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INTERCOMPARISON OF GEOS-A OBSERVATION SYSTEMS

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ABSTRACT

The current status of NASA's Geodetic Satellite Observation Systems Intercomparison Investigation is presented. A number of accurate short orbital arcs (1/4 orbit) were determined with tracking data from the GEOS-A satellite tracking systems. Types of systems included were the NASA Goddard Range and Range Rate (GRARR), Laser and MOTS camera systems, the Army Sequential Collation of Range (SECOR) system, the Navy Tranet doppler system and the Air Force PC-1000 camera.

Error model coefficients derived for the various systems include zero-set bias, timing bias, and refraction anomaly. These are determined to an accuracy better than the 10 meter goal of the investigation. Random noise estimates for these data were also determined. The Short Orbital arc technique of intercomparison is shown to give results consistent with intercomparisons of data from collocated Laser and GRARR systems at Rosman, North Carolina.

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INTERCOMPARISON OF GEOS-A OBSERVATION SYSTEMS

J. H. Berbert

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1.0 INTRODUCTION

The GEOS-A satellite was launched by the National Aeronautics and Space Administration (NASA) November 6, 1965, and has undergone the most intensive tracking effort ever attempted with an earth satellite. As part of the National Geodetic Satellite Program, GEOS-A is helping to achieve three major goals. These are:

1. The establishment of a World Geodetic Datum accurate to 10 meters.
2. The determination of the earth's gravity field to 5 parts in 10^8.
3. The intercomparison and determination of systematic errors of the various geodetic tracking systems to accuracies consistent with the geodetic goals.

To accomplish these inter-related tasks the satellite was designed to be dense, compact, and symmetrical to minimize drag and solar radiation perturbations. It was placed in an orbit high enough to reduce drag effects, but low enough to be measurably affected by the variations in the earth's gravity field. Finally, it carried cooperative instrumentation to enable tracking by a great number of the most highly accurate radio and optical geodetic tracking systems available today.

The types of tracking stations which participated on GEOS-A are listed in Table 1. The number of participating stations fluctuated during the active lifetime of GEOS-A between the minimum and maximum figures shown for each network.

Most of the tracking systems participating in the intercomparison investigation were assigned primarily to other tasks and were utilized for this investigation at relatively small extra effort. However, a few systems were located and operated temporarily for the purpose of supporting this investigation. For several months four (4) Army Secors and four (4) Air Force cameras were located at the extremes of the Southeast U.S. Super Survey (SEUSS) in a coordinated effort to provide intercomparison data with a minimum uncertainty due to survey errors. Also, an Air Force camera and several NASA cameras were temporarily collocated at the Jupiter, Florida, Smithsonian Astrophysical Observatory (SAO) camera site for comparisons of data obtained from the different types of cameras and reduced through different data reduction programs. Later the NASA Goddard Laser was collocated with the Goddard Range and Range Rate (GRARR) system at Rosman for comparisons of GRARR data with the more accurate Laser, avoiding survey and timing uncertainties by operating at the same site and from the same clock. Finally, the NASA Special Optical (SPEOPT) Minitrack Optical Tracking System (MOTS) camera network was established primarily to support the intercomparison investigation by adding optical data near the beginning and end of passes over the short arc intercomparison network.

2.0 METHODS OF INTERCOMPARISON

Intercomparison of data from the tracking system is done through the best fitting orbit computed from the appropriately weighted tracking data. The accuracy of the orbit computations is limited by uncertainties in the present knowledge of the various perturbing forces on the satellite and systematic errors in the tracking data. In general, the longer the orbit the more important it is to correct for all the known perturbing forces and systematic errors and the more damaging the uncertainties become. Some advantage, analogous to the final adjustment of data on the closure of a conventional survey, is gained when the computed orbit is long enough to include several consecutive revolutions over the same tracking stations, and gained again each half day later when the earth has rotated around to the other side of the orbit. These closures in the tracking data help to strengthen and stabilize the orbital solution. However, it is believed that the present uncertainties in the tracking systems, time, survey, and gravity field are too difficult to separate by long arc orbits alone.

