M. D., and Brooks, R. L., "GEOS I Tracking Station Positions on the SAO Standard Earth (C-5)," NASA Technical Note D-5034, August 1968.

3. Lerch, F. J., Doll, C. E., Moss, S. J., and O'Neill, B., "The Determination and Comparison of the GRARR MADGAR Site Location," NASA Technical Note D-5033, August 1968.

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