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1.0 INTRODUCTION

Prior to 1975, most determinations of the geocentric gravitational constant (GM) employed radiometric data from near-earth tracking of lunar and interplanetary probes. Reported GM results having sigmas less than 0.8 km^3/sec^2 are shown in Figure 1. GM values from Rangers 8 and 9 (Sjogren, et.al., 1966), Surveyors 5 and 6 (Wong, 1968), Pioneer 7 (Anderson and Hilt, 1969), and Mariner 5 (Pease, et.al., 1969) are all consistent at the 1σ level. A value of 398601.13 km^3/sec^2, based on Ranger results, was adopted by the Smithsonian Astrophysical Observatory for both their 1966 Standard Earth (Lundquist and Veis, 1966) and 1969 Standard Earth (Gaposchkin and Lambeck, 1970), and was widely used prior to Mariner 9 for earth satellite orbit determinations. The Lunar Orbiter 2 GM value (Mottinger and Sjogren, 1967) seems to have been largely ignored, probably because of its inconsistency with the lunar probe results and the reference of the investigators for a "more realistic" sigma of 0.7 km^3/sec^2 (Esposito and Wong, 1972). The Venera GM (Akim, et.al., 1971) also had virtually no impact at the time of its publication, due to its inconsistency with the accepted value and the listing of its error at 1.0 km^3/sec^2 maximum possible error. As shown in Figure 1, however, the Lunar Orbiter 2 and Venera results are consistent with more recent GM determinations.

Discounting the Lunar Orbiter and Venera results, the Mariner 9 GM, first presented in 1972 (Esposito and Wong, 1972), was a sharp drop from previous values. Refined analysis of the Mariner 9 data and preliminary Mariner 10 analysis (Esposito and Ng, 1976) produced even further reductions in GM estimates. The most recent GM estimates based on interplanetary probe tracking are from Vikings 1 and 2 (Esposito, 1978) and bracket the Mariner 9 and 10 values.

Within the last three years, several new methods have been used for GM determination, with results (shown in Figure 1) that are consistent with those from Mariner 9 and later radiometric tracking of interplanetary probes. These methods include lunar laser ranging (Williams, 1977), lunar laser ranging combined with very long baseline interferometry (VLBI) observations of lunar radio transmitters (King, et.al., 1976), laser ranging of the LAGEOS