Limiting the length of the orbit helps separate the tracking system errors by reducing the effect of the errors in time, survey, gravity field and the other perturbations noted in Table 2. Collocation of a very accurate tracking system such as a Laser for comparison with another tracking system further helps separate the tracking system errors by further minimizing time and survey differences between the systems. Table 2 indicates for the several methods of intercomparison of GEOS-A data which methods are affected by the present uncertainties in systematic errors and perturbing forces. Additional perturbations which must be included in the medium and long arc orbits are drag and luni-solar gravity. The uncertainties in these perturbations have little effect on the GEOS-A orbits however.

Because of the need in this study to isolate the system errors from the other errors affecting the orbit, only the collocation and short arc methods of intercomparison have been used here. As the other errors become better determined, the medium and long arc intercomparison methods will become more practical and more desirable.

A computer program called the GEOS Data Adjustment Program (GDAP) (1) was written to determine by a minimum variance least squares fit the orbital elements for the short arc and collocation methods of intercomparison. Besides the orbital elements, GDAP can solve for a variety of system errors including zero-set bias errors, time errors, linear scale errors, residual errors in refraction coefficient, and survey errors.

Coefficients of the spherical harmonics expansion for the earth's gravity field are not solved for in GDAP, since they have been better determined through gravimeter data and the combined data from many satellites.

3.0 INTERCOMPARISON RESULTS

3.1 Short Arc Secor-GRARR Intercomparison (2)

The first intercomparison investigation results were obtained with 4 GEOS-A passes taken on January 1 to 4, 1966, a few days after the 4 Continental United States (CONUS) Secors became operational. For these passes, range data from the GRARR in North Carolina and from the 4 Secors in Virginia, Mississippi, Georgia, and Florida were combined to derive single pass orbital elements, station locations, and range and time biases. Advantage was taken of the location of 3 of the Secors on the SEUSS survey to constrain these station locations to ±2 meters. In this analysis it was found that:

- The largest indicated timing difference between Secor and GRARR on a single pass was -1.6±1.0 ms. The average difference over all 4 passes was 0.2 ms.
- The largest Secor zero-set range bias on a single pass was 17±7 meters. The average zero-set bias over all 4 passes at a single station never exceeded 5.5 meters.
- The largest GRARR zero-set range bias on a single pass was -27±7 meters. The average zero-set bias over all 4 passes was -20.5 meters. In investigating this bias several small corrections previously neglected in the boresight tower calibrations were discovered. They add up to a -9.7 meter bias in the range data unless removed in the preprocessing by adding +9.7 meters to the GRARR range measurements. Removing this known -9.7 meter bias from the average bias of -20.5 meters leaves an unexplained zero-set bias of -10.8 meters in the Rosman GRARR.
- The random error in the Secor data was found to vary between 1.7 and 4.6 meters in good agreement with the theoretical estimate for night operations of from 2.7 to 3.5 meters. (3)

- The random error in the GRARR data was found to be about 12.0 meters in fair agreement with the theoretical estimate of 9.5 meters. (4) About a third of this arises from unmodelled variations in transponder delay as a function of doppler frequency. (5)

3.2 <u>Collocated Laser-GRARR Intercomparison</u> (5)

Goddard has developed a Laser tracking system which is probably accurate to 2 meters in range and can produce range rate through an orbital fit to the range data good to about 1 cm/sec. This Laser was collocated with the Rosman GRARR system during the period July-November 1966. During this time 10 sets of simultaneous Laser - GRARR tracking data on GEOS-A were obtained. Table 3 shows the results of these passes where GDAP was used to regress only on GRARR zero-set range data bias and time bias relative to the Laser.

