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AN INTERCOMPARISON OF SOME RESULTS FROM GEOS-I DATA BASED UPON SECOR SHORT ARC vs. OPTICAL LONG ARC REFERENCE ORBITS

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SUMMARY

This report presents the results of an evaluation of certain range measurement data sets from the U.S. Army Sequential Collation of Range (SECOR) Tracking System. The data considered here were obtained from the GEOS-I satellite by SECOR tracking stations in the Eastern United States, at Herndon, Virginia; Greenville, Mississippi; Homestead, Florida and Ft. Stewart, Georgia, during the period December 31, 1965 to January 5, 1966.

Optical reference orbits were taken as a standard for this evaluation and compared with results obtained using SECOR short arcs as a reference. The optical reference orbits utilized GEOS-I flash sequence data and some passive observations from five major geodetic optical tracking networks. The networks and camera types consisted of the Smithsonian Astrophysical Observatory (SAO) Baker-Nunn, the Goddard Space Flight Center (GSFC) 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. The SECOR data consisted of fourteen station passes during four "quad" passes over the United States. Simultaneous data from the Goddard Range and Range Rate System (GRARR) were also available during these four passes affording the opportunity to intercompare the evaluation of this instrument based on an optical reference orbit with earlier results obtained using the SECOR data as a standard (Reference 1).

The results presented here were obtained by comparing measured ranges from both the SECOR and GRARR systems with those computed from the optical reference orbit. For each station pass, estimates of the zero-set range bias, timing error and random error were made based on the residual differences between the observed and calculated ranges. Whereas SECOR zero-set errors ranged from +17 meters to -13 meters as determined from a short arc SECOR reference orbit, these same errors had values ranging from +60 meters to -6 meters referenced to the long arc optical orbit. Significantly, the GRARR A-channel* zero set range bias errors, which ranged from -8 meters to -17 meters using the SECOR reference orbit were between +2 and -2 meters based on an optical reference orbit. The data used in this evaluation were obtained from Mr. John Berbert, GEOS Principal Investigator, and are identical with those used in Reference 1.

*See Appendix A,1.2 for definition of the GRARR A-channel frequency.

SECOR data available in the second week of January 1966 were also investigated. Preliminary results indicate that some of these data contained ambiguities of 256 meters and 512 meters and associated timing errors of approximately fifty milliseconds. These data were obtained from the Geodetic Satellite Data Service (GSDS), National Space Science Data Center. This report does not address itself to the evaluation of this data set primarily because the large timing errors are believed to be due to an improper time indicator on the data submitted to the GSDS. Presently these data including the above data analyzed in this report are being re-evaluated and reprocessed by the Army Map Service for the GSDS. The data sets in the GSDS were previously preprocessed by another organization.

Since the results of this paper were first obtained and presented at the GEOS NASA Headquarters Meeting on December 12-14, 1967, the Army Map Service has reported to the authors that the SECOR data analyzed in this report is faulty and not truly representative of the SECOR tracking system. In reviewing the paper the Army Map Service indicated that the relative timing errors (when associated with the clock) between the SECOR stations in a given quad pass cannot be as large as 10 milliseconds if the data is preprocessed correctly. It is felt, however, that this paper has the following merit. It demonstrates the wide differences in results that may be obtained between certain short arc and long arc methods for evaluating and intercomparing tracking data when the data contains unexpectedly large systematic errors and biases.

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AN INTERCOMPARISON OF SOME RESULTS FROM GEOS-I DATA BASED UPON SECOR SHORT ARC vs. OPTICAL LONG ARC REFERENCE ORBITS

1.0 INTRODUCTION

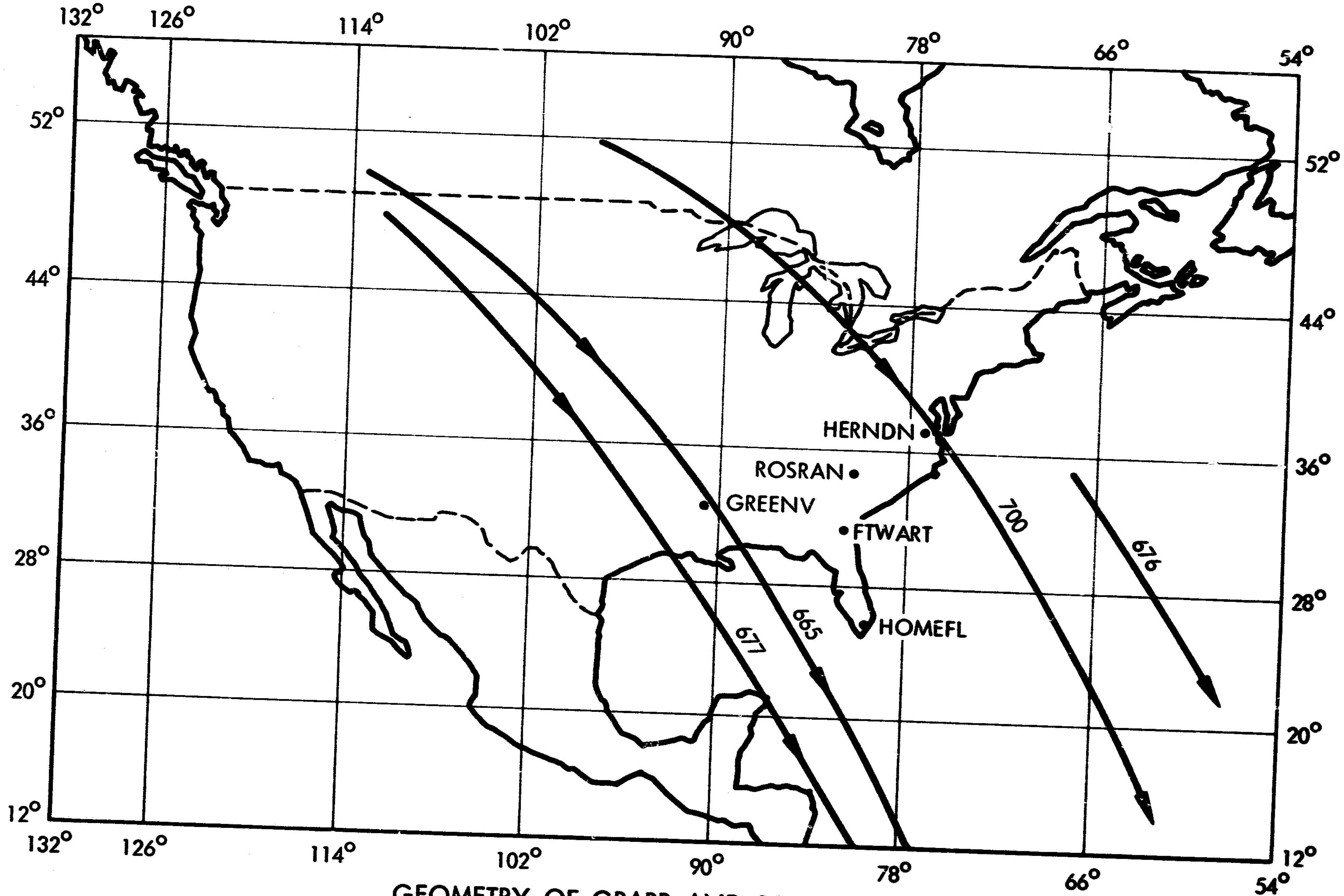
This report compares SECOR and GRARR tracking system results based on SECOR short arc vs. optical long arc reference orbits. The tracking system results are expressed in terms of zero-set range bias, timing error, and random error estimates. The short arc results are analyzed in Reference 1 and presented herein for convenient reference. The SECOR data sets used in the long arc evaluation are identical with those used in Reference 1. The data evaluated were in the period December 31, 1965 through January 5, 1966 taken on the GEOS-I satellite.

The SECOR data consisted of fourteen station passes during four satellite passes over the United States. Four SECOR stations were involved in taking these data; they were located at: Herndon, Virginia; Greenville, Mississippi; Homestead, Florida and Ft. Stewart, Georgia. In addition to the simultaneous SECOR and optical data during these four passes, GRARR measurements from Rosman, North Carolina were available. The four quad passes are summarized in Table I and Figure 1.

Table I
Summary of GRARR and SECOR Passes

Pass No.	Date	Time	Maximum Elevation Angle				
			SECOR				GRARR
			HOMEFL	FTWART	GREENV	HERNDN	ROSRAN
665	1/1/66	08^h	64.3°	N/A	80.7°	32.5°	51.8°
676	1/2/66	06^h	27.5°	38.0°	28.4°	68.0°	43.3°
677	1/2/66	08^h	48.3°	40.8°	69.6°	25.3°	40.2°
700	1/4/66	06^h	N/A	55.4°	33.7°	70.2°	62.7°

Pass 700 over ROSRAN was from the C channel transponder, the other three passes were from the A channel. See Appendix A, 2.1 for definition of channel frequencies.



GEOMETRY OF GRARR AND SECOR PASSES

Figure 1

Proper names for the station designations, given in Table I and elsewhere, are presented in Appendix D.

The long arc and short arc orbital solutions are discussed in Sections 1.1 and 1.2 respectively. Section 2 presents the evaluation of the range measurements with the results, and Section 3 presents the conclusions. A set of Appendices presenting detailed information are provided and referred to appropriately in the report.

1.1 Intercomparison with Long Arc Orbital Solutions

The reference orbits used for this evaluation were estimated from optical data using the orbit determination program NONAME (Reference 2). The optical data used are flash sequence data (active) and some passive observations made from five major geodetic optical tracking networks. The networks and camera types consisted of the SAO Baker-Nunn, the GSFC STADAN and SPEOPT MOTS 40" and 24", the USAF PC-1000, and the USC&GS BC-4.

