The Development of NASA Gravity Models and their Dependence on SLR

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Abstract

Satellite laser ranging data has been an integral part of Earth gravity model development since the days of the earliest GEM (Goddard Earth Models) in the 1970's. SLR data have contributed both directly in the form of tracking of the multiplicity of satellites that have made up these solutions, and indirectly in the definition and stabilization of the terrestrial reference frame. The evolution of the SLR technology required improvements in modeling and yielded ever-refined models. In this paper, we will review the contribution of SLR data, starting with the first generation laser systems in the early 1970's. The launch of LAGEOS-1 and its contribution will be highlighted. The intensive effort to develop an improved geopotential model prior to the launch of TOPEX/Poseidon will be reviewed. Finally we will provide some perspectives on the use of SLR data in current geopotential solutions with CHAMP data.

Satellite laser ranging (SLR) data have been used in the development of satellite-derived geopotential models since the early 1970's. SLR systems provide an unambiguous measurement of range, with well-calibrated system biases, which over the last 10 to 15 years are rarely present at a level exceeding 1 cm. The SLR data formed the core of state-of-the-art gravity models developed at the Goddard Space Flight Center starting with GEM-5 including GEM-9, GEM-L2, GEM-T1, JGM-2, JGM-3 and EGM-96. The international laser network tracks a host of retroflector-equipped satellites having different orbit characteristics providing a sound distribution of orbits for geopotential recovery. In addition, the SLR data also contribute indirectly to gravity model development through their use in defining tracking station positions, earth orientation, and the reference frame and its scale. As the SLR system evolved and increasingly more precise data became available, SLR data forced users to modify and improve both measurement and force modeling to become commensurate with the accuracy of the data.

Today, the role SLR data played in the development of geopotential models is largely taken for granted, and we increasingly debate their role in an era of missions such as CHAMP and GRACE which use Global Positioning System (GPS) technologies for their prime orbit determination (more about that later in the paper). The role of SLR has always been assessed within the mix of tracking technologies in use. For example, it is worth noting that prior to the launch of LAGEOS in the mid-1970's and the development of the new generation laser systems, the available SLR data were not as strong a contributor as optical tracking of satellites. According to *Lerch et al.* [1985a], "… In fact, prior to LAGEOS, solutions derived from camera data showed better results when comparisons were made with surface gravity than solutions from laser data. In particular, significantly lower correlations between coefficients were seen in the optical solutions…". SLR systems evolved to become the mainstay for gravity modeling efforts by the late 1970's, and we are confident that SLR will continue playing an important role complementing GPS capabilities (for example, see Luthcke et al., this issue) in the future.

In order to appreciate how SLR data came to make a significant contribution, it is instructive to review the state of the art in 1977, with the GEM-9 solution [*Lerch et al.*, 1977]. GEM-9 was a solution to degree and order 20 in spherical harmonics. GEM-9 incorporated data from 31 satellites, including SLR tracking of GEOS-3, LAGEOS-1, and Starlette. The bulk of the data however, came from optical tracking of satellites such as the Baker-Nunn cameras operated by the Smithsonian Astrophysical Observatory (SAO). In addition, various electronic tracking types were used, including interferometers and TRANET Doppler systems. S-Band radar data acquired on Landsat-1 were also used. The accuracy of the various data types is summarized in Table 1. Although the optical data had an accuracy of only 2 arcsec, the tracking networks were more globally distributed than that of SLR stations at the time and data from many more optically tracked satellites were available. For example, 27 different stations supplied the Baker-Nunn optical data of 24 satellites. In contrast, the newer generation lasers (accuracy of 5-40 cm) operated by GSFC, the SAO and France tracked four satellites from a total of ten stations. Thus, since the optical satellites supplied data at a breadth of inclinations from a more global network, it is understandable that they were a more valuable contributor to the GEM-9 solution.

Table 1. Measurement Systems and Their Accuracy in GEM-9.

System	**Type of Measurement**	**Accuracy**
Cameras	Directions (□, □)	10-30 m
Interferometers	Directions (direction cosines)	100-200 m
Radar	Range/Range-rate	3-10 m
Doppler	Range-rate	3-7 m
Laser	Range	5 cm-1 m

Subsequent to GEM-9, over the next twenty years, three satellites dominated geopotential model development: LAGEOS-1, Starlette, and TOPEX/Poseidon. The orbit and mission characteristics of LAGEOS-1 are well known and are summarized in Table 2. The objective was to launch a test mass into Earth orbit that could serve as a passive target for tracking by the laser tracking network. At the mean altitude of 5900 km, the expected lifetime was several million years, warranting a plaque embedded in its core designed by the late Carl Sagan.