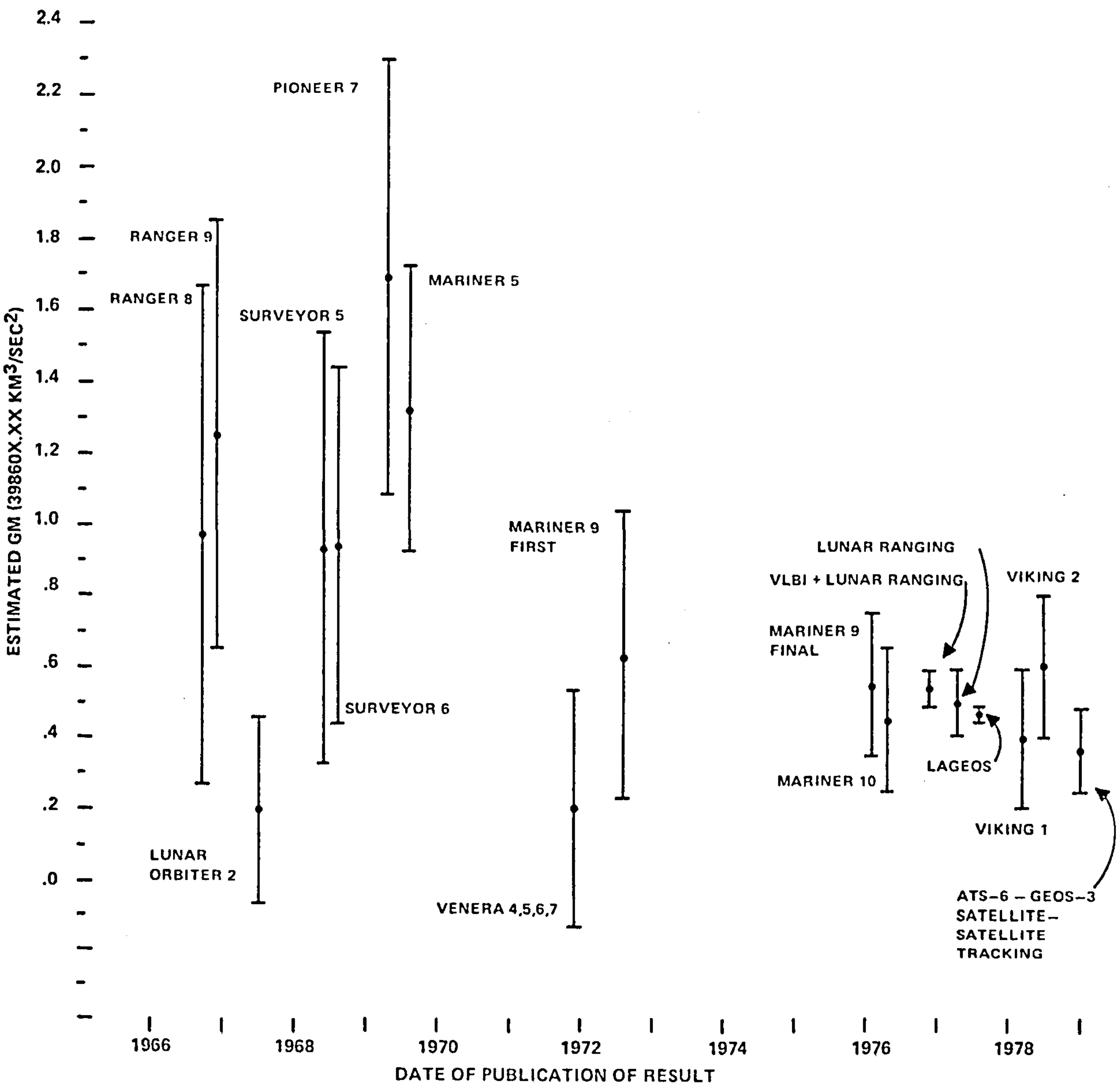

FIGURE 1. PUBLISHED VALUES OF GM WITH STANDARD DEVIATIONS LESS THAN 0.8 km^3/sec^2. BARS SHOW 1σ ERROR ESTIMATES. FOR VENERA 4,5,6,7 THE PUBLISHED 1.0 km^3/sec^2 "MAXIMUM POSSIBLE ERROR" (AKIM, ET. AL., 1971) WAS ASSUMED TO BE A 3σ VALUE. ALL VALUES HAVE BEEN REFERENCED TO A SPEED OF LIGHT OF 299792.458 km/sec.

satellite (Lerch, et.al., 1977), and the satellite-satellite tracking method to be discussed in this paper. Each of these methods has produced results with sigmas which are lower than any of the results from interplanetary probe tracking. Whether this is indicative of a higher level of accuracy, or less conservatism among investigators, remains to be seen from more refined data analyses and new GM determinations. However, the post 1975 results are consistent to within the quoted 1σ levels, suggesting that very accurate results are now being obtained, particularly from methods using laser ranging data. On the other hand, it should be emphasized that accurate results will be consistent, but that consistent results are not necessarily accurate. The effects of measurement noise on a GM determination are easy to calculate, but the effects of systematic errors can be very difficult to reliably assess due to problems either in modeling the errors or in estimating their magnitude. Furthermore, the same systematic errors can affect different GM determination methods in a similar manner. The primary advantage of using different methods is that the common systematic errors are minimized, thus providing checks on the results and error analyses for the different solutions. It is believed that the method discussed in this paper has some error sources that are common to the LAGEOS solution*, but is unlikely to have any significant errors common to any of the other solutions.

2.0 METHOD AND DATA SET

Accurate determination of GM using only low altitude earth orbiting satellites has not been possible due to uncertainties in the geopotential (e.g., as expressed via spherical harmonics) and high correlations between simultaneously estimated GM and station position heights. The use of both a high altitude satellite and a low altitude satellite, along with the constraint obtained from measuring the relative motion between the satellites leads to reduced sensitivity to geopotential model errors, and a reduction in the correlations between estimated station heights and GM.

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* Primarily the geopotential coefficient set.

During the first two months after the launch of GEOS-3 in April, 1975, Satellite-Satellite Tracking Experiment (SSE) Rosman (N.C.) to ATS-6 to GEOS-3 range rate data was taken. GEOS-3 is in a near circular orbit with a nominal altitude of 843 km, and an inclination of 115°. ATS-6 is in a geosyncronous orbit and, during the period of interest, was located at longitude 94°W. In addition to the SSE range rate data, ground tracking of GEOS-3 by lasers and C-band radars was also used. Although some ranging data from Rosman to ATS-6 to GEOS-3 was taken, none was used because of bias uncertainties.

From error analyses of GM estimation using SSE data, the dominant error sources were identified as station positions, geopotential coefficients, and solar radiation pressure on ATS-6. The effects of these error sources were minimized by using arc lengths of one half day or less, and the best available geopotential model. Since no sufficiently accurate station position set was available, the coordinates of all the GEOS-3 tracking stations were adjusted, except for one longitude which was arbitrarily fixed.

Four sets of data were selected for use in various combinations. Table 1 shows the basic set of half-day arcs, each containing 4 passes of SSE data along with at least 4 passes of ground tracking by the GEOS-3 calibration area stations indicated. Two of these arcs begin with North-South passes through the calibration area and two begin with South-North passes.

The second set of data, shown in Table 2, contains 1-2 revolution arcs of GEOS-3, each including SSE tracks on successive revolutions. Again there is a geometric balance of passes between North-South and South-North passes in order to obtain the maximum degree of cancellation of geopotential model errors.

The third set of data (Table 3) contains only NASA laser tracking of GEOS-3, with the arc lengths only slightly greater than one revolution. This data set was chosen because of its high concentration of high accuracy unbiased ranging data from the three NASA laser sites at Goddard, Bermuda and Grand Turk. (Only Goddard and Grand Turk lasers tracked during the SSE tracking period.) Although this laser data set did not contribute strength directly to the GM recovery, it did provide strength for station position estimation.