The following earth and force models were used in this evaluation:

- SAO C5 Standard Earth (Appendix D)
- SAO M1 Gravity Model (Appendix C)
- Perturbations due to solar and lunar gravity (Appendix C)
- Perturbations due to solar radiation pressure (Appendix C)

The preprocessing of all data sets is discussed in Appendix B.

Six reference orbits were fitted to data sets from the period analyzed, five of the orbits were fitted to long arcs (greater than six revolutions) and the other was fitted to a medium arc (1/4 to 6 revolutions). The orbital solutions were fitted to overlapping data sets in order to assess the effects any errors in the orbital solutions were having on the evaluation. Summaries of the orbital solutions and root mean squares of fit are given in Tables II and III. A more complete description of the data sets is given in Appendix A.

The optical long arc intercomparison results for the SECOR and GRARR tracking system are discussed in Section 2 and presented in Tables IV, V, and VI, respectively, in terms of a zero-set range bias, timing, and random error estimate for each station pass. These results may be compared with the corresponding short arc results in Tables X, XI, and XII.

Table II
Summary of Orbital Solutions

Solution No.	Approximate Arc Length	Time of 1st 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	2-1/2 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.

Table III
Root Mean Squares about the Orbital Solutions

Orbital Sol^{n}	No. of Obs.	Rms. of Fit (Secs. of Arc)
1	1057	3.08
2	631	2.55
3	532	2.74
4	644	2.45
5	444	2.33
6	236	2.17

1.2 Intercomparison with Short Arc Orbital Solutions

Several intercomparisons for the evaluation of the SECOR range measurements have been conducted using short arc orbital solutions and intervisible techniques. These are:

(1) Short arc orbital solutions (up to 15 minutes duration) determined from optical observations (Reference 4).

(2) Short arc orbital solutions determined from SECOR and GRARR range measurements (Reference 1).

(3) Comparison of SECOR range measurements with those determined from intervisible optical observations (Reference 4).

The short arc results of item (2) above based on SECOR reference orbits are presented in Section 2.2 and may be compared with the corresponding long arc results presented in Section 2.1. The GRARR data used in the above analyses was not subjected to any smoothing and thus exhibit larger random error estimates than the smoothed data used in the long arc results. See Tables VI and XI, Random Error Estimates in the GRARR ROSRAN column.

2.0 EVALUATION OF THE RANGE MEASUREMENTS

The SECOR and GRARR range measurements were corrected for refraction (Appendix B) and the GRARR measurements were in addition corrected for transponder delay and known cable bias at Rosman (Reference 3). The GRARR measurements evaluated in this report have been smoothed over two minute intervals using a sixth order polynomial. 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.

The following error model was fitted to the range residuals:

$$\Delta R = \Delta B + \Delta t \dot{R}$$

where

ΔR = Observed range minus calculated range,

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

Δt = error in the 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. Some of this error may be due to the uncertainty of the gravity field and station coordinates.

This model was fitted to the range residuals from each station for each pass separately using the method of least squares to solve for the unknown parameters ΔB and Δt.

2.1 Results from the Long Arc Orbital Solutions

The zero-set range bias, timing and random error estimates obtained from the 5-1/4 day reference orbit are summarized in Tables IV-VI, and the range residuals from this orbit are summarized in Figures 2-5. These results indicate that although the random error estimates for the SECOR and GRARR systems

Table IV
Summary of Zero-Set Error Estimates (Meters)
(Range Bias)

Pass No.	SECOR Stations				GRARR Station
	HOMEFL	FTWART	GREENV	HERNDN	ROSRAN
665	36.6	N/A	60.1**	43.1	- 2.0
676	20.9	8.3	29.7	- 3.7	2.3
677	17.0	-1.8	33.5	3.5	0.2
700	N/A	9.7**	46.9**	11.3**	20.6*

Table V
Summary of Timing Error Estimates (Millisecs)

Pass No.	Station				
	HOMEFL	FTWART	GREENV	HERNDN	ROSRAN
665	0.2	N/A	- 6.4	3.8	1.0
676	-8.1	-3.2	-12.3	-3.2	-6.3
677	-2.4	1.6	- 3.6	2.6	-0.2
700	N/A	-2.7	-12.9	-3.2	-5.4*

Table VI
Summary of Random Error Estimates (Meters)

Pass No.	Station				
	HOMEFL	FTWART	GREENV	HERNDN	ROSRAN
665	3.0	N/A	2.0	1.1	4.5
676	1.5	5.1	2.6	3.1	2.9
677	1.6	6.3	2.2	1.0	3.2
700	N/A	2.9	1.2	2.0	5.8*

*This pass is a C channel pass; the other three are from the A channel.
**These are extrapolated estimates since the station did not track until the satellite was moving away from the station.

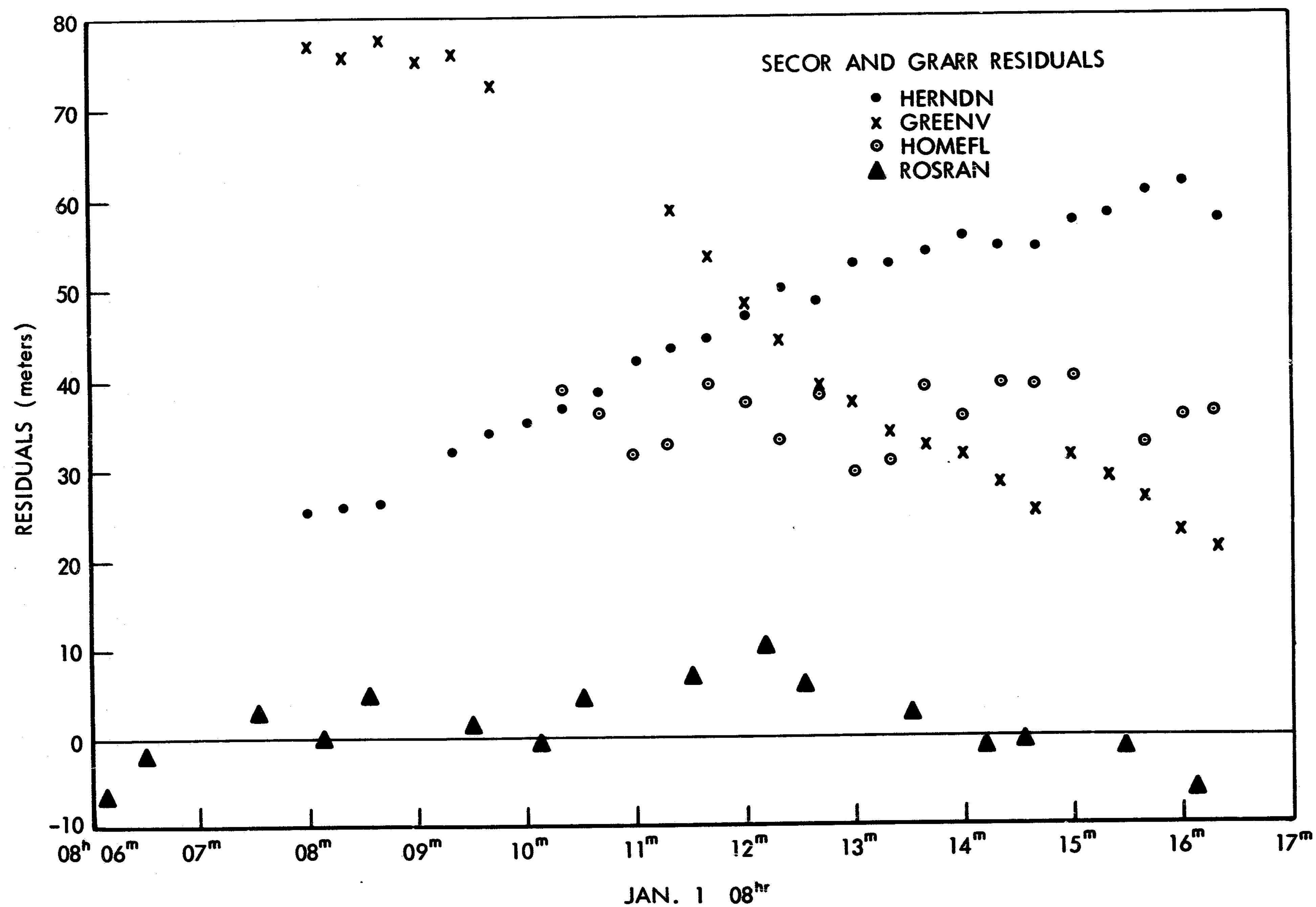

SECOR AND GRARR RESIDUALS
HERNDN
GREENV
HOMEFL
ROSRAN
RESIDUALS (meters)
80
70
60
50
40
30
20
10
0
-10
08h 06m
07m
08m
09m
10m
11m
12m
13m
14m
15m
16m
17m
JAN. 1 08hr