The average GRARR range random error of 6.8 meters for these 10 passes agrees well with the theoretical value of 5.8 meters, which applies after modelling of the transponder delays vs doppler is taken into account. However, the range rate random error of 6.9 cm/sec (5.1 cm/sec after removal of the outlier pass) is considerably larger than the theoretically expected value of 1.2 cm/sec. (4) The GRARR range rate residuals are quite systematic, forming an S-shaped curve from plus to minus 5 cm/sec. Various additional GRARR error model terms including a linear scale error were tried in the regression solutions and found to reduce the range rate residuals to about 1 cm/sec in better agreement with the theoretical random error value.

The GRARR zero-set range bias is statistically determined to 1 or 2 meters on each pass but varies from one pass to the next so that the average value of -5.3 meters is determined only to ±12.4 meters. This result is not significantly different from the -10.8±4.9 meter GRARR bias derived from the earlier Secor-GRARR passes in January. If the 3 outlier passes are discarded, the bias is determined more precisely as -5.3±2.5 meters, which satisfies the transponder specification of 0±7.5 meters but is less consistent with the short arc result.

The GRARR time bias relative to the Laser decreased significantly from October to November. The average value of the time bias of -2.07 ms is puzzling since the Laser clock was synchronized to the GRARR clock to better than 0.05 ms during each pass. However, it can be shown that due to the quadratic nature of the calibration curve for transponder delay vs doppler frequency, a drift in the GRARR transponder oscillator frequency can appear as small biases in both GRARR range and timing. For example, a drift of 8.5 KHz, as allowed by the transponder oscillator design specifications could appear as a range zero-set bias of -0.34 meters and an associated time bias of -0.22 ms, and more if the specifications are exceeded. This may explain part of the observed range and time biases of -5.3 meters and -2.07 ms.

3.3 Short Arc Intercomparison of Secor, GRARR, Tranet and Cameras

3.3.1 Data Added to Short Arc Intercomparisons

More recently, with the continued development of the GDAP computer program, it has become possible to add camera angle data and Tranet and GRARR doppler data to the short arc passes described above. Doppler data from 1 GRARR and 2 Tranet systems and optical data from several Air Force PC1000 cameras and several MOTS cameras were added to the range data from the 4 Secors and 1 GRARR. In Table 4 the data included in these computer runs is indicated with X. Additional NASA Minitrack, Tranet doppler, and SAO and NASA camera data obtained on these passes will be added in the future. Data taken but not yet included is indicated with O. The last letter in the station names is always R, D, or A, indicating the system measures range, range rate, or angle.

3.3.2 Error Model Solutions Adding Doppler and Camera Data

The Secor and GRARR range and time biases were not significantly changed by the addition of the doppler and camera data. The average GRARR zero-set range bias shifted insignificantly from -10.8±4.9 to -12.0±4.9 meters. The average random error in the Secor range data increased slightly from 2.5 to 3.2 meters, whereas, for the GRARR range data, it decreased slightly from 12.0 to 11.6 meters. Orbital residuals plots of typical Secor and GRARR range data are shown in Figure 1.

The camera orbital residuals varied from 0.8 to 3.1 seconds of arc per pass. Typical camera orbital residuals plots are given in Figure 2.

Bias and scale errors for the 2 Tranet stations were insignificant beyond the ±3 cm/sec bias and 4 parts in 10^6 scale determination capability of these data sets. Doppler orbital residuals for Tranet and GRARR data are given in Figure 3. The GRARR range rate orbital residuals were reduced from a systematic S-shaped curve with a sigma of 5 cm/sec to the random plot with the 0.7 cm/sec sigma shown in Figure 3 by the addition of a linear scale error model term to the GRARR range rate error model. This scale error is not consistent, varying from 4 to 17 parts in 10^6 over the 4 passes. An explanation for this term is being sought. Solutions for other error model terms such as residual refraction and survey were insignificant for these passes.