Table 2. LAGEOS (Laser Geodynamics Satellite).

Characteristics	Mission objectives ¶
Spacecraft: spherical, 60 cm diameter; 426 retroreflectors; mass 409.965 kg. • Semimajor axis: 12265 km. • Inclination: 109.8°. • Eccentricity: 0.004	Determine • relative tectonic plate motion to 1 cm/yr (averaged over four years) • vertical motions to 2 cm/yr (averaged over four years). • station locations to within 10 cm.

¶ From the Project Plan for LAGEOS Earth dynamics, August 1975.

At the time of the LAGEOS launch, lasers with a precision of 40 cm (e.g., the lasers operated by the SAO) provided the bulk of the tracking support. The full potential of the SLR data and the LAGEOS-1 satellite were realized only with the deployment of the 'new' generation lasers where upgrades like pulse-choppers delivered data at the precision of 2-5 cm [*Smith et al., 1985; Lerch et al*., 1985b]. *Lerch et al.* [1985b] and *Reigber et al.* [1985] included significant quantities of the post-1979 LAGEOS-1 data in the geopotential solutions, GEM-L2, and GRIM3-L1. Like GEM-9, GEM-L2 included coefficients to 20x20 as well as selected other harmonics to 30x30. GRIM3-L1 was a solution to 36x36 that also incorporated mean-gravity anomalies derived from SEASAT.

The size of the gravitational perturbations on near-Earth orbits attenuate with altitude [*Kaula*, 1966]. The LAGEOS Mission was designed to leverage this fact, and by orbiting at nearly one Earth radius, the tracking data acquired on this satellite effectively isolated the contributions of the lowest degree terms in the gravity model. These data complemented the data acquired by strong satellites such as Starlette, which orbited at altitudes of 800-1100 km. The LAGEOS tracking passes were longer and a larger fraction of the orbit was observed. Figure 1 illustrates the typical SLR tracking coverage available for a low altitude satellite (Starlette) and for LAGEOS. By virtue of all these factors, the quality of the low-degree harmonics was significantly improved in geopotential models that incorporated LAGEOS-1 data. As a result, *Lerch et al.* [1985b] report that fits on 15-day arcs from 1979 through 1980 improved from 12 to 39 cm with GEM-9 to 6 to 18 cm with GEM-L2. While GEM-L2 was a milestone in geopotential model development, the LAGEOS data remained vital in subsequent solutions. The LAGEOS SLR strongly and uniquely sense the low degree field, and allow the higher degree harmonics to which lower orbiting satellites are more sensitive to be decorrelated.

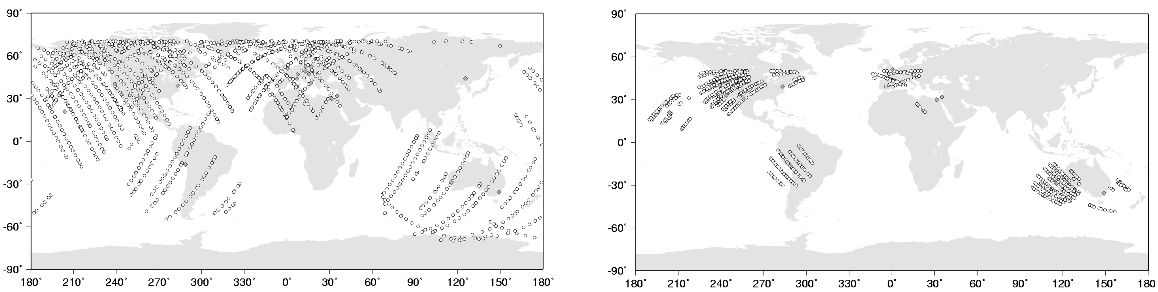

Figure 1. SLR Tracking of LAGEOS-1 (left) and Starlette (right) (10-day arcs, Epoch: 930707).