Figure 2

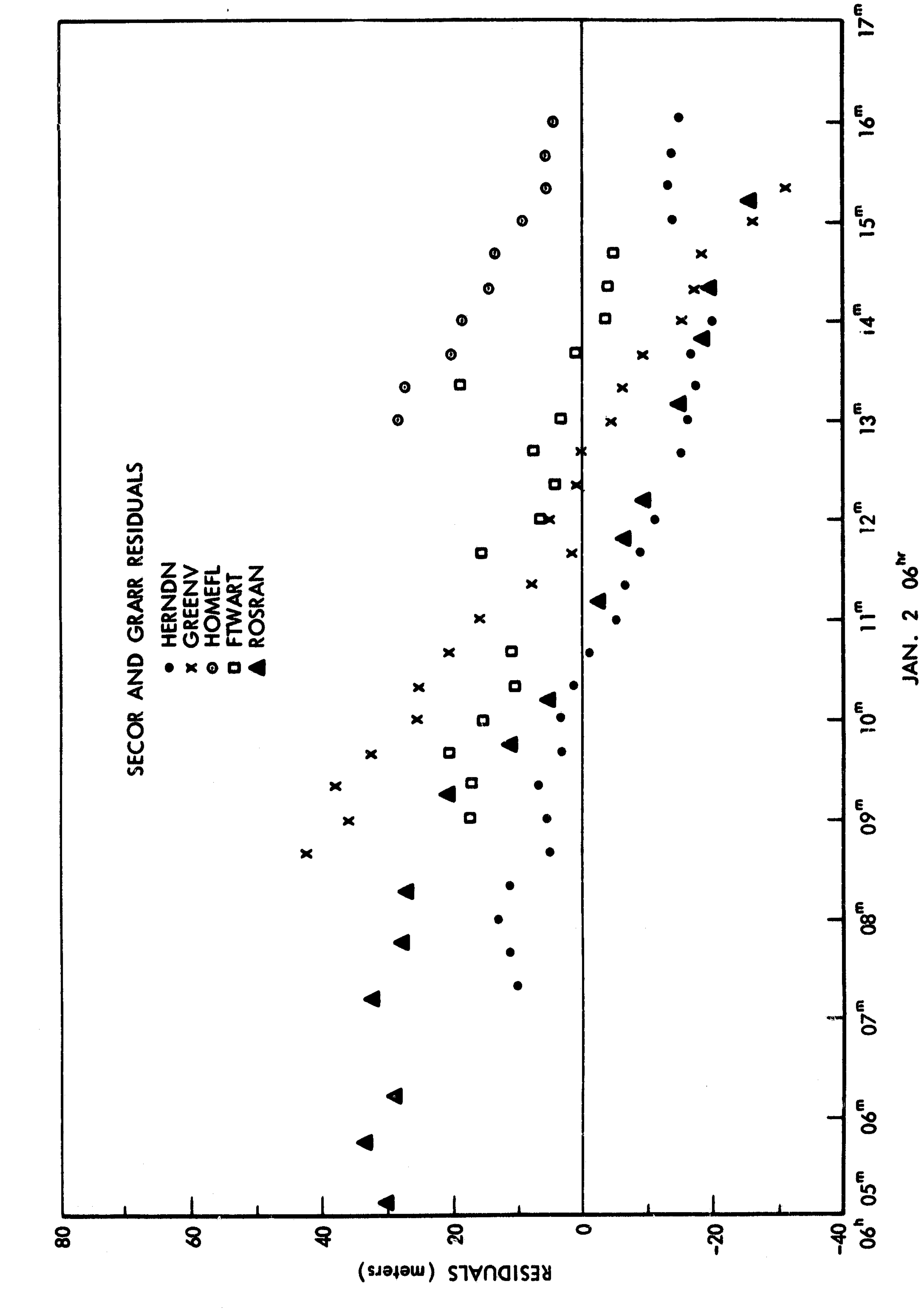

SECOR AND GRARR RESIDUALS
HERNDN
GREENV
HOMEFL
FTWART
ROSRAN
RESIDUALS (meters)
80
60
40
20
0
-20
-40
06h 05m
06m
07m
08m
09m
10m
11m
12m
13m
14m
15m
16m
17m
JAN. 2 06hr

Figure 3

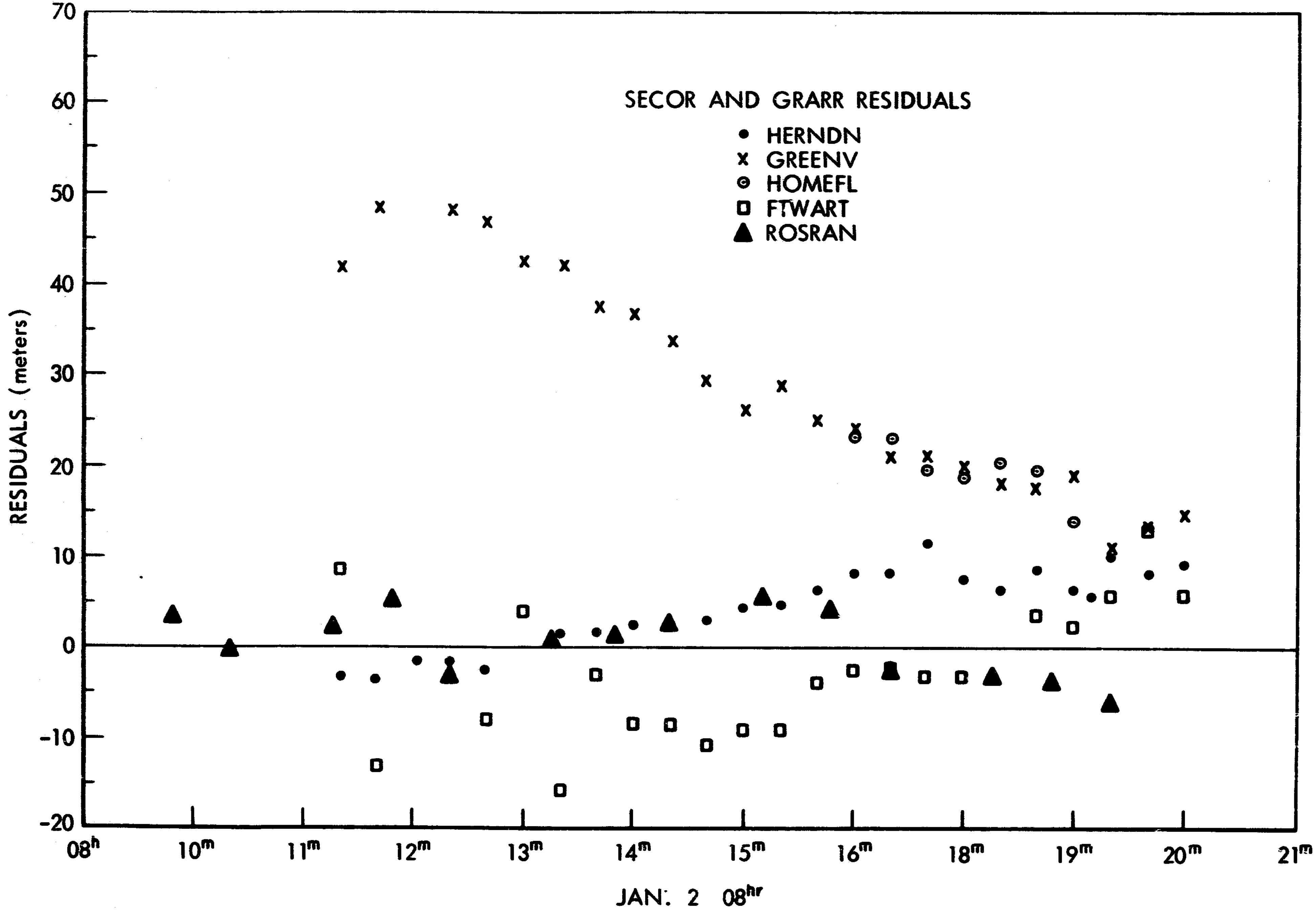
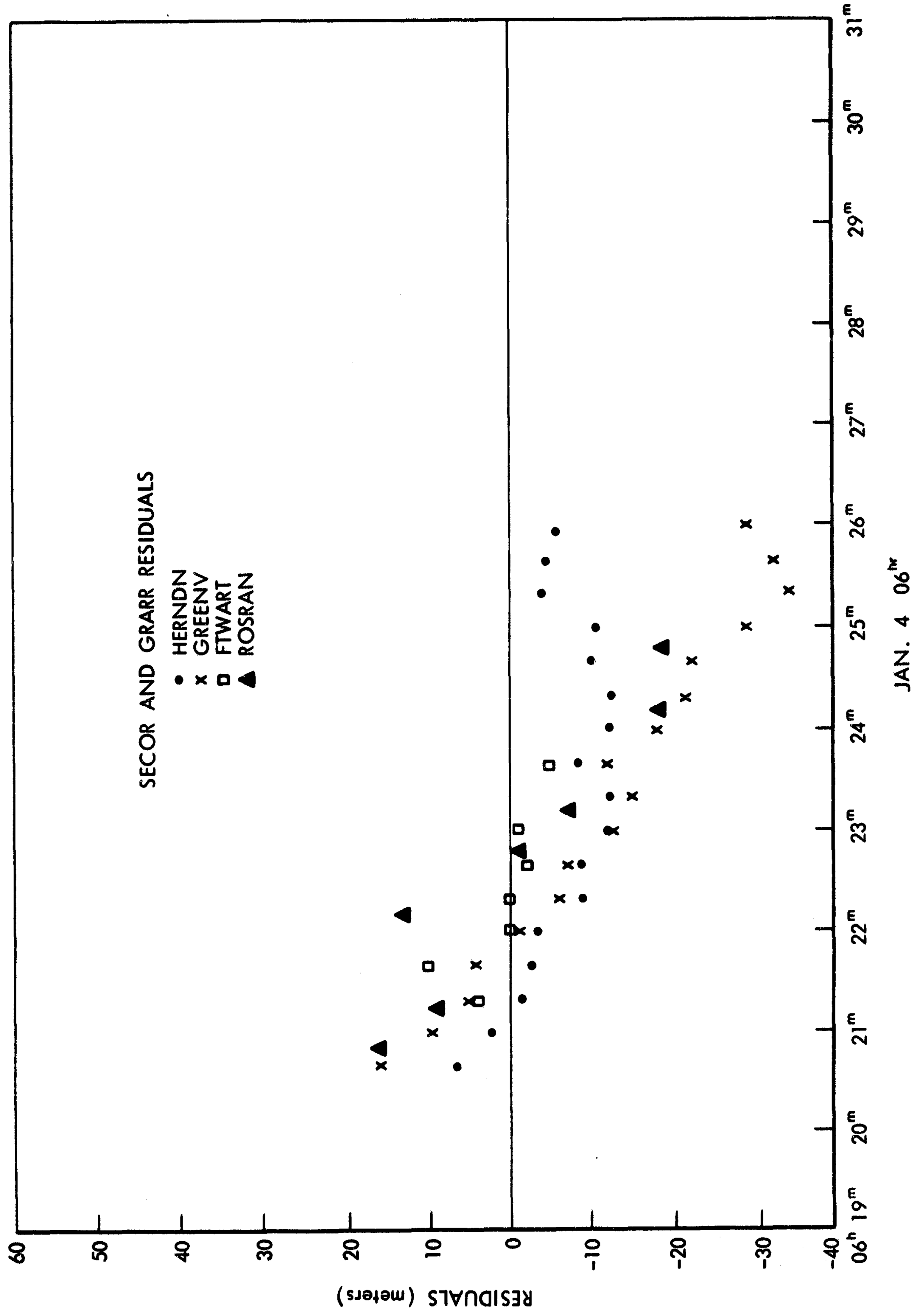