3.3.3 Effect of Data Input on Error Model Solutions and Orbital Residuals

Several GDAP computer runs were made on orbit 700 to determine the effect of the input data selection on the derived error model coefficients. Run 1 included data from 3 Secors, 1 GRARR, 3 cameras, and 1 Tranet. Run 2 deleted the Tranet data. Run 3 deleted the Tranet and camera data. Run 4 deleted the Tranet, camera, and GRARR doppler data leaving only the Secor and GRARR range data in the orbit and error model determination. An examination of the various bias, time, scale, and survey error model coefficients showed no very significant changes in values from one run to the next for the systems remaining in the solution. However, as systems were dropped out of the solutions, the mean and standard deviations of their orbital residuals jumped to significantly larger values as shown in Table 5. This is undoubtedly due to slight adjustments in the best fitting orbital elements for the different data inputs. The orbital elements appear to adjust so as not to significantly change the results for the data participating in the orbital element and error model coefficient determinations.

4.0 FUTURE PLANS

Before analyzing many more short arc passes, an effort will be made to improve the survey at most of the camera sites in the short arc intercomparison net. This will be done by combining simultaneous camera observations in a large scale survey adjustment which is expected to reduce survey errors to 2 or 3 meters for the interior stations and to 5 meters or better for the peripheral stations. (1) This will permit a tighter constraint on the survey error model coefficients and help reduce the uncertainty in the other error model coefficients and orbital elements.

When this is done, about 100 short arc passes distributed throughout the GEOS-A lifetime will be analyzed intercomparing data from all the participating tracking systems including SAO camera data and NASA Minitrack data as well as all those systems used in this report. This should result in a detailed time history of the system biases, etc. over a period of about a year. These results may be used for correcting the data from the intercomparison network systems for use in geodetic applications. The results may also serve as a guide on how to weight the data from similar systems outside the intercomparison network.