TABLE 1. SUMMARY OF SSE RANGE RATE AND GROUND TRACKING DATA

(HALF–DAY ARCS)

	DATA SPAN	REV. NO. OF GEOS-3 ORBIT	STATIONS TRACKING*	DIRECTION
4/26/75 HALF DAY ARC	21^h15^m–09^h50^m, 4/27	239	SSE	N–S
		240	SSE, 4760, 4860, 7063	
		241	4860	
		245	SSE, 4760, 4840, 7063	S–N
		246	SSE, 4760, 4840, 7068, 7063	
4/27/75 HALF DAY ARC	06^h44^m–00^h37^m, 4/28	245	SSE, 4760, 4840, 7063	S–N
		246	SSE, 4760, 4840, 7068, 7063	
		253	SSE, 4760	N–S
		254	SSE, 4760, 4840, 7068	
		255	4840	
5/10/75 HALF DAY	22^h50^m–10^h30^m, 5/11	438	SSE, 4760	N–S
		439	SSE, 4760, 4860	
		444	SSE, 4760, 4840	S–N
		445	SSE, 4840, 7063	
5/12/75 HALF DAY ARC	08^h10^m–01^h57^m, 5/13	458	SSE, 4760, 4860	S–N
		459	SSE, 4760, 4860, 7063	
		466	SSE	N–S
		467	SSE, 4760, 4860, 7068	
		468	4860	

LEGEND

*SSE – Rosman range rate tracking of GEOS-3 through ATS-6.
4860 – Wallops Island FPQ–6 C–Band Radar
4840 – Wallops Island FPS–16 C–Band Radar
4760 – Bermuda FPQ–6 C–Band Radar
7063 – Goddard Laser
7068 – Grand Turk Laser
7067 – Bermuda Laser

TABLE 2. SUMMARY OF SSE RANGE RATE AND GROUND TRACKING DATA

(SHORT ARCS WITH TWO CONSECUTIVE SSE PASSES)

DATE	DATA SPAN	REV. NO. OF GEOS-3 ORBIT	STATIONS TRACKING*	DIRECTION
4/26/75	$21^{h}16^{m}-00^{h}50^{m}$	239	SSE	N–S
		240	SSE, 4760, 4860, 7063	
		241	4860	
4/27/75	$06^{h}47^{m}-09^{h}06^{m}$	245	SSE, 4760, 4840, 7063	S–N
		246	SSE, 4760, 4840, 7068, 7063	
4/27/75	$21^{h}07^{m}-23^{h}27^{m}$	253	SSE, 4760	N–S
		254	SSE, 4760, 4840, 7068	
		255	4840	
4/28/75	$22^{h}21^{m}-00^{h}54^{m}$	267	4760	N–S
		268	SSE, 4760, 4860, 7068	
		269	SSE, 4760, 4860	
5/11/75	$08^{h}08^{m}-10^{h}29^{m}$	444	SSE, 4760, 4840	S–N
		445	SSE, 4840, 7063	
5/12/75	$08^{h}10^{m}-10^{h}29^{m}$	458	SSE, 4760, 4860	S–N
		459	SSE, 4760, 4860, 7063	

*See Table 1 legend.

TABLE 3. SUMMARY OF TWO PASS ARCS OF LASER DATA

DATE	DATA SPAN	REV. NO. OF GEOS-3 ORBIT	STATIONS TRACKING*	DIRECTION
7/26/75	18^h28^m–20^h15^m	1525	7063, 7067, 7068	S–N
		1526	7063, 7068	
8/8/75	10^h37^m–12^h22^m	1704	7063, 7067, 7068	N–S
		1705	7063	
8/27/75	12^h41^m–14^h25^m	1974	7063, 7067, 7068	N–S
		1975	7063	
9/4/75	22^h06^m–23^h53^m	2093	7067	S–N
		2094	7063, 7067, 7068	
11/26/75	08^h04^m–09^h53^m	3259	7063, 7067	S–N
		3260	7063, 7067, 7068	
2/23/76	08^h22^m–10^h09^m	4518	7067, 7068	N–S
		4519	7063, 7067, 7068	

*See Table 1 legend.

The fourth data set consisted of 4 single passes of GEOS-3 with the ground tracks shown in Figure 2. These passes were each tracked by the three NASA laser stations. Whenever these arcs were used, they were always heavily weighted and were used solely to enforce a good set of baselines between the 3 stations.

In general, data weights used were based on the following sigmas:

Data Type	Sigma
SSE Range Rate	1 mm/sec
C-Band Range	1 m
Laser Range	.1 m (data set 3 not used)
Laser Range	1 m (data set 3 used)