SECOR AND GRARR RESIDUALS
HERNDN
GREENV
HOMEFL
FTWART
ROSRAN
RESIDUALS (meters)
70
60
50
40
30
20
10
0
-10
-20
08h
10m
11m
12m
13m
14m
15m
16m
18m
19m
20m
21m
JAN. 2 08hr

Figure 4



SECOR AND GRARR RESIDUALS
• HERNDN
x GREENV
□ FTWART
▲ ROSRAN
RESIDUALS (meters)
60
50
40
30
20
10
0
-10
-20
-30
-40
06^h 19^m
20^m
21^m
22^m
23^m
24^m
25^m
26^m
27^m
28^m
29^m
30^m
31^m
JAN. 4 06^{hr}

Figure 5

are comparable (an average of $\sim 3_m$ for SECOR and GRARR A channel), the SECOR data sets display significantly larger and less stable zero-set biases than the GRARR system A channel. Similarly the estimates of the timing errors are uniformly larger for the SECOR system than for the GRARR system. The fact that the relative station timing errors are large within a given SECOR quad pass is an indication of faulty data as reported by the Army Map Service (See Summary). The SECOR stations within a quad are referenced to the same master clock, but for these passes the master clock was not carefully synchronized with any universal time system.

The estimates obtained from the five overlapping reference orbits are summarized in Tables VII-IX, in general these results agree reasonably well with the estimates obtained from the 5-1/4 day arc. The only estimates that show appreciable variation when estimated from different orbital solutions are some of the extrapolated (Table IV) zero-set error estimates. The consistency of the overlapping results tends to indicate that the orbital uncertainties are contributing very little error to the results.

Table VII
Summary of Zero-Set Errors for Overlapping Arcs (Meters)
(Range Bias)

Station: HOMEFL

Pass No.	Orbital Solution				
	2	3	4	5	6
665	39.1	—	—	—	—
676	25.8	—	21.0	21.0	22.6
677	19.3	—	27.3	27.3	22.5
700	N/A	N/A	N/A	—	—

Station: FTWART

Pass No.	Orbital Solution				
	2	3	4	5	6
665	N/A	—	—	—	—
676	13.3	—	10.0	10.0	11.1
677	- 0.1	—	6.6	6.6	3.1
700	—	2.0	13.8	—	—

Table VII (continued)
Summary of Zero-Set Errors for Overlapping Arcs (Meters)
(Range Bias)

Station: GREENV

Pass No.	Orbital Solution				
	2	3	4	5	6
665	59.0	—	—	—	—
676	35.5	—	32.5	32.5	33.8
677	36.4	—	39.8	39.8	37.3
700	—	36.3	51.4	—	—

Station: HERNDN

Pass No.	Orbital Solution				
	2	3	4	5	6
665	43.0	—	—	—	—
676	0.8	—	- 0.1	- 0.1	- 0.1
677	4.8	—	12.0	12.0	8.6
700	—	7.6	19.8	—	—

Station: ROSRAN

Pass No.	Orbital Solution				
	2	3	4	5	6
665	- 2.8	—	—	—	—
676	6.6	—	2.7	4.2	5.2
677	1.4	—	6.0	7.4	4.4
700	—	15.8	21.5	—	—

Table VIII
Summary of Timing Errors for Overlapping Arcs (Millisecs)

Station: HOMEFL

Pass No.	Orbital Solution				
	2	3	4	5	6
665	1.0	—	—	—	—
676	- 8.2	—	- 9.0	- 9.0	- 5.3
677	- 2.3	—	- 2.3	- 2.3	- 4.2
700	—	N/A	N/A	—	—

Station: FTWART

Pass No.	Orbital Solution				
	2	3	4	5	6
665	N/A	—	—	—	—
676	- 2.8	—	- 3.7	- 3.7	- 0.1
677	1.7	—	1.6	1.6	- 0.2
700	—	- 2.3	- 2.1	—	—

Station: GREENV

Pass No.	Orbital Solution				
	2	3	4	5	6
665	- 4.7	—	—	—	—
676	-12.1	—	-12.9	-12.9	- 9.5
677	- 3.6	—	- 4.0	- 4.0	- 5.6
700	—	-12.0	-12.6	—	—

Table VIII (continued)
Summary of Timing Errors for Overlapping Arcs (Millisecs)

Station: HERNDN

Pass No.	Orbital Solution				
	2	3	4	5	6
665	5.4	—	—	—	—
676	- 2.8	—	- 3.4	- 3.4	0.0
677	2.8	—	3.0	3.0	1.0
700	—	- 2.9	- 3.0	—	—

Station: ROSRAN

Pass No.	Orbital Solution				
	2	3	4	5	6
665	0.9	—	—	—	
676	- 6.1	—	- 6.4	- 6.9	- 3.5
677	- 0.4	—	- 0.1	- 0.3	- 2.3
700	—	- 4.8	- 6.5	—	

Table IX
Summary of Random Errors for Overlapping Arcs (Meters)

Station: HOMEFL

Pass No.	Orbital Solution				
	2	3	4	5	6
665	3.1	—	—	—	—
676	1.4	—	1.5	1.5	1.5
677	1.6	—	1.7	1.7	1.6
700	—	N/A	N/A	—	—

Table IX (continued)
Summary of Random Errors for Overlapping Arcs (Meters)

Station: FTWART

Pass No.	Orbital Solution				
	2	3	4	5	6
665	N/A	—	—	—	—
676	5.3	—	5.2	5.2	5.2
677	6.0	—	5.6	5.6	5.9
700	—	2.8	2.8	—	—

Station: GREENV

Pass No.	Orbital Solution				
	2	3	4	5	6
665	3.2	—	—	—	—
676	2.6	—	2.6	2.6	2.6
677	2.5	—	2.9	2.9	2.5
700	—	1.1	1.2	—	—

Station: HERNDN

Pass No.	Orbital Solution				
	2	3	4	5	6
665	1.8	—	—	—	—
676	2.5	—	2.5	2.5	2.7
677	0.9	—	0.8	0.8	0.9
700	—	2.2	1.8	—	—

2.2 Results from Short Arc Orbital Solutions

A number of short arc and geometric intercomparisons using optical data as a reference were performed by Berbert et al. (Reference 4). These results are generally in agreement with the long arc optical evaluation of the SECOR system.

Table IX (continued)
Summary of Random Errors for Overlapping Arcs (Meters)

Station: ROSRAN

Pass No.	Orbital Solution				
	2	3	4	5	6
665	5.2	—	—	—	—
676	3.0	—	2.9	3.0	2.9
677	3.5	—	3.[illegible]	4.0	3.5
700	—	4.7	6.4	—	—

The zero-set, timing and random error estimates obtained using short arc orbital solutions determined from SECOR and GRARR range measurements are summarized in Tables X - XII; the zero-set and timing errors were found to be in disagreement with those obtained in the present analysis. The agreement as noted above between the optical short arc, intervisible optical comparison and optical long arc evaluation of these SECOR and GRARR data leads one to speculate on the cause of the disagreement with the SECOR short arc analysis. In this regard, it is probable that a portion of the unexpectedly large range zero-set error in the SECOR data was absorbed in the other state variables for the SECOR short arc solution. The SECOR results from the other solutions show consistency because they were derived from optical data which have little or no systematic error and were recorded by instruments which were synchronized to a common universal time system.

Table X
Summary of Zero-Set Error Estimates (Meters)
(Range Bias)

Pass No.	SECOR Stations				GRARR Station
	HOMEFL	FTWART	GREENV	HERNDN	ROSRAN
665	-4	N/A	17	-13	-17
676	8	-11	- 2	9	- 8
677	5	- 5	10	- 3	-13
700	N/A	2	- 3	2	- 4*

*This pass is a C channel pass; the other three are from the A channel.

Table XI
Summary of Random Error Estimates (Meters)

Pass No.	Station				
	HOMEFL	FTWART	GREENV	HERNDN	ROSRAN
665	3.2	N/A	3.5	2.1	11.3
676	1.7	2.7	3.4	1.8	11.9
677	2.4	1.9	2.7	2.3	10.9
700	N/A	1.7	4.6	2.4	14.1*

*This pass is a C channel pass; the other three are from the A channel.

Table XII
Summary of Timing Differences for Rosman Relative to SECOR Master Station at Herndon

Pass No.	Timing Differences (Millisecs)
665	+0.4
676	+1.0
677	-1.6
700	+0.9

The magnitude of the SECOR biases found using optical reference data for this time period would preclude the use of these range measurements to determine the reference orbits. Again the results point to the faultiness of the SECOR data as reported by the Army Map Service.