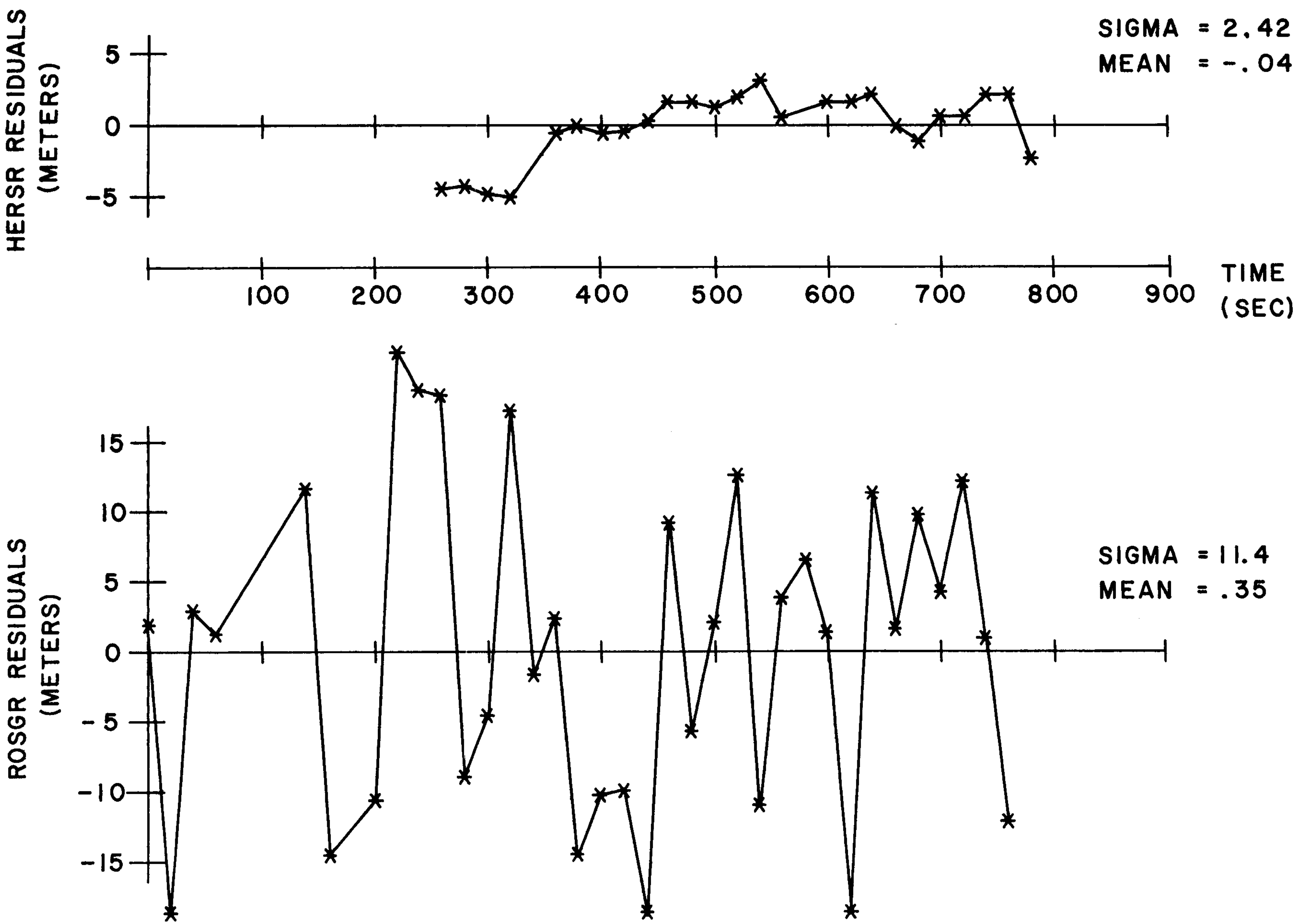

FIGURE 1. ORBITAL RESIDUALS FOR HERNDON SECOR AND ROSMAN GRARR RANGE DATA ON ORBIT 665

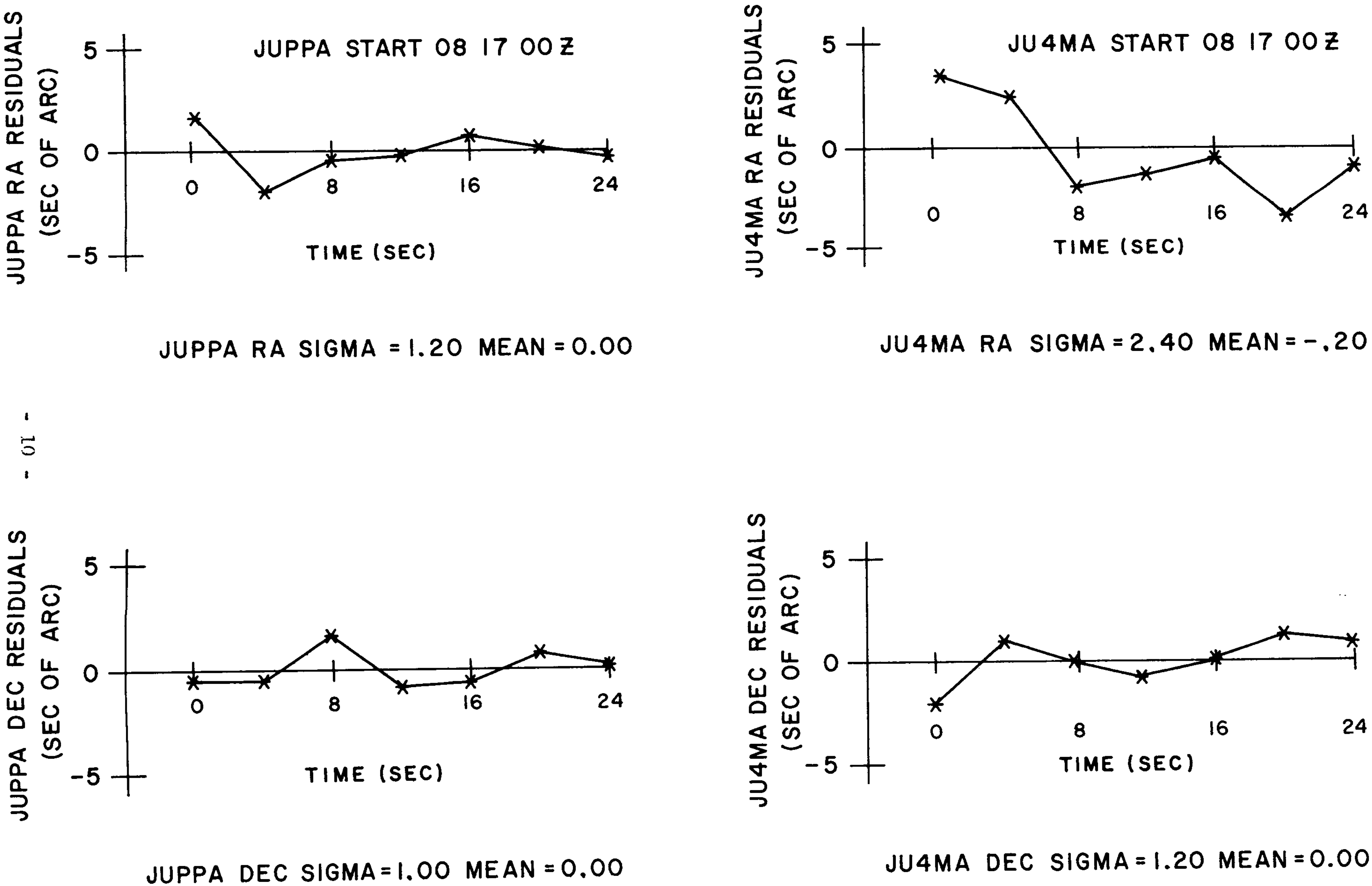

FIGURE 2. ORBITAL RESIDUALS FOR JUPITER PC1000 AND JUPITER MOTS-40 ANGLE DATA ON ORBIT 677

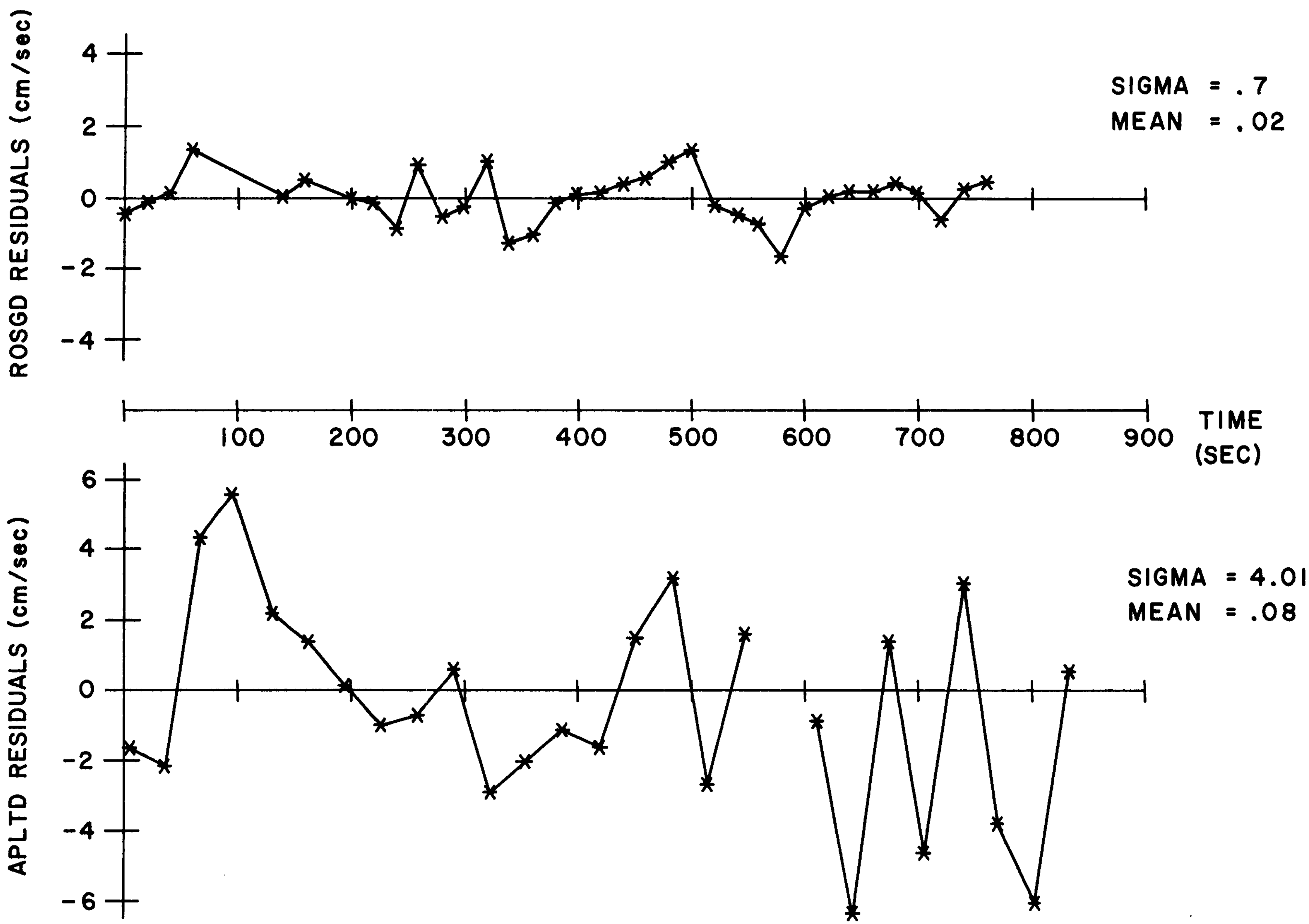

FIGURE 3. ORBITAL RESIDUALS FOR APL TRANET AND ROSMAN GRARR DOPPLER DATA ON ORBIT 665

Table 1. GEOS-A Tracking Systems

RADIO SYSTEMS	INTERCOMP. NET Min.	INTERCOMP. NET Max.	WORLD NET Min.	WORLD NET Max.	FREQ. (Mc/s) Up/Down	DATA MEASURES	ESTIMATED ACCURACY