Following LAGEOS-1 and Starlette, in the past twenty years, the most important mission for satellite geodesy was TOPEX/Poseidon. TOPEX was conceived as a successor to the SEASAT mission and its objective was to map the ocean topography synoptically every ten days [*Stewart et al*., 1986; *Fu et al.*, 1994]. In order to use effectively the high-quality altimeter data (1-2 cm precision), the orbit of TOPEX had to be determined as accurately as possible. It was recognized that the largest contributor to the altimeter error budget was the gravity model error. For example, even with GEM-L2, the predicted radial orbit error due to the gravity model on the TOPEX orbit was 65 cm, far in excess of the initial mission goals of a radial orbit error of only 13 cm [*Tapley et al.,* 1994; *Nerem et al.,* 1994]. Thus, NASA and the TOPEX/Poseidon Project funded a long-lead project to develop an improved geopotential model in advance of the TOPEX Mission, starting in 1985.

The first step in the TOPEX gravity model effort was the development of the GEM-T1 model. The data selection criteria for satellites to be included in GEM-T1 were: (1) quality, quantity and global distribution of data; (2) uniqueness of perturbations on the satellite; (3) similarity of the orbit anticipated to that of TOPEX; (4) distribution of data over the satellite's apsidal period; (5) the sensitivity of the satellite's orbit to weaknesses in existing gravity models [*Marsh and Born*, 1985]. Of the sixty satellites that could provide geodetic quality data at the start of the TOPEX gravity effort, 17 were selected for inclusion in the first TOPEX gravity model, GEM-T1 [*Marsh et al.,* 1987]. Of these ten were satellites tracked by SLR, and included 'new' generation (1978 or later) data from LAGEOS-1, Starlette, BE-C and Seasat (see Table 3). These 17 satellites formed the core of all subsequent GSFC models from GEM-T1 through EGM96. SLR data provided the bulk of the data for the GEM-T1 solution that was complete to 36x36.

Table 3. Satellite data included in GEM-T1.

Satellites	Data Type	No. of Obs.
LAGEOS-1, Starlette, Geos-1, Geos-2, Geos-3, BE-C, Seasat, D1-C, D1-D, Peole	SLR	444,408
Seasat, Oscar-14	Doppler	201,140
Geos-1, Geos-2, Anna, Telstar, BE-C, BE-B, Courier 1B, Vanguard-2RB, Vanguard-2, D1-C, D1-D, Peole	Camera	153,140

Additional SLR data were included in GEM-T2, the reiteration and successor model of GEM-T1 [*Marsh et al.,* 1990]. In addition to newer LAGEOS-1 and Starlette data, new generation SLR data (1980) were added from GEOS-1, and GEOS-3. SLR tracking of Ajisai, launched by Japan in 1986, was also incorporated into GEM-T2. Ajisai is located in a high, 1500 km orbit, at an altitude similar to that of TOPEX/Poseidon, albeit at a different inclination. GEM-T2 also added additional Doppler data and optical data, as well as bringing the total number of satellites to 31 and solved for select resonance orders beyond degree 36 through degree 50.

In addition to the static or mean geopotential, gravity solutions must also account for the changes in the tidally induced mass deformations in the Earth's potential due to tides. The Starlette satellite, in particular, was launched with the intent of contributing to our knowledge of the solid Earth and ocean tides [*CNES,* 1975]. Over the years, various analyses assessed the use of satellite data for determination of ocean tidal parameters (e.g., *Lambeck et al.,* 1974; *Marsh and Williamson*, 1978; *Cazenave and Dailet*, 1981). However the GEM-9 and GEM-L2 solutions did not model the ocean tides and did not attempt any solutions for ocean tidal parameters. Nonetheless, the simultaneous estimation of both the coefficients and the static geopotential is essential if only to obtain the best solution for the static geopotential. For example, the effect of ocean tides on a five-day Starlette orbit has an RMS effect of at least 43 cm [*Williamson and Marsh*, 1985], well within the sensitivity of the new generation (post-1978/79) SLR data. Thus the GEM-T1 through GEM-T3 solutions directly modeled 32 tide lines (600 coefficients) and estimated resonant coefficients in the long period (Mm, Mf, Sa, Ssa), diurnal (K1, O1, P1), and semidiurnal (K2, M2, S2, N2 T2) bands. The EGM96 tidal modeling and estimation was expanded over that done for the GEM-T1/T2/T3 series (see *Lemoine et al.*, 1998, section 6.4.8 for a detailed discussion). The ocean tide modeling is a very specific example of how the precision of the SLR data required steady improvements in modeling capability. The evolution of the parameterization in the GEM models is summarized in Table 4. The precision of the SLR data required improvements in all aspects of measurement and force modeling, and in that respect significantly advanced space geodesy.