3.0 CONCLUSIONS

There are significant discrepancies between the results obtained from the long arc optical reference orbits and those from the short arc SECOR reference orbits. Whereas the SECOR zero-set errors ranged from +17 to -13 meters as determined from a SECOR reference orbit, these same errors had values ranging from +60 to -6 meters when referenced to an optical orbit. Significantly, the GRABR A channel zero-set errors which ranged from -8 to -17 meters when evaluated with a SECOR orbit were between +2 and -2 meters in the optical solution. The large zero-set range biases and timing errors in the SECOR data sets, as detected in the optical long arc reference orbits, were probably absorbed in the other SECOR short arc state variables and thus they became obscured in the short arc results.

The large zero-set range biases and the relative station timing errors within a SECOR quad pass point to the fact that these SECOR data sets are faulty as reported by the Army Map Service (see Summary). As a consequence of these results and the results reported in the Summary on the specific data sets received from the Geodetic Satellite Data Service (GSDS), all the SECOR data in the GSDS are being re-evaluated and reprocessed by the Army Map Service. These SECOR data sets were previously preprocessed by another organization. The new SECOR data sets will be intercompared with the optical reference orbits when they become available.

4.0 REFERENCES

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2. NASA Contract Document: "Interim Status Report on Program Development and GEOS-A Data Analysis," (NAS-5-9756-44A, 55, 71), Wolf Research and Development Corporation, August 1967.

3. Lerch, F. J., Marsh, J. G., O'Neill, B., "Evaluation of the Goddard Range and Range Rate System at Rosman by Intercomparison with GEOS-I Long Arc Orbital Solutions."

4. Berbert, et al., Unpublished Results

APPENDIX A

SUMMARY OF DATA SETS AND ORBITAL SOLUTIONS

1.1 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 A-1 and A-2. These figures serve to illustrate that the majority of the tracking stations were located in North America.

Due to the station mutual visibility scheduling of the GEOS-I spacecraft (Reference 1), flash sequences occurring over North America were observed by many tracking stations simultaneously.

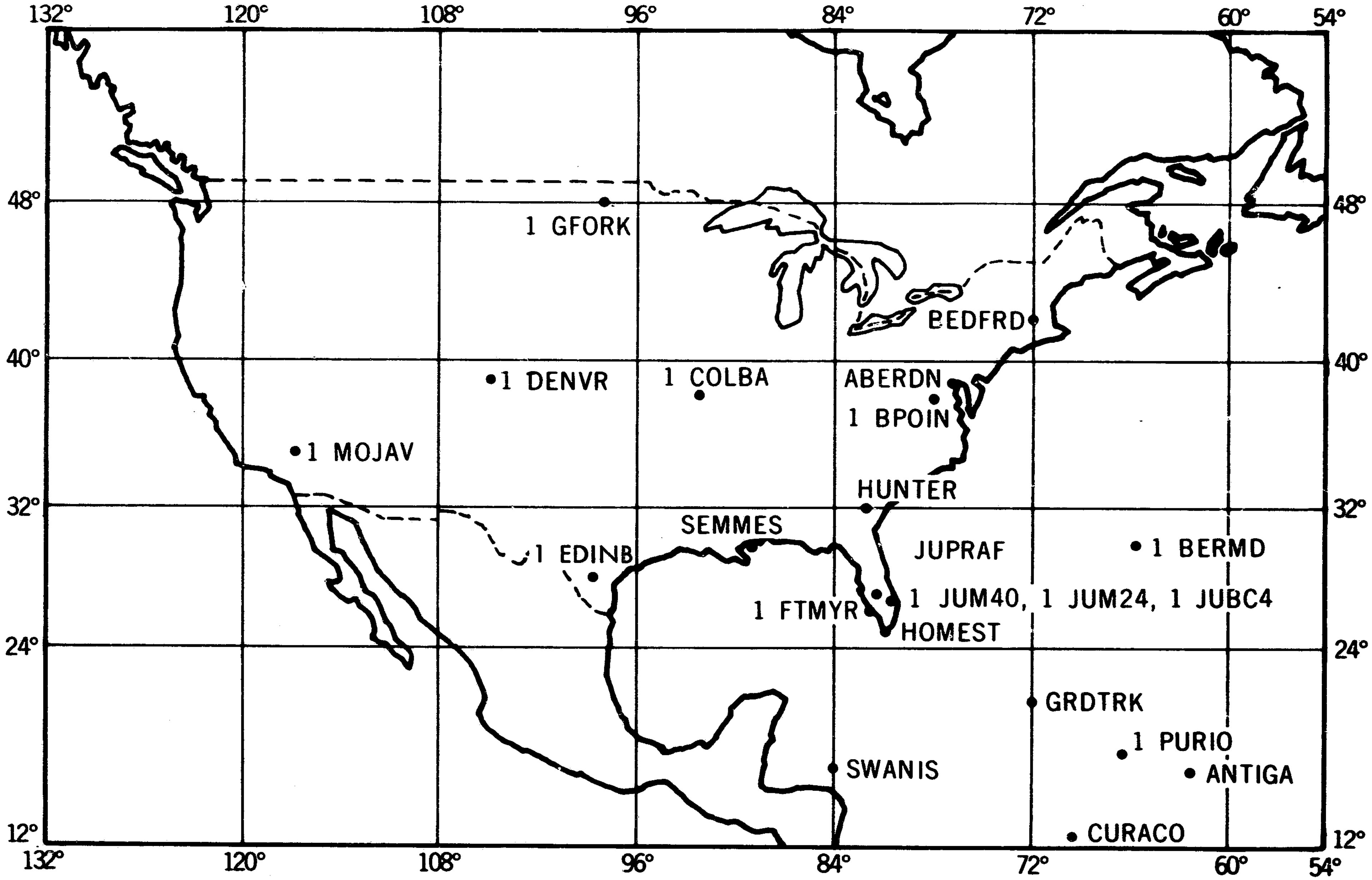
Observations from two periods in January 1966 were used. The two periods were:

1. December 31, 1965 to January 5, 1966

2. January 11 to January 17, 1966

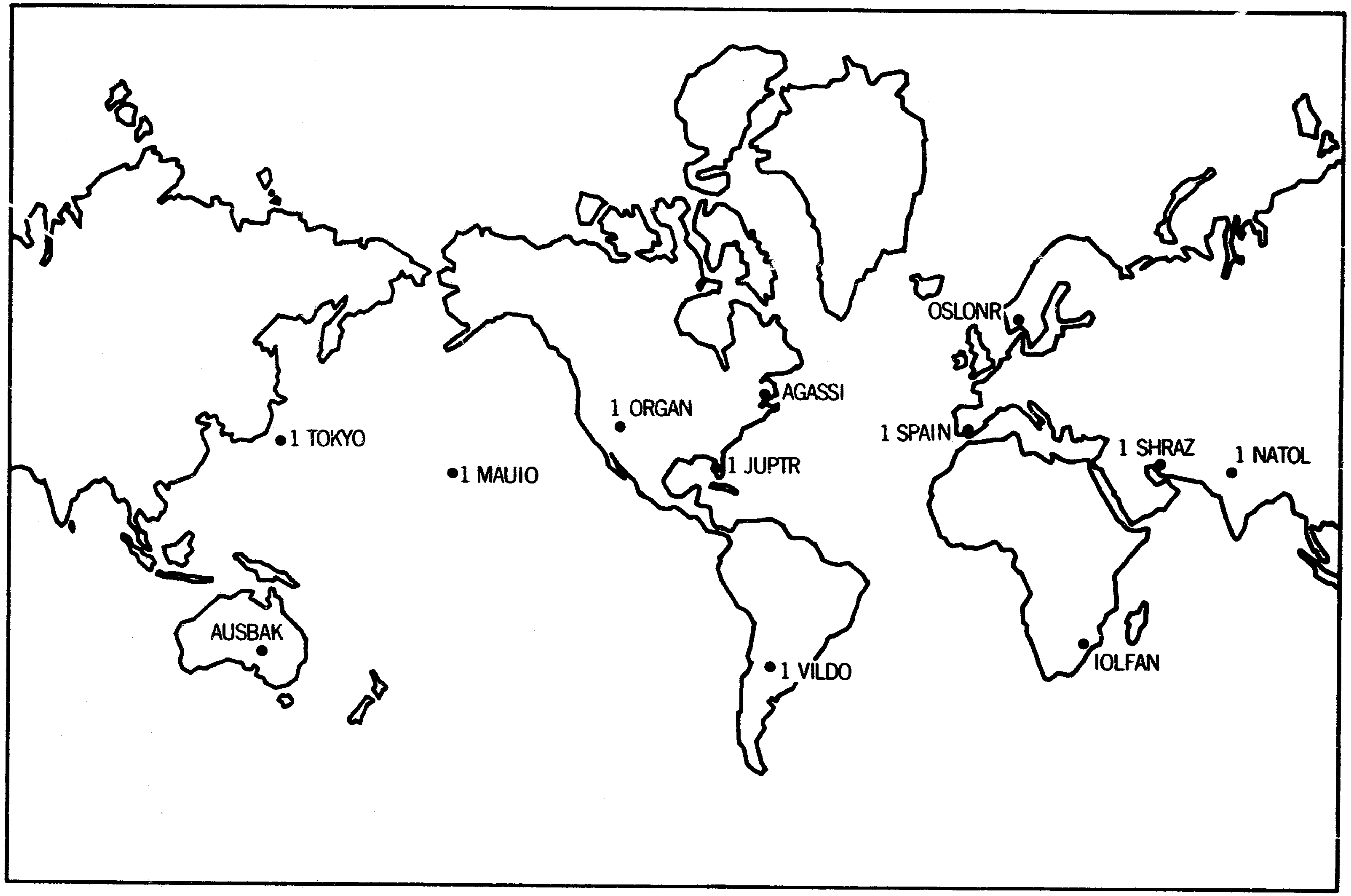
The complete data sets that were used from each period are summarized in Tables A-I and A-II, and Figures A-3 and A-4. Tables A-I and A-II summarize the observations by network and tracking station within the network, and Figures A-3 and A-4 indicate the data coverage by time.