Army/SECOR	1	4	1	9	420.9/224.5,449.0	R	10 meters
Navy/TRANET	4	7	17	21	None/162,324,972	$\dot{R}$	5 cm/sec
NASA/Minitrack	3	6	9	12	None/136.8	A	20 sec arc
NASA/GRARR	1	1	3	3	2271/1705	R&$\dot{R}$	10 meters & 5cm/sec
TOTAL	9	18	30	45			
LASERS							
NASA/LASER	0	1	0	1	Opt. Freq.	R	2 meters & 1cm/sec
SAO/LASER	0	1	0	1	Opt. Freq.	R	2 meters
TOTAL	0	2	0	2			
CAMERAS							
Air Force/PC 1000	0	14	1	14	Opt. Freq.	A	1 sec arc
NASA/STADAN MOTS	5	7	11	14	Opt. Freq.	A	1 sec arc
NASA/SPEOPT MOTS	8	12	8	12	Opt. Freq.	A	1 sec arc
SAO/Baker Nunn	4	7	11	14	Opt. Freq.	A	2 sec arc
ESSA (C&GS)/BC-4	1	8	1	8	Opt. Freq.	A	2 sec arc
INTERNAT'L/OPT.	0	0	12	15	Opt. Freq.	A	1 sec arc
TOTAL	18	48	44	77			

Table 2. Intercomparison Methods Affected by Systematic and Perturbing Force Errors

Methods of Intercomparison	System	Time	Survey	Earth Gravity	Mean Pole	Center of Mass	Solar Rad. Pressure
Collocation	X						
Short Arc (0 - 1/4 orbit)	X	X	X				
Medium Arc (1/4 - 6 orbits)	X	X	X	X	X	X	
Long Arc (6 or more orbits)	X	X	X	X	X	X	X