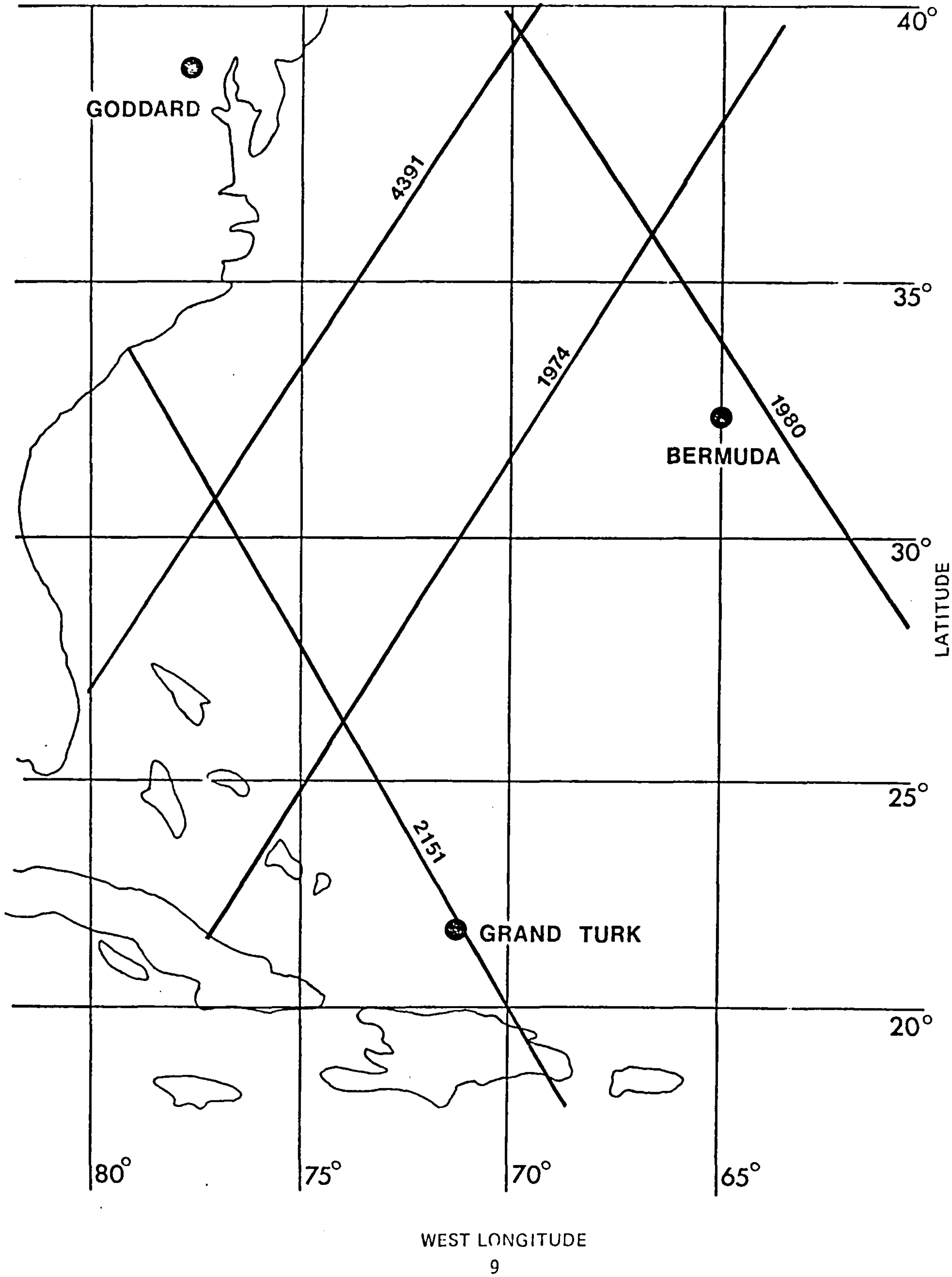
In spite of the apparent low weight given to the C-band data, it is essential to the solution because of the fact that the radars tracked continuously on almost all passes for which the spacecraft was above 10° maximum elevation angle. Because of some bias uncertainty, a bias was adjusted for each radar for each arc.

3.0 TRACKING POINT CORRECTIONS

Precision reduced laser data is corrected during preprocessing so that the measurement is effectively made to the spacecraft center-of-mass. C-band data is flagged according to the transponder used (coherent or non-coherent), and is corrected in the GEODYN data reduction (T. Martin, et.al., 1972) to a spacecraft center-of-mass measurement. The coherent C-band transponder was used for all the passes listed in Tables 1 and 2.

The SSE measurements to GEOS-3 are made to one of four antennas located in four quadrants around the spacecraft, each about a half meter from the center-of-mass. The data formats do not allow for the identification of the particular antenna in use, although the schedule normally calls for switching to the antenna closest to ATS-6. Based on the scheduling procedure, and the fact that all antennas are at the same vertical distance from the spacecraft

FIGURE 2. GROUND TRACKS FOR SINGLE PASS LASER ARCS



center-of-mass, the tracking point correction was made as if the transponder were located on a ring of 41.42 cm radius about the GEOS-3 vertical axis, 52.35 cm below the spacecraft center-of-mass.

The effect of the correction on SSE range rate measurements is on the order of 1 mm/sec, as is shown in Figure 3 which gives the effect of making the correction on measurements on GEOS-3 Rev 240. The effects on the GEOS-3 orbit are shown in Figure 4, with the orbit estimations having also included a GM adjustment (Data Set 1 + Data Set 4). The main effect of making the correction is to move the orbit up by about the amount of the z offset, requiring a corresponding adjustment in GM.

Table 4 shows the effects of the tracking point correction on estimated GM for various arcs which will be discussed below. The effects on the half day arc solutions are on the order of +0.07 km^3/sec^2, while 1-2 Rev arc solutions are affected by a lesser amount and in the opposite direction. All GM solutions quoted below have had the tracking point correction applied.

4.0 ESTIMATED VALUES OF GM

The data sets discussed above have been reduced in various combinations and with 4 different gravity models. The gravity models used were:

GEM 7 (Goddard Earth Model 7) - contains no GEOS-3 data.

PGS558 - A very preliminary version of GEM 9 - contains some arcs of GEOS-3 ground tracking data.

GEM 9 [Lerch, et.al., 1977] (Goddard Earth Model 9) - contains LAGEOS data and extensive GEOS-3 data.

GEM 10 [Lerch, et.al., 1977] (Goddard Earth Model 10) - same data as GEM 9 plus surface gravity data.

