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Station Position Results Using Concentrated C-Band Tracking of GEOS-3

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SECTION 1.0

INTRODUCTION

During the past decade, satellite geodesy has progressed to the stage where achievable accuracies are frequently comparable to or better than those obtainable by more conventional terrestial surveying methods, including both rod and chain triangulation and geodimeter traverses. This progress has been due in part to the development of more accurate instrumentation (particularly lasers), but also to refinements in the model for the geopotential field. Great progress has already been made in the estimation of spherical harmonic representations of the geopotential field, using "conventional" ground tracking data alone. When the mass of altimeter data from GEOS-3 is optimally utilized, substantially more accurate models are expected.

Although satellite geodesy is perhaps most appropriate for tying together points on a global scale, the results should be consistent with the normal surveys on the various datums throughout the world. Transformation to local (generally continental) datums from center-of-mass systems derived using satellite techniques has been a common method of checking the accuracy of results. Historically, there have been two problems associated with this progress. First, the scale of the satellite results, and particularly the estimated station heights, has been largely imposed by the value of the geocentric gravitational constant which had to be supplied from non-satellite estimation processes - such as from launches of inter-planetary probes. At least until the last several years, the uncertainty in this constant has been on the order of 1 ppm and a significant source of error in estimation of the heights of satellite tracking sites relative to the earth's center-of-mass. The second problem, not unrelated to the first, is that comparisons of satellite derived coordinates with local survey coordinates have generally included a scale factor between the two systems, in addition to origin and orientation parameters. The result has been the utilization of enough parameters in the transformation that satisfactory agreement between local datum and satellite derived coordinates was achieved. In the satellite estimation process, the only parameter whose scale should be considered uncertain is GM_e. But, when one attempts to find a value of GM_e for which the satellite results and the local surveys will be consistent, the result is so low ($\sim 398600.0 km^3/sec^2$) that no one believes the result. A resolution of this paradox is now apparently at hand, and includes the acceptance of problems with some ground surveys.

Satellite derived positions are now approaching the accuracy of conventional surveys on all levels. For several years, Geoceiver derived coordinates with stated relative accuracies of 1 m in each coordinate have been claimed from the use of Navy navigation satellites. These positions have, however, also been subject to the scale uncertainty, with 5 m C.O.M. accuracy estimates.

In this paper, we consider the utilization of laser and C-Band tracking of GEOS-3 for the estimation of a set of global station positions, with the dominant set of tracking from the continental United States. This set of positions is based predominantly on one day arcs of GEOS-3 during a 10 day concentrated tracking period between February 23, 1976 and March 5, 1976. These arc lengths are sufficiently long that station latitudes could be estimated for all stations and longitudes could be estimated for all except one reference station. All station heights were estimated.

SECTION 2.0
SOLUTION TECHNIQUE

The data set utilized consisted of the following arcs:

7 1 day arcs of C-Band, laser, and S-Band data

18 single pass arcs of data from lasers at Goddard, Bermuda, Grand Turk, and Patrick AFB, Florida.

All passes included tracking by at least 3 lasers. On two passes, there was tracking by all 4 lasers.

All range data in the one day arcs was weighted with σ's of 1 m. All laser data was used, and the C-Band data was sampled at 1 data point per 6 seconds down to an elevation cutoff of 10°. Except for a few passes, a separate bias was estimated for each C-Band radar in each arc. This treatment was used because it is conveniently implemented in the GEODYN data reduction program (T. Martin, et.al., 1976). Day to day bias stability of a meter or more has been demonstrated for a number of C-Band radars (Krabill and C. Martin, 1978).

The objective in this weighting scheme was to obtain laser positions at the 4 calibration area sites with very accurate baselines, orientation, relative heights, and center-of-mass heights. The baseline, and most of the relative height information, was obtained from the heavily weighted single pass laser arcs. Since, however, the short arcs have practically no orientation or absolute height information, these are provided by the long arcs. The laser positions should thus be useful for the computation of both very precise short arcs, and for the estimation of center-of-mass orbits of one or more revolutions in length.