Table 3. Simultaneous Laser-GRARR Passes at Rosman

				GRARR			
Run No.	1966 Date	Laser Pass Duration (sec)	Laser R(rms) (meters)	R(rms) (meters)	$\dot{R}$(rms) (cm/sec)	Range Bias (meters)	Time Bias (millisec)
1	Aug. 10	96	4.3	12.9		- 5.6±1.0	-1.40±0.77
2	Oct. 6	205	1.7	6.4	21.6*	8.7±1.3*	-3.75±0.52
3	Oct. 7	377	1.6	6.5	5.4	10.6±0.8*	-3.28±0.23
4	Oct. 8	344	1.2	6.1	3.3	- 3.6±0.8	-4.04±0.28
5	Nov. 15	174	1.6	5.6	3.3	- 4.1±2.2	-1.73±1.27
6	Nov. 18	305	1.0	6.1	8.6	-35.2±1.0*	-0.82±0.42
7	Nov. 19	153	2.3	5.7	9.9	- 4.7±1.5	-0.77±0.11
8	Nov. 20	416	1.6	6.2	2.0	- 2.6±0.6	-1.47±0.17
9	Nov. 20	336	1.1	6.2	5.8	-10.1±1.1	-2.02±0.44
10	Nov. 21	423	1.6	6.2	2.4	- 6.5±0.7	-1.41±0.17
	Average		1.8	6.8	6.9	-5.3±12.4	-2.07±1.19
	(Average with outlier passes removed)				(5.1)	(-5.3±2.5)	

*Outlier Passes

Table 4. Data Analyzed for Four Selected Short Arcs in January 1966

Instrument	Station	Orbit Number 665	676	677	700
Secor	HERSR	X	X	X	X
Secor	HOMSR	X	X	X	
Secor	GRESR	X	X	X	X
Secor	FTWSR		X	X	X
GRARR	ROSGR	X	X	X	X
GRARR	ROSGD	X	X	X	X
Tranet	APLTD	X	X	X	X
Tranet	LACTD		X	X	X
Tranet	ANCTD		O	O	O
Minitrack	BPOIA	O	O	O	O
Minitrack	FTMIA	O			O
Minitrack	NEWIA		O		
Minitrack	COLIA	O	O		O
Minitrack	GFOIA			O	
Minitrack	MOJIA	O		O	
PC1000	HOMPA	X'*	X		
PC1000	HUNPA	X	O	X	
PC1000	JUPPA		X	X	
PC1000	SEMPA		X	X	
PC1000	GRDPA				X
PC1000	CURPA				X
PC1000	ANTPA				X
PC1000	BEDPA				X
Baker Nunn	ORGBA	O	O	O	O
Baker Nunn	CURBA		O		O
Baker Nunn	JUPBA			O	
STADAN MOTS	BPOMA				O
STADAN MOTS	FTMMA	X'	X		
STADAN MOTS	MOJMA			X'	
SPEOPT MOTS	DENMA	O		O	O
SPEOPT MOTS	BERMA		X		O
SPEOPT MOTS	JU2MA		X	X	
SPEOPT MOTS	JU4MA		X	X	
SPEOPT MOTS	COLMA				O

*X' means 2 plates were obtained during the pass.

Table 5. Means and Standard Deviations of Orbital Residuals for Different Data Inputs on Orbit 700

Data Input	GDAP RUN 1	2	3	4
Average of 3 SECORS (meters)	- 0.01 ± 3.3	- 0.07 ± 3.3	- 0.01 ± 3.1	- 0.02 ± 3.2
1 GRARR (meters)	+ 0.5 ±11.6	+ 0.4 ±11.7	+ 0.3 ±11.8	+ 0.1 ±11.7
1 GRARR (cm/sec)	+ 0.1 ± 1.1	- 0.1 ± 1.1	0.0 ± 2.1	+ 1.6 ± 5.3
Average of 3 PC1000 (arcsec)	- 0.4 ± 7.8	- 0.6 ± 7.8	- 9.4 ±10.6	- 8.4 ±10.2
1 Tranet (cm/sec)	+ 0.3 ± 5.0	+14.0 ± 7.9	+13.6 ± 9.6	+15.6 ± 9.7

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