The data set combinations used were:

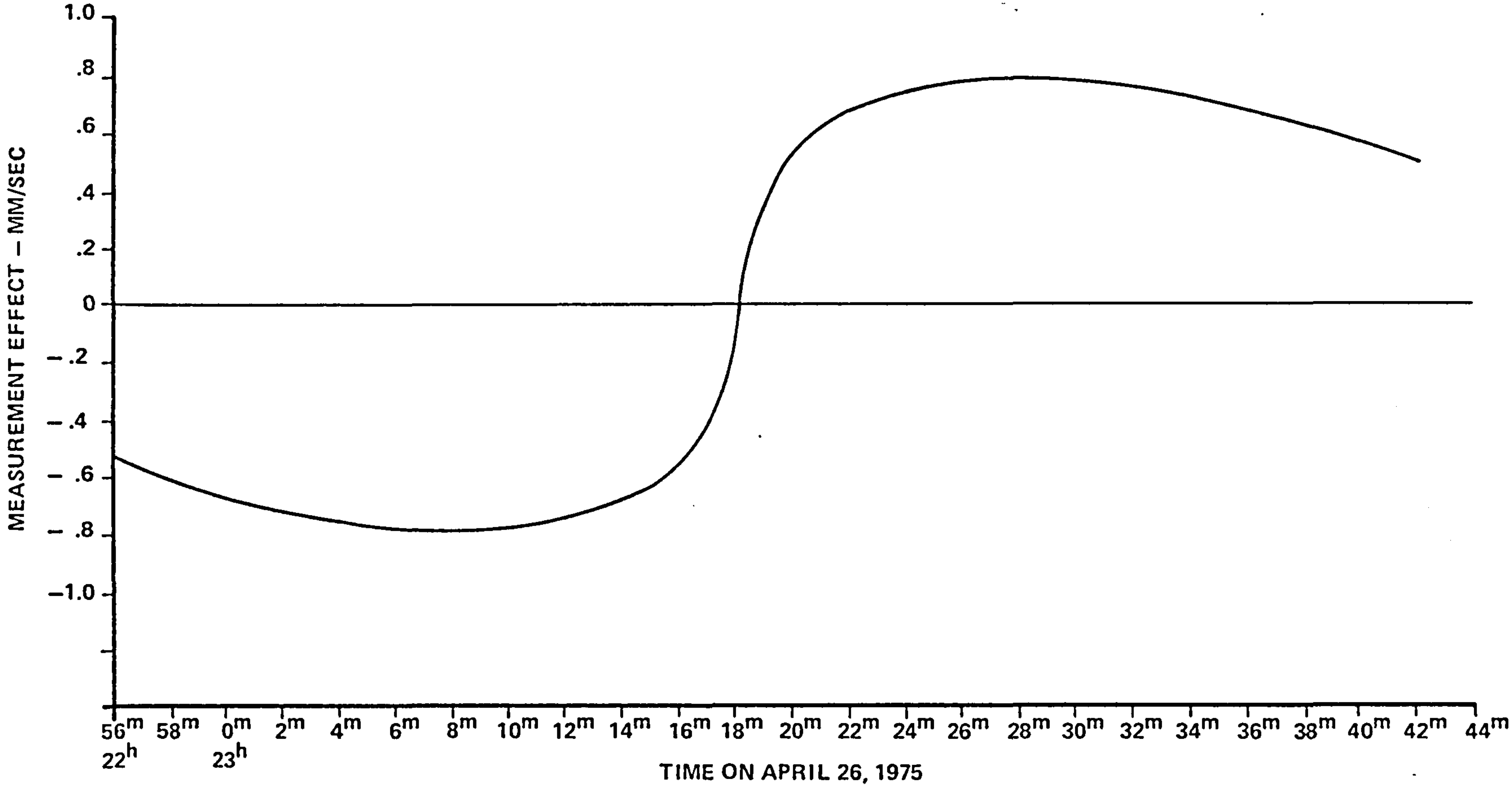


FIGURE 3. EFFECT OF TRACKING POINT CORRECTION ON SSE MEASUREMENTS ON GEOS-3 REV 240

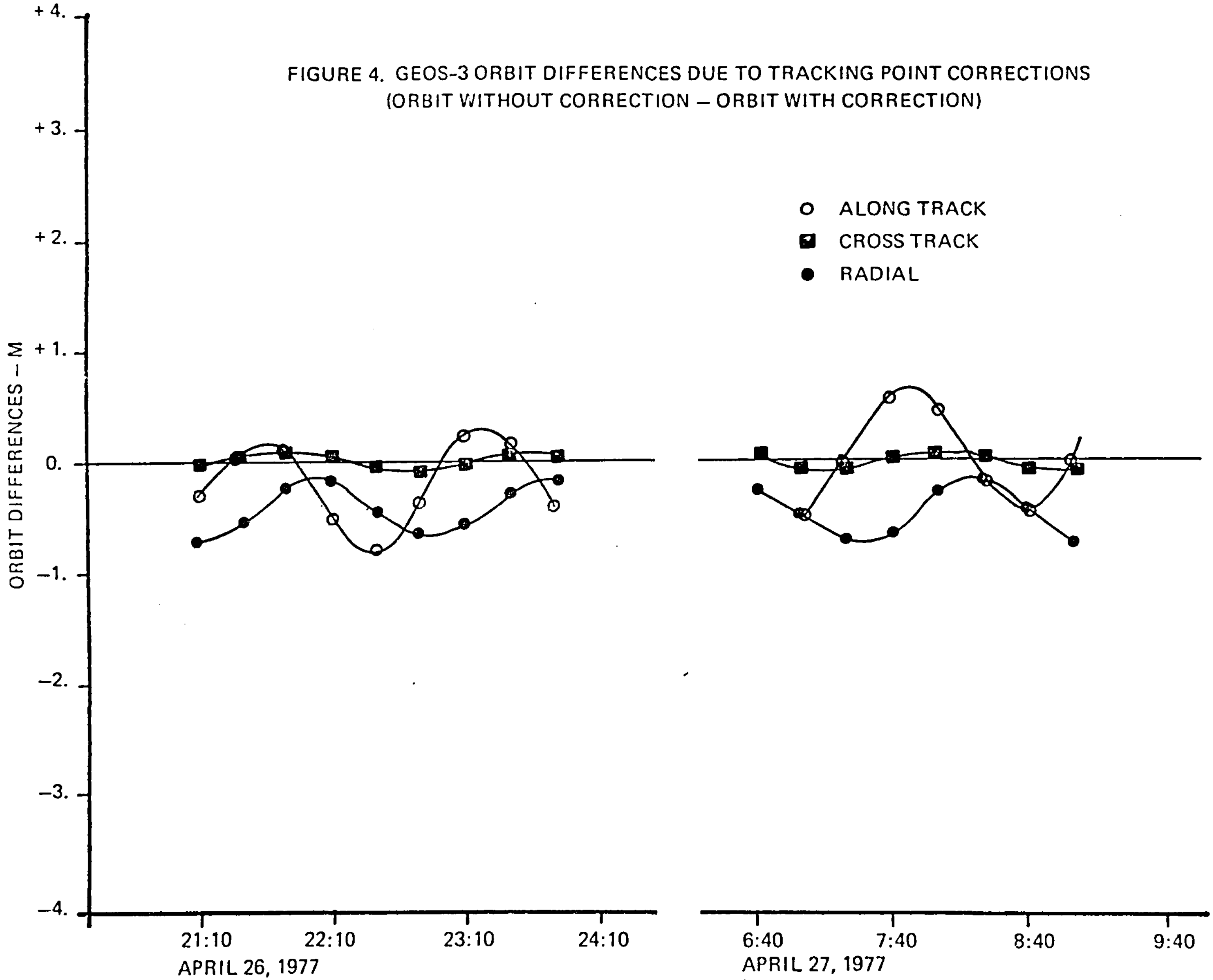


FIGURE 4. GEOS-3 ORBIT DIFFERENCES DUE TO TRACKING POINT CORRECTIONS
(ORBIT WITHOUT CORRECTION – ORBIT WITH CORRECTION)

TABLE 4. EFFECT ON GM DUE TO SSE TRACKING POINT CORRECTION

ARC	GM INCREMENT
4/26 Half Day Arc	+ .081 km^3/sec^2
4/27 Half Day Arc	+ .059
5/10 Half Day Arc	+ .077
5/12 Half Day Arc	+ .068
4/26, 5/12 Half Day Arcs	+ .072
4/27, 5/10 Half Day Arcs	+ .064
4 HALF DAY ARCS	+ .070
SHORT SSE ARCS (σ_L = .1 m)	– .015

1. Separate half day arcs from Data Set 1, plus Data Set 4.

2. Pairs of half day arcs from Data Set 1, plus Data Set 4.

3. Data Set 1 plus Data Set 4.

4. Data Set 2 plus Data Set 3.

5. Data Set 2 plus Data Set 4.

Table 5 shows the recovered values of GM for these various data set combinations and the 4 different gravity models. For a given gravity model, the major variations between solutions are due to different sensitivities to systematic errors, since only the short arc solutions are significantly affected by measurement noise. Such variations between solutions do not exceed 0.2 km^3/sec^2, even including the weakest solutions. Excluding the two weaker half day arc solutions (May 10 and May 12) and the relatively weak SSE short arc and two pass laser arc solution, the solution to solution variations range from .127 km^3/sec^2 for GEM 7 down to .049 km^3/sec^2 for GEM 10. In fact, the GEM 10 solution using all 4 half day arcs shows perfect agreement with the short arc GEM 10 solution. On the basis of consistent results using different data sets, the GEM 10 solutions would thus be expected to provide the most accurate GM value.

A further basis for the choice of the GEM 10 results is provided by data fit to the GM and orbital solutions. Figure 5 shows the SSE range rate residual fit from the 4 half day arc solution, plotted against the recovered value of GM. GEM 10 gives an rss of 1.11 mm/sec, compared to an rss of 1.16 mm/sec for GEM 9. While this reduction is less than 5%, it is a definite reduction, particularly when it is considered that the actual noise levels are around 1 mm/sec. The fits for PGS558 and GEM 7 are worse. Consequently, the adopted solution is the 4 half day SSE arc solution, with a GM value of 398600.36 km^3/sec^2.