The gravity model used for the final station estimation solution was the GEM-9 model (Lerch, et.al., 1977). Several of the preliminary GEM-9 solutions were utilized in the data evaluation process prior to the availability of GEM-9.

Overall station heights are determined by the value of GM_e used in the solution. For lack of anything better, the value recovered with the GEM-9/10 geopotential models was used. This value, 398600.64 km^3/sec^2, is the same as that estimated from lunar laser ranging data (Williams, 1974) and is within approximately 0.1 km^3/sec^2 of other recent GM_e estimates. In the GEM-9/10 solutions, GM_e is determined primarily by LAGEOS tracking data.

SECTION 3.0
STATION POSITION RESULTS

The estimated set of geodetic coordinates are listed in Table 1. All coordinates are independently adjusted except for

1. The longitude of STALAS, which is constrained to the GSFC'73 value (Marsh, et.al., 1973).

2. The relative coordinates of

   a. The Bermuda laser and C-Band radar

   b. The two Wallops C-Band radars

   c. Stations 4742 and 4452 on the island of Kauai (Hawaii)

   Separations between these pairs of stations were constrained to the local survey values.

It will be noted that stations in close proximity (less than 4 miles) have been constrained to adjust together. This results in positions with a higher degree of internal consistency then would be the case with independent adjustments. It does, however, reduce the set of checks which can be made on the validity of the solution.

Table 1. Estimated C-Band and Laser Coordinates

Station Name	Number	Geodetic Latitude (Deg, Min, Sec)	Geodetic Longitude (Deg, Min, Sec)	Height (Meters)
		Geodetic Coordinates*		
STALAS	7063	39 1 13.3843	283 10 19.7510	14.96
BDILA1	7067	32 21 13.8003	295 20 37.8985	-26.53
NBER05	4760	32 20 52.6323	295 20 47.3765	-18.88
GRTLAS	7068	21 27 37.8189	288 52 4.9867	-22.10
RAMLAS	7069	28 13 40.6886	279 23 30.3059	-27.05
NWALI8	4840	37 50 28.8957	284 30 53.5420	-29.98
NWALI3	4860	37 51 37.0117	284 29 26.4000	-27.43
ETR313	4013	26 36 56.2052	281 39 7.7066	-21.20
ETRANT	4061	17 8 37.1790	298 12 26.8721	-5.07
ETRMRT	4082	28 25 28.9359	279 20 7.9908	-23.20
WSG219	4150	38 58 43.9386	249 53 20.1810	1296.11
WSM350	4160	32 21 24.3204	253 37 14.9930	1194.12
WTRPPQ	4260	37 29 52.1543	237 30 0.9544	12.64
WTRVAN	4280	34 39 57.0649	239 25 6.8838	80.84
WTRKPT	4282	21 34 19.7500	201 44 0.1158	298.58
PMRPM4	4446	34 7 22.4154	240 50 42.9324	-22.56
PMRMR3	4452	22 7 57.9513	200 16 25.5264	503.85
NELHAR	4610	39 18 30.5537	244 54 48.0277	2800.74
WTRKAU	4742	22 7 24.7030	200 20 3.7350	1168.96
KWAJM4	4959	8 43 17.6057	167 43 36.0208	4.43
KALCOR	4966	9 23 55.2274	167 28 55.9490	59.84
FRGM10	4960	49 8 42.4363	12 52 39.5260	654.55
WSM398	4198	32 25 21.1072	253 36 35.0614	1183.94

*a_e = 6378145 m, 1/f = 298.255

SECTION 4.0
COMPARISONS ON THE NAD

Several comparisons were made between the estimated set of positions and local coordinates on the NAD 27. The first of those, shown in Table 2, compares the baselines between stations based on NAD coordinates, and based on the estimated set of center-of-mass coordinates given in Table 1. Only continental U.S. stations are listed. In addition, several continental U.S. stations have been omitted. The Merritt Island C-Band radar was not used because of its proximity to the Patrick laser, although the two stations were independently estimated. Similarly, only one of the White Sands main base stations was used. And the Ely, Nevada C-Band radar (Station 4610) was not used because of rather drastic revision of its NAD coordinates within the last several years, resulting in some question as to their validity.