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 A-III - A-V and Figures A-5 and A-6. 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 A-VI.



STADAN, SPEOPT AND USAF CAMERA STATIONS

Figure A-1



SAO BAKER-NUNN STATIONS

Figure A-2

Table A-I
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

Table A-I (Continued)
Summary of Optical Measurements by Station for Period 1

Network	Station	Camera Type	No. of Observations*	Type	No. Passes/ No. Flash Sequences
USAF (Cont'd)	HOMEST	PC-1000	94	Active	4/6
	JUPRAF	"	17	"	2/2
	BEDFRD	"	22	"	2/2
	ABERDN	"	74	"	6/6
	TOTAL:		413		
TOTAL OF ALL OBSERVATIONS = 1057 TOTAL PASSIVE OBSERVATIONS = 42					21/ Passive 70/86 Active 91 Total Station-Passes

*Right ascension plus declination measurements

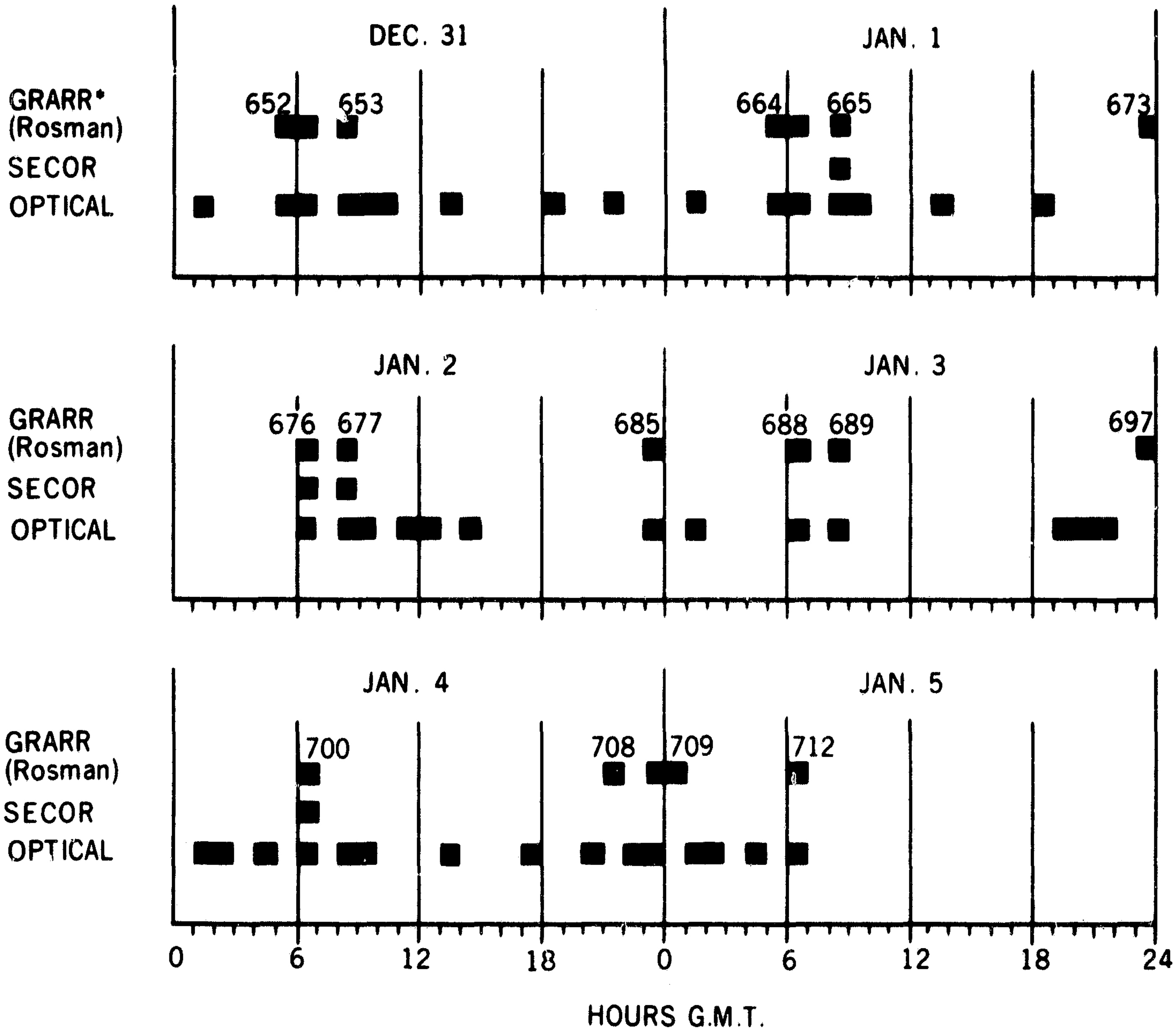
Table A-II
Summary of Optical Measurements by Station for Period 2

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

Table A-II (Continued)
Summary of Optical Measurements by Station for Period 2

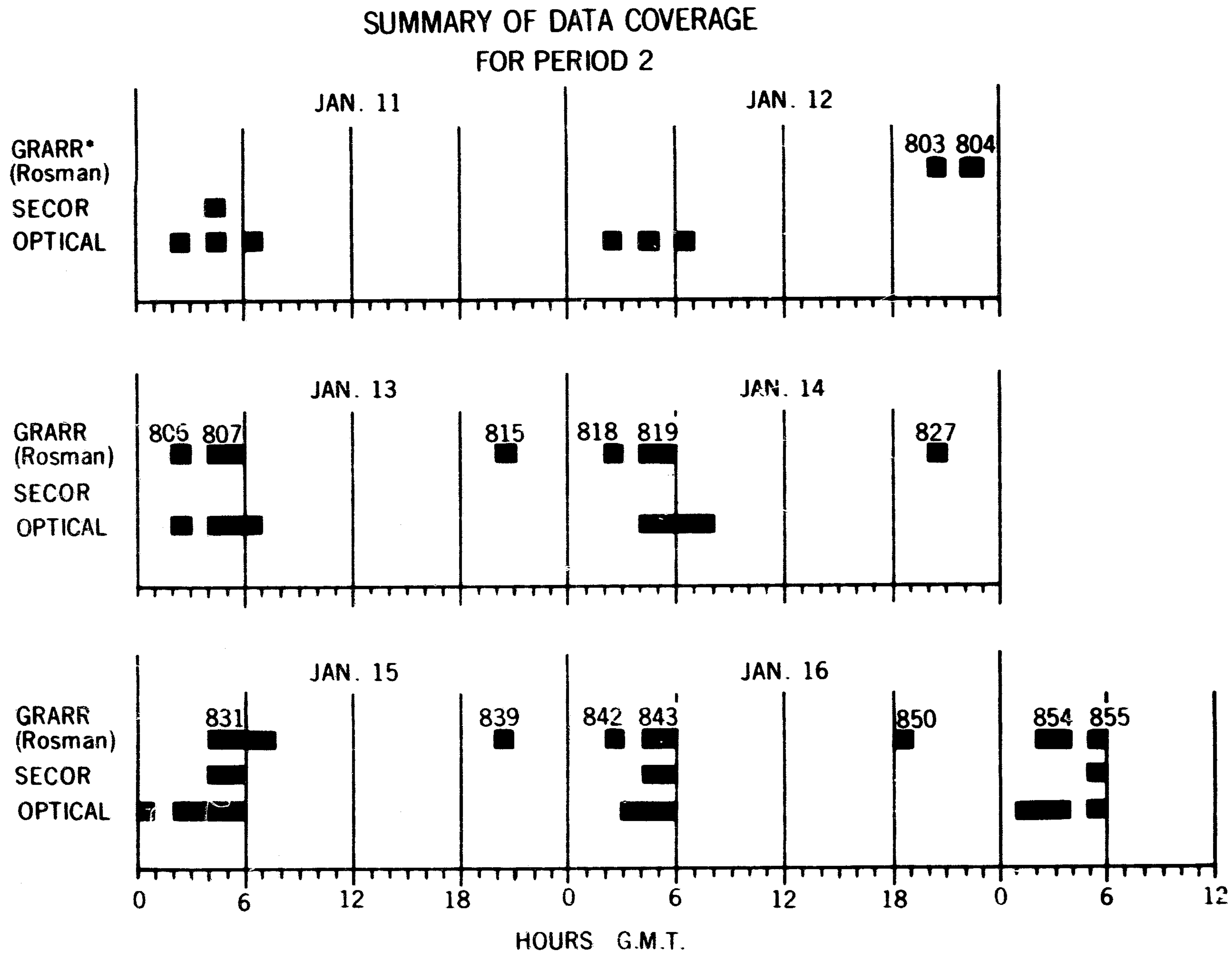
Network	Station	Camera Type	No. of Observations	Type	No. Passes/ No. Flash Sequences
SPEOPT (Cont'd)	1BERMD	MOTS 40"	10	Active	1/1
	1PURIO	"	34	"	3/3
	1GSFCP	"	40	"	3/3
	1DENVR	"	82	"	5/6
	1JUM24	MOTS F24"	62	"	5/5
	1JUM40	MOTS F40"	70	"	5/5
	1JUBC4	BC4	65	"	4/5
	TOTAL:		654		
STADAN	1BPOIN	MOTS 40"	41	Active	4/4
	1FTMYR	"	168	"	7/12
	1MOJAV	"	87	"	5/7
	1COLEG	"	30	"	2/2
	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	BC4	14	Active	1/1
TOTAL OF ALL OBSERVATIONS = 1856 TOTAL PASSIVE OBSERVATIONS = 27					14/ Passive 109/139 Active 123 Total Station-Passes