The gravity model performance on TOPEX/Poseidon provides one index that illustrates the improvement in the geopotential modeling engendered directly, and indirectly by SLR through the 1980's and the early 1990's. The radial orbit error due to the geopotential is given in Table 5 for the full suite of the GEM and JGM models. With GEM-L2, the radial orbit error due to the geopotential was 65 cm, whereas with the initial tuned TOPEX model, JGM-2, the predicted radial orbit error was 2.2 cm. The TOPEX radial orbit error due to the geopotential was further reduced to 0.9 cm with JGM-3, due to the addition of the GPS tracking data of TOPEX/Poseidon [*Tapley et al*., 1996].

Table 4. Parameterization of GEM Models.

Solution	Field	Ref. Sys/ Nutation	Solid Tides	Ocean Tides	CTRS	Drag	Most Recent SLR data
GEM-9	20x20	1950/ Wollard. No relativity	None	None	CIO	Jacchia 1971 w. 24 hr Kp	1976
GEM-L2	20x20	"	(1)	32 lines (600 coef.)	CIO	Jacchia 1971 w. 24 hr Kp	1981
GEM-T1	36x36	J2000/ Wahr. No relativity	(2)	32 lines (600 coef.)	"zero-mean"	Jacchia 1971 w 24 hr Kp	1984
GEM-T2	36x36 +	"	(2)	32 lines (600 coef.)	"zero-mean"	+DTM w. 3hr Kp	1987
GEM-T3	50x50	"	(2)	"	"zero-mean"	+DTM w. 3hr Kp	1989
JGM-1	70x70	J2000/ Wahr, w. relativity	(2)	96 lines (6000+ coef.)	IERS w. dynamic polar motion	+ MSIS w. 3hr Kp	1991
EGM96	70x70 ¶	"	(3)	(4)	"	"	1995

(1) $k_2 = 0.29$; $e_2 = 2.018°$; $h_2 = 0.60$; $l_2 = 0.075$.
(2) $k_2 = 0.30$; $e_2 = 0°$; $h_2 = 0.609$; $l_2 = 0.0852$, frequency dependence.
(3) $k_2 = 0.30$; $e_2 = 0°$; $h_2 = 0.609$; $l_2 = 0.0852$, frequency dependence assuming 421 FCN period
(4) 35,000+ terms
¶ The EGM96 solution has two parts: a 70x70 portion using satellite tracking data, direct radar altimetry and surface gravity, and a high degree portion based on surface gravity data and altimeter-derived anomalies through degree 360 (see *Lemoine et al*., 1998, for more details.)

Table 5. Gravity model performance on TOPEX/Poseidon.

Model	Radial Orbit Error (cm)
GEM-L2 (1982)	65.4
GEM-T1 (1987)	25.0
GEM-T2 (1990)	10.2
GEM-T3 (1991)	6.8
JGM-1 (1992)	3.4
JGM-2 (1993)	2.2
JGM-3 (1995)	0.9

We summarize the data content of the Goddard gravity solutions by data type in Figure 2. In strictly numerical terms, SLR data dominate the geopotential solutions from GEM-L2 through JGM-1. The continuous or near-continuous tracking provided by DORIS, GPS, and TDRSS begin to make their impact in the 1990's. The DORIS data in JGM-1, JGM-2 and EGM96 come from two satellites: SPOT-2 and TOPEX/Poseidon. The large quantity of DORIS data in EGM96 is due to the inclusion of two years of direct TOPEX altimetry, which required the inclusion of the SLR and DORIS data over the 1993-1994 time span. Even in EGM96, the SLR data still supply data that form the core of the solution and that define the reference frame of the solution. The SLR data from Stella aid in the determination of the zonals and resonance terms that affect the sun-synchronous SPOT-2 and ERS orbits. The SLR data supply the temporal coverage necessary to estimate the tidal resonance terms to which various satellite orbits are sensitive.