Based on the baseline comparisons in Table 2, it is evident that at least one of the station location sets is considerably in error. All but two of the estimated baselines are larger than the NAD baselines, and a scale factor of 1.4 ppm is required to obtain the best fit transformation between the two datums. However, certain of the differences are known to be due to errors in NAD coordinates. The laser baselines will be discussed below. However, a geoidimeter traverse (Klosko and Krabill, 1974) comparison is available for the Merritt Island to Wallops baseline, with the results shown in Table 3. The precise traverse and C-Band estimated cords are in virtually perfect agreement. Such close agreement is no doubt accidental, but it does indicate that the East Coast distance discrepancies in Table 2 are largely due to NAD survey error. Also shown in Table 3 are comparisons of

Table 2. Comparison of Intersite Distances from Estimated Station Positions with Intersite Distances from NAD Positions

Station to Station		NAD Baseline	Estimated Baseline	Difference	PPM
7063	7069	1244983.26 m	1244990.70 m	-7.45 m	-6.0
7063	4860	172715.34 m	172716.71 m	-1.37 m	-7.9
7063	4150	2843155.00 m	2843151.08 m	3.92 m	1.4
7063	4160	2740350.23 m	2740351.69 m	-1.47 m	-0.5
7063	4260	3895446.41 m	3895450.67 m	-4.26 m	-1.1
7063	4280	3834730.59 m	3834730.72 m	-0.14 m	-0.0
7063	4446	3737515.50 m	3737517.58 m	-2.09 m	-0.6
7069	4860	1167354.07 m	1167362.01 m	-7.94 m	-6.8
7069	4150	2943072.82 m	2943077.30 m	-4.48 m	-1.5
7069	4160	2498959.17 m	2498964.23 m	-5.06 m	-2.0
7069	4260	3952385.33 m	3952397.31 m	-11.98 m	-3.0
7069	4280	3783158.07 m	3783165.34 m	-7.27 m	-1.9
7069	4446	3658200.60 m	3658209.61 m	-9.01 m	-2.5
4860	4150	2978706.66 m	2978705.31 m	1.35 m	0.5
4860	4160	2842196.83 m	2842200.66 m	-3.84 m	-1.3
4860	4260	4030166.42 m	4030173.41 m	-6.99 m	-1.7
4860	4280	3960249.43 m	3960252.32 m	-2.90 m	-0.7
4860	4446	3860379.48 m	3860384.39 m	-4.91 m	-1.3
4150	4160	808115.11 m	808120.21 m	-5.10 m	-6.3
4150	4260	1094859.28 m	1094866.31 m	-7.03 m	-6.4

Table 2. (Cont.)

Station to Station		NAD Test Set Baseline	Estimated Baseline	Difference	PPM
4150	4280	1047618.54 m	1047621.31 m	-2.77 m	-2.6
4150	4446	970994.11 m	970997.28 m	-3.17 m	-3.3
4160	4260	1572991.45 m	1572999.21 m	-7.76 m	-4.9
4160	4280	1340602.24 m	1340604.97 m	-2.73 m	-2.0
4160	4446	1204159.84 m	1204162.87 m	-3.03 m	-2.5
4260	4280	358537.45 m	358539.29 m	-1.84 m	-5.1
4260	4446	481073.77 m	481076.74 m	-2.96 m	-6.2
4280	4446	144352.08 m	144352.33 m	-0.25 m	-1.7

Table 3. Comparison of Estimated Chord Distances with Local Surveys and Precise Traverse

Chord	Survey		Estimated Distance	Difference (Estimate-Survey)
	Source	Distance		
Merritt Island to Patrick AFB (Sta 4082 to Sta 7069)	NAD Survey	22550.67 m	22550.12 m	-.55 m
Merritt Island to Wallops Island (Sta 4082 to Sta 4860)	Precise Traverse	1,149,612.0 m	1,149,612.05 m	.05 m
WSM398 to WSM350 (Sta 4198 to Sta 4160)	NAD Survey	7369.84 m	7369.62 m	-.22 m

the Merritt Island - Patrick and Radar 398 - Radar 350 (at White Sands) chords as computed from the NAD survey and from the center-of-mass positions in Table 1. The agreements to within 55 cm at Patrick and 22 cm at White Sands are quite good, considering that these baslines were estimated without having any passes in the solution with simultaneous track on both ends of either baseline.