SUMMARY OF DATA COVERAGE
FOR PERIOD 1



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

Figure A-3



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

Figure A-4

Table A-III
Summary of Orbital Solutions

Period 1			
Solution No.	Approximate Arc Length	Time of 1st 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	2-1/2 days	01/03/66 01 hr	01/05/66 0[illegible]
4	2 days	01/02/66 06 hr	01/04/66 06
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 A-IV
Subsets of Optical Measurements used in Orbital Solutions
from Period 1

		No. of Observations				
Network	Station	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

Table A-IV (Continued)
Subsets of Optical Measurements used in Orbital Solutions from Period 1

		No. of Observations				
Network	Station	Arc 2	Arc 3	Arc 4	Arc 5	Arc 6
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	212	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	113	91	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

Table A-V
Subsets of Optical Measurements Used in Orbital Solution from 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	83	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

Table A-V (Continued)
Subsets of Optical Measurements Used in Orbital Solution
from Period 2

Network	Station	No. of Observations Arc 1	Arc 2	Arc 3	Arc 4
USAF (Cont'd)	ABERDN	68	42	14	20
	HOMEST	51	51	51	69
	TOTAL	393	319	208	261
US C & GS	TIMINS	14	14		
Total of all Observations		1133	956	704	853

Table A-VI
Root Mean Squares about the Orbital Solutions

Orbital Sol^{n}	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

SUMMARY OF ORBITAL SOLUTIONS
for PERIOD 1

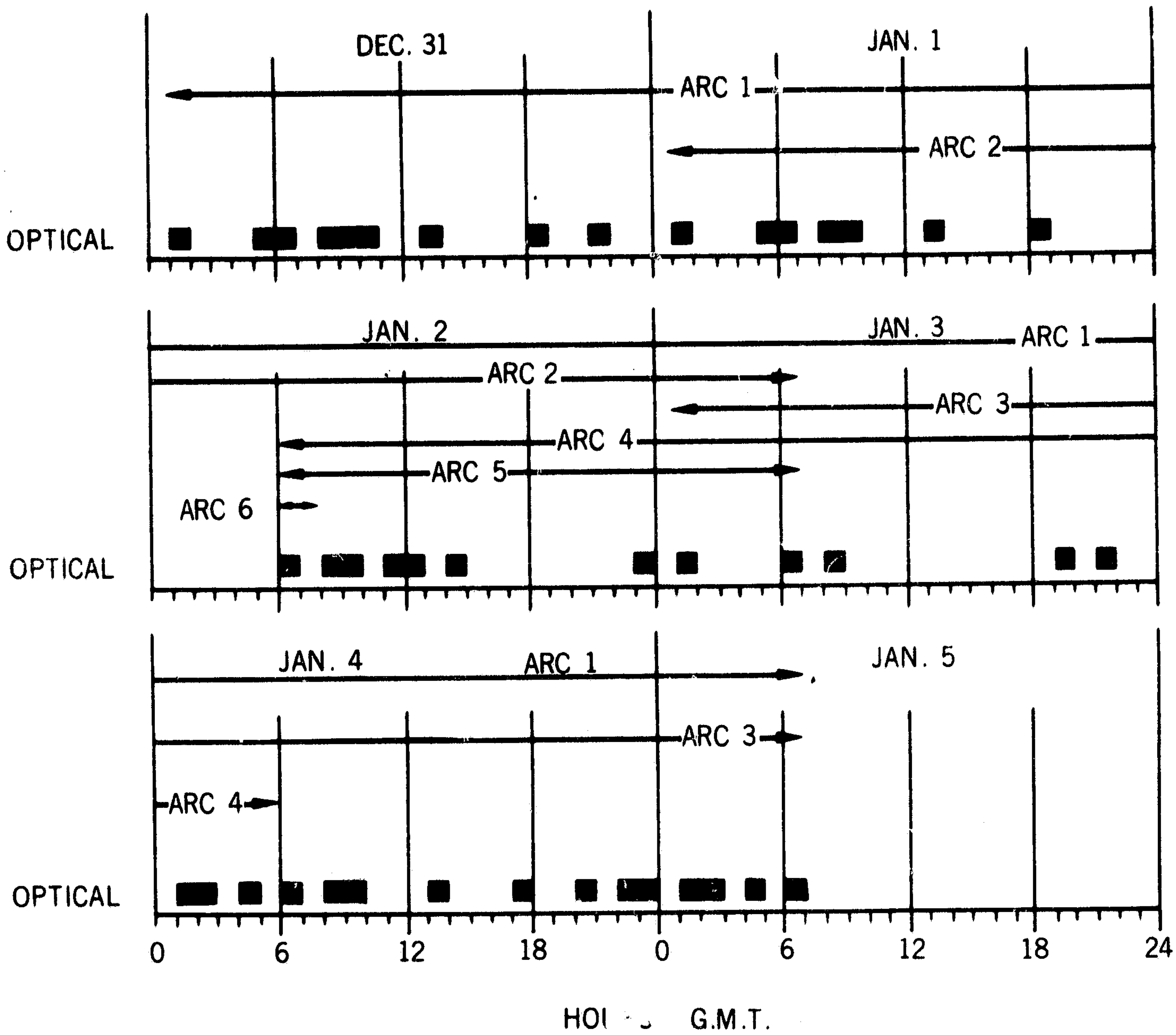


Figure A-5

SUMMARY OF ORBITAL SOLUTIONS
for PERIOD 2

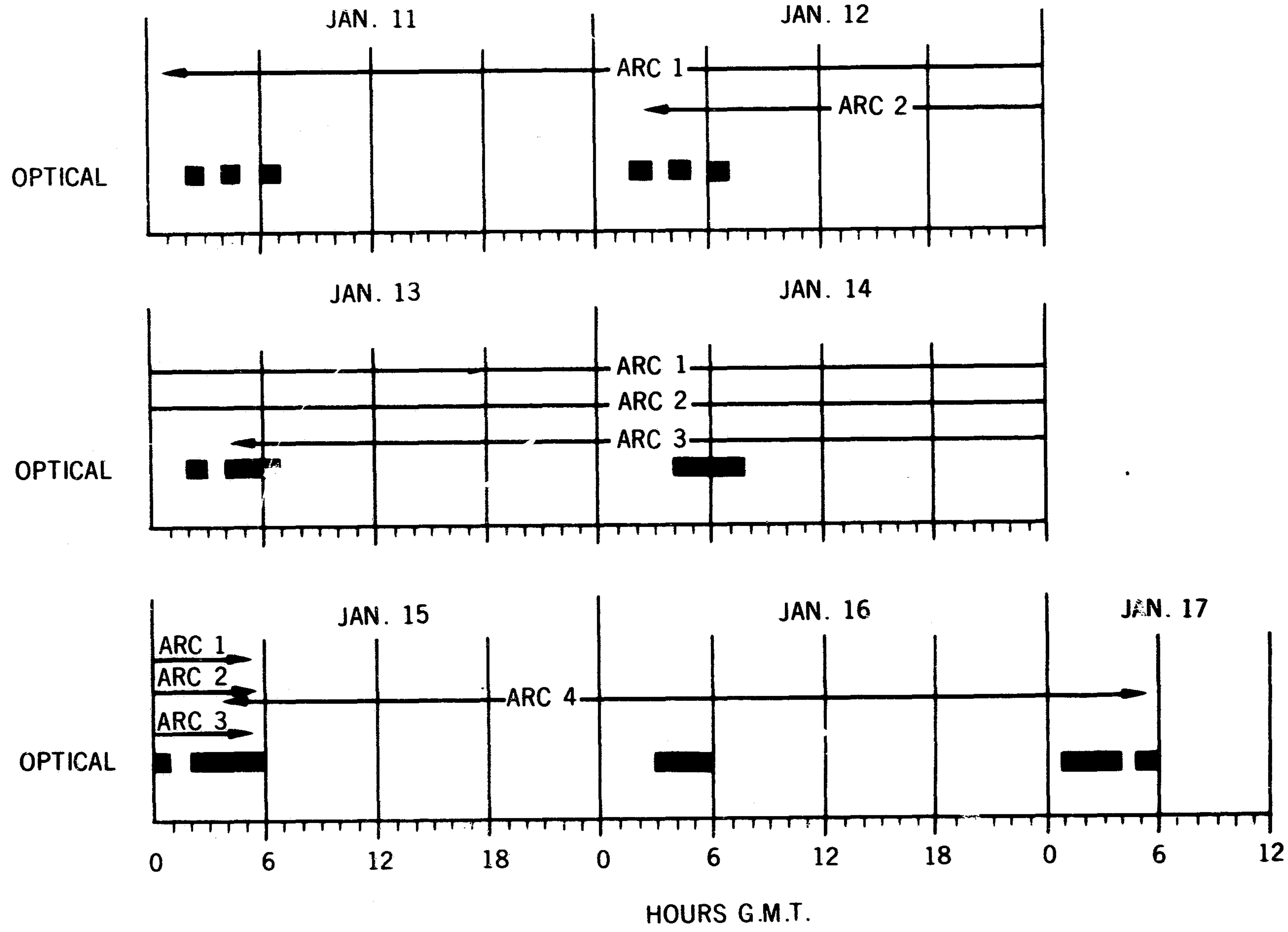


Figure A-6

1.2 GRARR DATA

The Goddard Range and Range Rate (GRARR) Tracking System (Reference 2) 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 polynominal smoothing program. The data was smoothed over two minute periods and smoothed values were calculated at 32 second intervals within these periods.

1.3 SECOR DATA*

The SECOR system which is operated by the Army Map Service, operates on the principle of "trilateration." Three or four ground stations make range observations, which are in effect simultaneous, by means of a transponder in the satellite. One station is designated as the master station and transmits a special pulse every 50 milliseconds. This pulse is then retransmitted by the satellite and received by all the stations. At each station, the pulse enables the contents of the digital servo to be recorded on magnetic tape.