The accuracy of the solution depends upon the geopotential model error, and the degree to which the combination of arcs has led to a cancellation of geopotential and other error effects. The dominant error source is considered to be geopotential model error, followed by solar radiation pressure modeling

TABLE 5. RECOVERED VALUES OF GM (IN KM^3/SEC^2) FROM ATS–6 TO GEOS–3 SSE RANGE RATE DATA AND GROUND TRACKING OF GEOS–3. LISTED VALUES ARE GM – 398600. KM^3/SEC^2

GRAVITY MODEL USED	4/26/75 HALF DAY ARC σ_L = .1 m	4/27/75 HALF DAY ARC σ_L = .1 m	5/10/75 HALF DAY ARC σ_L = .1 m	5/12/75 HALF DAY ARC σ_L = .1 m	MULTIARC OF 4/26 AND 5/12 HALF DAY ARCS σ_L = .1 m	MULTIARC OF 4/27 AND 5/10 HALF DAY ARCS σ_L = .1 m
GEM7	.516 ± .008	.572 (± .008)	.652(± .014)	.462(± .015)	.508(± .007)	.617 (± .007)
PGS558	.537	.468	.475	.319	.504	.496
GEM9	.415	.358	.441	.336	.415	.394
GEM10	.368	.321	.317	.252	.370	.352

GRAVITY MODEL USED	MULTIARC OF 4/26, 4/27, 5/10 AND 5/12 HALF DAY ARCS σ_L = .1 m	MULTIARC OF 6 SHORT SSE ARCS PLUS	
		6 TWO PASS LASER ARCS σ_L = 1.0 m	4 SINGLE PASS LASER ARCS σ_L = .1 m
GEM7	.567 (± .005)	.505 (± .035)	.490 (± .024)
PGS558	.501	.355	.399
GEM 9	.400	.258	.332
GEM10	.355		.355

NOTE: NUMBERS IN PARENTHESES ARE UNCERTAINTIES DUE TO NOISE ONLY. DATA SET FOR ALL HALF DAY ARC SOLUTIONS ALSO INCLUDES 4 SINGLE PASS LASER ARCS.