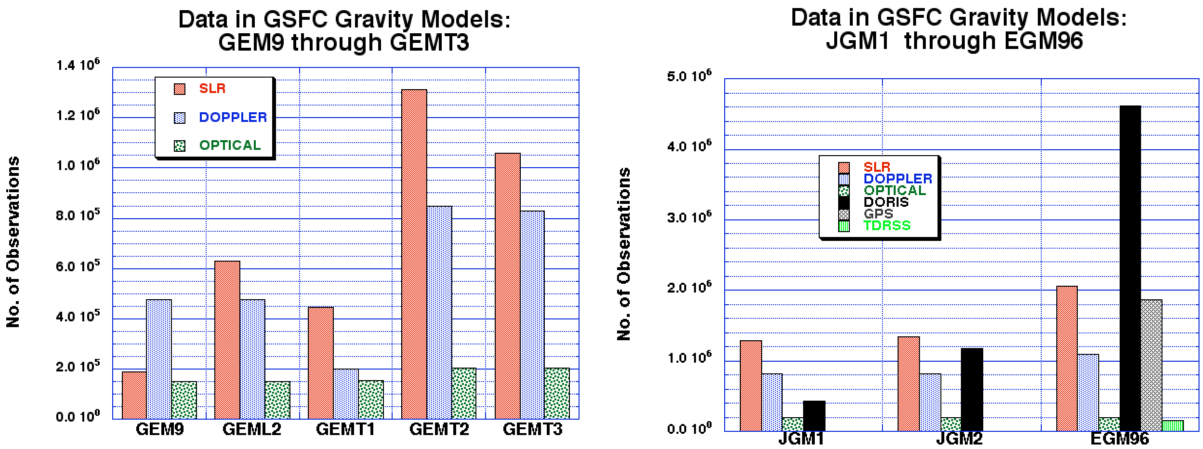

Figure 2. Data Content in GSFC Gravity Models: GEM-9 through EGM96.

SLR data have formed the core of geopotential models developed at the Goddard Space Flight Center for over twenty years. The data types used in the past and likely to be used in the future are shown in Figure 3. Even with the precision GPS and accelerometry data provided by the CHAMP satellite, the supplementary tracking supplied by other tracking types (GPS, SLR, DORIS) is necessary to fully define the resonance and zonal terms to which different satellite orbits are sensitive [*Reiber et al*., 2002; *Lemoine et al*., 2003]. This is true not withstanding the ability of the CHAMP data to improve dramatically the high degree modeling of the geopotential. In an era of GRACE and GOCE, the SLR data will at a minimum be required to help define the reference frame in which these satellites analyze data. The SLR data will remain essential to validate the orbit quality and perform independent checks on the time variations in the long-wavelength field.

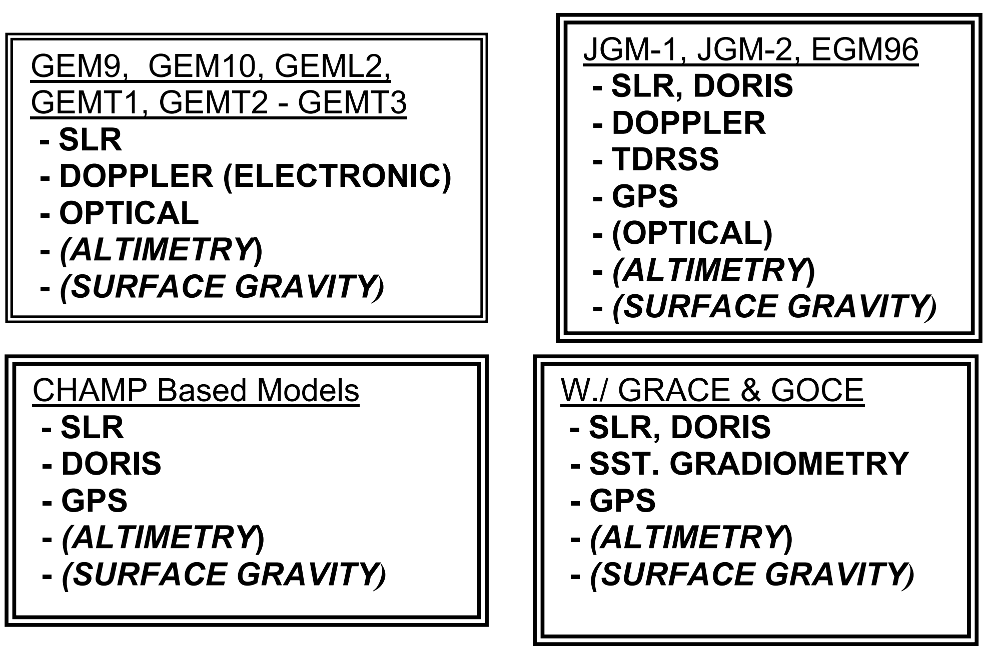

Figure 3. Data used in Geopotential Modeling.

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