The baseline distances in Table 2 between the East Coast stations and the White Sands stations (4150 and 4160) are conceivably within the accuracy of the recovered solution. The discrepancy in the station 4150 - station 4160 separation, however, cannot be explained. The estimated baseline should be accurate to at least the 1-2 m level. If so, this points to a problem with either the surveys or some transcription thereof.

The West Coast stations have posed a somewhat difficult problem. The only really satisfactory tie among the estimated positions is the Vandenberg - Pt. Mugu 20 cm agreement. The others are worse than expected, both between themselves and with the East Coast stations. As shown in Table 4, the survey agreement is very good in relative latitude, and in the Pt. Mugu - Vandenberg relative longitude. The Pillar Pt. longitude disagreement is almost 4 m and has not been explained. The relative heights are also in disagreement at the 4 m level, considerably higher than the expected error in the station adjustment results. It may be noted that the "NAD" positions used for the comparisons are from the "Vandenberg adjustment", completed in 1971 (Hieb, 1975), which included a geodimeter traverse along the West Coast. Agreement with the unadjusted positions would have been considerably worse.

Table 4. Differences Between Recovered California C-Band Positions and NAD Positions Transformed to WGS 72 System* (Recovered - NAD)

Station	$\Delta\phi$	$\Delta\lambda$	ΔH
4446	0".1461	0".6492	2.40 m
4280	0".1505	0".6461	4.96 m
4260	0".1351	0".4815	6.72 m

*Comparisons include the difference in ellipsoidal semi-major axes (6378145 m vs. 6378135 m) but ignore the differences in flattening (1/298.255 vs. 1/298.26).

In addition to possible survey problems and conceivable problems in the recovery, the distortion between the NAD and a center-of-mass system makes station comparisons in California somewhat uncertain. Table 5 shows the computed shifts between the estimated and NAD coordinates for the C-Band sites, and comparable shifts for Geoceiver sites in the general area (W. Strange, unpublished). These comparisons show a reasonably smooth and consistent latitude shift, and an increasingly negative longitude shift up the California coast. The longitude shifts at Pillar Pt. relative to Pt. Mugu are approximately 2 m larger for the estimated positions than for the Geoceiver positions. However, the Pillar Pt. longitude shift relative to Vandenberg is about 4 m less for the estimated positions than the Geoceiver positions. The height shifts agree in that Vandenberg should be shifted down the most. But the recovered heights indicate that the shifts for Pt. Mugu and Pillar Pt. should be approximately the same, whereas the Geoceiver heights indicate that Pt. Mugu should be shifted down about 4 m more than Pillar Pt. This would make the height discrepancies in Table 4 even worse.

Table 5. Shifts Between Center-of-Mass and NAD Coordinates for California C-Band Sites

	Estimated Positions		Nearby Geoceiver Positions		
Station	Coordinates	Diff. from NAD	Station	Coordinates	Diff. from NAD
Pt. Mugu (4446)	ϕ=34°7'22".4154 λ=240°50'42".9324 H=-22.56 m	0".0217 -3".396 -4.81 m	51141	ϕ=33°44'39".296 λ=241°35'44".705 H=66.13 m	-0".073 -4".14 -13.97 m
Vandenberg (4280)	ϕ=34°39'57".0649 λ=239°25'6".8838 H=80.839 m	-0".0749 -3".5454 -9.29 m	51188	ϕ=34°12'16".874 λ=241°49'43".791 H=432.62 m	-0".083 -4".06 -15.08 m
			51070	ϕ=34°22'44".388 λ=242°19'5".141 H=2154.19 m	-0".053 -4".131 -18.01 m
			51189	ϕ=34°45'59".647 λ=242°10'49".055 H=927.18 m	-0".169 -4".023 -15.62 m
Pillar Pt. (4260)	ϕ=37°29'52".1543 λ=237°30'0".9544 H=12.644 m	-0".4085 -4".0265 -5.18 m	51186	ϕ=37°48'21".623 λ=237°32'45".187 H=-38.63 m	-0".348 -4".677 -8.93 m