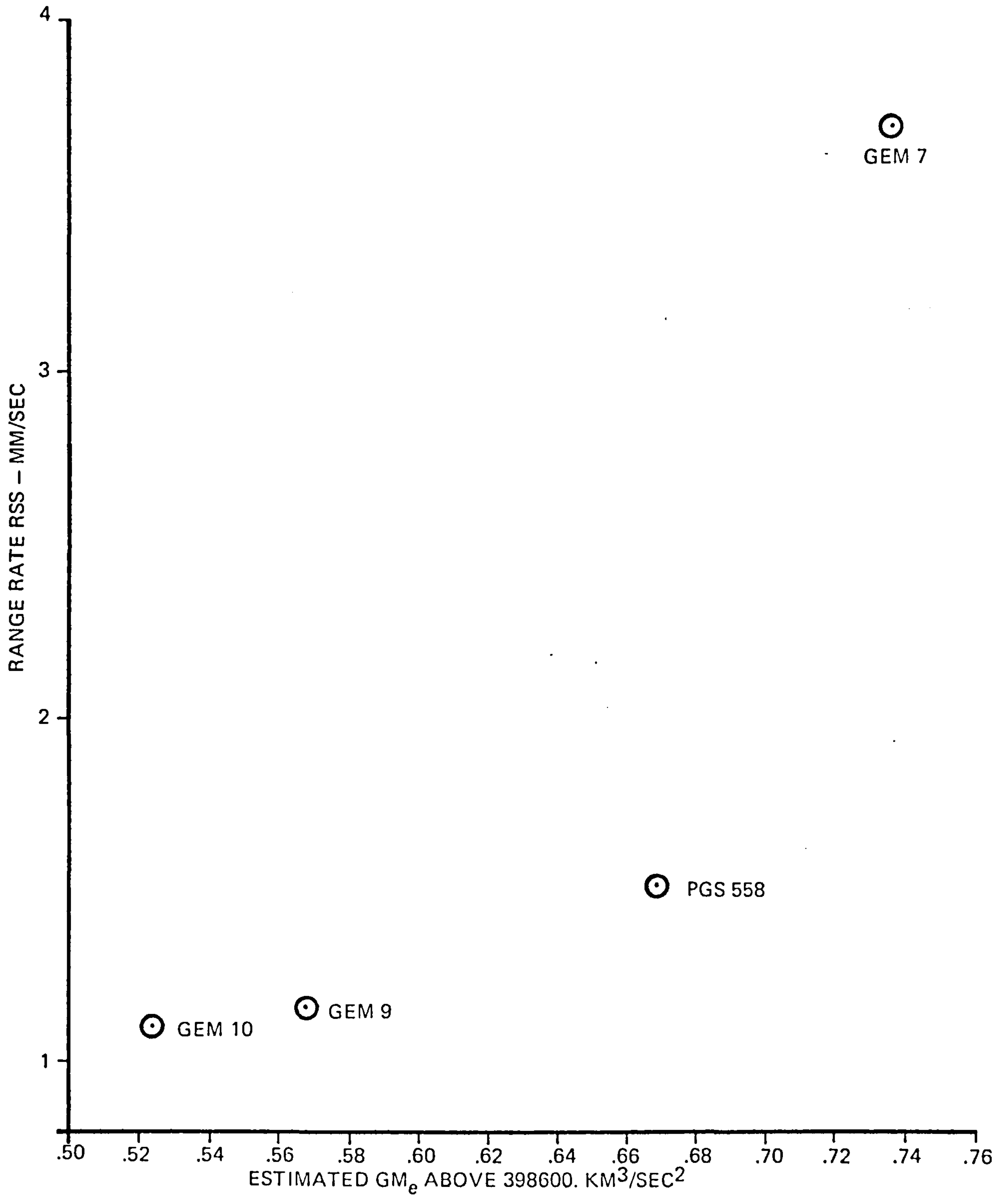


FIGURE 5. SSE RANGE RATE RSS FOR DIFFERENT GRAVITY MODELS IN 4 HALF DAY ARCS

for ATS-6 and propagation errors (tropospheric and ionospheric) for the C-band radar data. Although the geopotential errors are definitely correlated between all the models due to a common data set, the GEM 10 solution includes both GEOS-3 and surface gravity data that is not in GEM 7. From Table 5, the differences between the GEM 7 and GEM 10 results are 0.212 km^3/sec^2 for the 4 half day arc solutions and 0.135 km^3/sec^2 for the short arc solutions, for an average difference of 0.17 km^3/sec^2. On the basis of the rss fits shown in Figure 5, and assuming that goodness of fit has a one-to-one relation with accuracy, we deduce that the GEM 7 error is more than 3 times the GEM 10 error. Even assuming that the GEM 7 and GEM 10 errors have a correlation of 1.0, the expected value of the GEM 10 error is still $\frac{1}{\sqrt{2}}$ times the GEM 10 - GEM 7 difference, or 0.12 km^3/sec^2. Since the other errors are considered to have much smaller effects than this, we take 0.12 km^3/sec^2 to be the 1σ error level.

5.0 STATION POSITIONS

For the solutions quoted, all station coordinates were adjusted except for Rosman and the longitude of the Goddard laser (STALAS). Two station constraints were imposed: the two Wallops radars were constrained to move together and the Bermuda radar and laser were constrained to move together.

The recovered coordinates for the adopted set of half day arcs using GEM 10 are listed in Table 6. The baselines between the laser stations have been constrained by the 4 single pass laser arcs. These arcs were chosen on the basis of data coverage and geometry, and the use of more than 4 passes (some 19 or more are available for GEOS-3) would provide primarily redundancy. Estimated baselines between the laser stations are listed in Table 7. Based on comparisons with single pass solutions using a larger number of arcs (Dunn, et.al., to be published in JGR, 1978; C. Martin and Butler, 1977), the GEM 10 baselines are thought to be accurate to the 10-15 cm level.

The heights recovered are on the order of 20-40 cm lower than those in the GEM 10 [Lerch, et.al., 1977] solution. A somewhat larger difference might have been expected on the basis of the difference in GM (.12 km^3/sec^2). Based in part on comparisons with the other solutions whose GM values are listed in Table 5, a 1σ estimate of height error would be on the order of 50 cm.

TABLE 6. ESTIMATED STATION POSITIONS USING GEM 10 AND 4 HALF DAY ARCS OF SSE DATA

STATION NAME	STATION NUMBER	GEODETIC LATITUDE* DEG	MN	SECONDS	EAST LONGITUDE DEG	MN	SECONDS	HEIGHT* (METERS)
STALAS	7063	39	01	13.4065	283	10	19.7516**	18.28
BDALAS	7067	32	21	13.8176	295	20	37.9036	–22.94
GRTLAS	7068	21	27	37.8285	288	52	4.9952	–18.76
NWAL13	4860	37	51	37.0019	284	29	26.4003	–23.93
NWAL18	4840	37	50	28.8860	284	30	53.5421	–26.50
NBER05	4760	32	20	52.6390	295	20	47.3819	–15.29

* REFERENCE ELLIPSOID: a_e = 6378140 m, f = 1/298.255
SCALE BASED ON SPEED OF LIGHT OF 299792.458 km/sec.

** NOT ADJUSTED

TABLE 7. ESTIMATED BASELINES AND STATION HEIGHTS
USING DIFFERENT GRAVITY MODELS

MULTIARC OF
4/26, 4/27, 5/10 AND 5/12
HALF DAY ARCS

GRAVITY MODEL USED	BASELINES*			HEIGHTS		
	STA–BDA 1322700.m +	STA–GRT 2012700.m +	BDA–GRT 1364200.m +	STALAS (m)	GRTLAS (m)	BDALAS (m)
GEM7	41.92 m	24.25 m	64.53 m	17.85	–15.89	–22.44
PGS558	41.65	24.73	65.08	20.33	–16.54	–21.05
GEM9	41.82	24.57	65.08	18.67	–18.41	–22.66
GEM10	41.83	24.53	65.04	18.28	–18.76	–22.94

*SCALE BASED ON SPEED OF LIGHT OF 299792.458 m/sec.

6.0 CONCLUSIONS

Using tracking data involving two earth orbiting satellites is one of five methods which have been used for estimating GM during the past three years. All five methods give results within a 0.3 km^3/sec^2 band. The variety in the methods employed should be protection against the possibility that there is a common (overlooked) systematic error source affecting all the solutions. In fact, it may be possible to combine solutions and produce a more accurate GM value than any of the individual values.

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16. Abstract

Range rate tracking of GEOS-3 through the ATS-6 satellite has been used, along with ground tracking of GEOS-3, to estimate the geocentric gravitational constant. Using multiple half-day arcs, a GM of 398600.52 $\pm$ 0.12 km^3/sec^2 was estimated using the GEM 10 gravity model, based on a speed of light of 299792.458 km/sec. Tracking station coordinates were simultaneously adjusted, leaving geopotential model error as the dominant error source. Baselines between the adjusted NASA laser sites show better than 15 cm agreement with multiple short arc GEOS-3 solutions.

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