* Reference 3

REFERENCES

1. Lerch, F. J., Doll, C. E., Marsh, J. G., "Mutual Visibility Flash Schedule Determination System for the GEOS-I Satellite," GSFC Document X-552-67-439, August 1967.

2. Kronmiller, G. C., Jr., and Baghdady, E. J., "The Goddard Range and Range Rate Tracking System: Concept, Design, and Performance," GSFC Document X-531-65-403, October 1965.

3. Berbert, J. H., Reich, R., Stephenson, J., "Evaluation of Range Accuracy for the Goddard Range and Range Rate System at Rosman," GSFC Document X-514-66-513, October 1966.

APPENDIX B

PREPROCESSING OF 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 sperical 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.

Pre-processing includes, for example in the case of the SAO Baker-Nunn data, updating the observations from a mean equinox of 1950.0 to the true equinox of date through the luni-solar precession and nutation effects, the corrections for planetary aberration, the transformation of the A-S (SAO atomic time) time tag to UTC time. 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 of a millisecond or approximately 4.0 meters of satellite position.

Currently, the preprocessor transforms all right ascensions and declinations to the true equator and equinox of date 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 process from that epoch to the epoch 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 observations.

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.

2.2 NUTATION

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

$$Y = NX \tag{B-1}$$

where

$$Y = \begin{bmatrix} \cos\delta_m & \cos a_m \\ \cos\delta_m & \sin a_m \\ \sin\delta_m & \end{bmatrix} \tag{B-2}$$

$$X = \begin{bmatrix} \cos\delta_T & \cos a_T \\ \cos\delta_T & \sin \sigma_T \\ \sin\delta_T & \end{bmatrix} \tag{B-3}$$

$$N = \begin{bmatrix} 1 & \Delta\psi\cos\epsilon_m & \Delta\psi\sin\epsilon_m \\ -\Delta\psi\cos\epsilon_m & 1 & \Delta\epsilon \\ -\Delta\psi\sin\epsilon_m & -\Delta\epsilon & 1 \end{bmatrix} \tag{B-4}$$

where

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

a_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:

$$X = N^{-1} Y = N^T Y \tag{B-5}$$

2.3 PRECESSION

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

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

where

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

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

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

The inverse transformation is

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

Since the expressions 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. The above expression for P is rigorous. There are simple 3rd degree polynomials in time derived by Newcomb which permit the calculation of z, θ, and ζ. There exists an even simpler form of the matrix P which permits the calculation of its elements by means of 3rd degree polynomials expressed directly in terms of the variable t (time). This simplification by-passes the necessity of calculating the sines and cosines of the angles z, θ, and ζ. These simplified matrix elements are derived by expanding the sines and cosines of z, θ, and ζ, contained in the elements of P into a series, performing the necessary multiplications and dropping terms exceeding the 3rd degree. The appropriate polynomial expressions in t are then substituted into the remaining expressions containing z, θ, and ζ. After the necessary multiplications are again performed, all terms in t higher than the 3rd degree are dropped. The final expression for P then consists simply of 9 elements in the terms of a 3rd degree polynomial in time.

2.4 PREPROCESSING OF STADAN/GRARR OBSERVATIONS

The complete analysis and derivations of the various preprocessing corrections made to Goddard Range and Range Rate observations are contained in References 1 to 4 at the end of this Appendix. For this analysis the range corrections, ΔR, listed below were added algebraically to the measured values of range R_m as received from the Data Center.

1. Tropospheric and Ionospheric (Reference 1)

$$\Delta R_T + \Delta R_I = -\frac{k}{\sin E} \text{ meters}$$

where a nominal value of k = 3 is currently used.

E = elevation of satellite with respect to the observing station.

2. Transponder Delay (Reference 2)

$$\Delta R_{DA} = -3.32 \times 10^{-4}\ \dot{R}_m - 7.18 \times 10^{-8}\ \dot{R}_m^2 \text{ meters}$$

$$\Delta R_{DC} = +5.22 \times 10^{-4}\ \dot{R}_m + 8.34 \times 10^{-8}\ \dot{R}_m^2$$

$$+4.42 \times 10^{-12}\dot{R}^3 + 1.82 \times 10^{-15}\dot{R}^4 \text{ meters}$$

for A and C channels respectively.

3. Station Bias

$\Delta R = 9.7$ meters at ROSRAN

2.5 PREPROCESSING OF AMS SECOR DATA

The normal SECOR preprocessing by AMS was bypassed for the specific data sets analyzed in this report, and instead a special edit program was implemented by D. Brown Associates for use in the GDAP program (Reference 5, Reference 6).

REFERENCES

1. Martin, C. F., Caroll, C. L., "Tropospheric Refraction Corrections and Their Residual Errors," Prepared under Contract No. AF 08(606) - 5300 by Technical Staff, Range Development, Pan American World Airways, Inc. GMRD, Patrick AFB, Florida, February 1964.

2. Berbert, J. H., Reich, R., "NASA-GSFC Final Report on GRARR/GEOS-A Data Validation," GSFC I-Document in Preparation.

3. J. J. Freeman Associates Inc., "Final Report on Ionospheric Correction to Tracking Parameters," NASA Contract NAS5-9782.

4. Watkins, E. R., Rose, D. H., "Description of the GRARR Data Preprocessing Program for the CDC - 160A," GSFC Document.

5. Berbert, J. H., Reich, R., Stephenson, J., "Evaluation of Range Accuracy for the Goddard Range and Range Rate System at Rosman," GSFC Document X-514-66-513, October 1966.

6. D. Brown Associates, Geodetic Data Analysis for GEOS-A, NASA Contract NAS5-9860.

APPENDIX C

FORCE MODELS USED IN THE NONAME ORBIT DETERMINATION PROGRAM

3.1 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.

3.2 THE EARTH'S GRAVITATIONAL FIELD

The formulation of the geopotential used is:

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

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 latitude

λ is the sub-satellite east longitude measured from Greenwich

$P_n^m(\sin\phi)$ 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 SAO M-1 earth gravitational model (Reference 1) 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 5) is listed in Table I. 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 2.

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:

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

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

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

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:

$$\ddot{x}_{\oplus} = \frac{\partial u}{\partial r}\frac{\partial r}{\partial x} + \frac{\partial u}{\partial \phi}\frac{\partial \phi}{\partial x} + \frac{\partial u}{\partial \lambda}\frac{\partial \lambda}{\partial x};\ \ddot{y}_{\oplus},\ \ddot{z}_{\oplus} \qquad \text{(C-3)}$$

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

3.3 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 (Reference 3) which can be treated as the potential function U. For the solar perturbation $R_{\odot}$ takes the form

Table I
SAO M-1 HARMONIC COEFFICIENTS (NORMALIZED)

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

$$R_{\odot} = \frac{Gm_{\odot}}{r_{\odot}} \left[\left(1 - \frac{2r}{r_{\odot}} S + \frac{r^2}{r_{\odot}^2}\right)^{-1/2} - \frac{rs}{r_{\odot}}\right] \tag{C-4}$$

where

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

$m_{\odot}$ = the mass of the sun

$\vec{r}_{\odot}$ = 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

The acceleration of the satellite due to the sun is then

$$\ddot{x}_{\odot} = \frac{\partial R_{\odot}}{\partial r}\frac{\partial r}{\partial x} + \frac{\partial R_{\odot}}{\partial \lambda}\frac{\partial \lambda}{\partial x} + \frac{\partial R_{\odot}}{\partial \phi}\frac{\partial \phi}{\partial x};\ \ddot{y};\ \ddot{Z} \tag{C-5}$$

where ϕ and λ are the latitude and longitude of the satellite respectively. The lunar perturbations are found from equation (C-4) 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.

3.4 SOLAR RADIATION PRESSURE

The acceleration acting on a satellite due to solar radiation pressure is formulated as follows (Reference 4)

$$\ddot{x}_{RAD} = -\frac{AP_{\odot}}{m}\gamma\nu L_x;\ \ddot{y}_{RAD},\ \ddot{z}_{RAD} \tag{C-6}$$

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

$$\gamma = (1 + \rho). \tag{C-7}$$

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.

3.5 ATMOSPHERIC DRAG

The atmospheric decelerations are computed as follows:

$$\ddot{x}_{DRAG} = \frac{\rho C_D A v v_x}{2m}; \ \ddot{y}_{DRAG}, \ \ddot{z}_{DRAG} \tag{C-8}$$

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

$$\vec{\nu} = \nu_x \hat{i} + \nu_y \hat{j} + \nu_z \hat{k} \tag{C-9}$$

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 D

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 1 TANAN 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

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	[illegible]8	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	Europe
		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	164	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

Table II

SAO – Optical – Continued

Source	Name	Station No.	Latitude	Longitude	Geodetic Height (meters)	Datum
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
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/Ṙ – 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.[illegible]	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	201 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 47.60	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

*MSL

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
	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
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 19.97	283 55 44.56	4	N.A.
			30 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
	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 29.60	182 37 49.53	6	C-5
	MAUIHI	5411	20 49 37.00	203 31 52.77	32	Old Hawiian
			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	5860	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
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.[illegible]	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 53 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	[illegible]30	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-RIR

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

Table XV
Navy Tranet-Doppler

Name	Station No.	Location
LASHAM	2006	Lasham, England
SANHES	2008	San 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
TWINOK	3452	Twin Oaks, Oklahoma
ROTHGR	3453	Rothwesten, West Germany
ATHNGR	3463	Athens, Greece
TORRSP	3464	Torrejon de Ardoz, Spain
CHOFUJ	3465	Chofu, Japan
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. Haramund Anis; 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., 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.