SECTION 5.0
LASER STATIONS

Some comparisons are available for validating the relative positions of the laser sites. Dunn, et.al. (1978), have processed basically the same set of single pass laser arcs for GEOS-3 that were used in our solution, with the objective of obtaining accurate baselines and relative heights. The baselines and relative heights from the Table 1 solution are listed in Table 6, and the comparisons with the pure short arc solution is shown in Table 7. The agreement in baselines for the NASA lasers is well within the uncertainty of both solutions. Although a figure of 20 cm has been quoted, the 1σ uncertainty is probably at the 10 cm level. Based on the sensitivity of the solution to changes in arc number, gravity model, etc., the relative height uncertainty is approximately 50 cm.

The relative Patrick position is less well determined than the other stations, largely because only a few (6) arcs of data were available for use in the solution. For this station, we estimate the baseline uncertainty to be approximately 50 cm, and the 1σ relative height uncertainty to be at about the same level.

Table 6. Estimates of Baselines and Relative Heights Between Laser Sites

Stations	Baseline	Relative Height
Goddard - Bermuda	1,322,742.03 m	41.49 m
Goddard - Grand Turk	2,012,724.63 m	37.06 m
Bermuda - Grand Turk	1,364,265.21 m	-4.43 m
Goddard - Patrick	1,244,990.70 m	42.01 m
Patrick - Bermuda	1,595,082.72 m	-0.52 m
Patrick - Grand Turk	1,213,393.34 m	-4.95 m

Table 7. Differences Between Estimated Baslines and Relative Heights and Short Arcs Results (Dunn, et.al.)

Stations	Baseline Difference	Relative Height Differences
Goddard - Bermuda	-9 cm	2 cm
Goddard - Grand Turk	-8 cm	-43 cm
Bermuda - Grand Turk	-4 cm	-46 cm
Goddard - Patrick	-40 cm	-76 cm
Patrick - Bermuda	-81 cm	78 cm
Patrick - Grand Turk	-50 cm	32 cm

SECTION 6.0
C-BAND STATION ACCURACY

Because of the preponderance of simultaneous and near simultaneous track, the positions for Atlantic and continental U.S. stations are considerably more accurately determined than are those stations without simultaneous tracking by continental stations. This is largely due to the minimization of orbit area in regions with large amounts of tracking and, by the same token, maximization of errors in regions of little tracking. Based on the sensitivity of the solution to the use of different gravity models, different methods of handling biases, different sets of data, and comparisons with other solutions, we estimate the accuracy of the adjusted stations to be 2 m for continental U.S. and Atlantic C-Band sites, 5 m for the Hawaii sites, and 10 m for the German and Kwajalein radars. The laser relative positions are more accurate as discussed above.

It will be noted that the solution has included a latitude adjustment for all stations, and that the comparison of the recovered latitudes with WGS 72 latitudes has shown approximately a 5 m difference. The GEM-10 (Lerch, et.al., 1977) latitudes for the NASA lasers, however, show an average difference of less than 1.4 m from the recovered latitudes. Accordingly, the uncertainty figures above should be interpreted as including latitude as well as heights. Longitude uncertainty is relative to STALAS.

SECTION 7.0
CONCLUSIONS

Using one day arcs of concentrated C-Band tracking of GEOS-3, station positions have been estimated which are believed to be accurate at the approximately 2 m level and considerably more accurate than most of the NAD surveys. The technique is capable of estimating all coordinates of all stations with the exception of a single reference longitude.

The primary error source is geopotential model error and thus, as more accurate models are developed, accuracies (even from re-reduction of existing data) can be improved. C-Band results would certainly provide a good check on the results from the re-adjustment of the North American Datum.