

SLR CONTRIBUTIONS TO DETERMINING THE GRAVITATIONAL FIELD AND ITS VARIATIONS

Steve Klosko
Raytheon ITSS
Greenbelt, MD 20770

Satellite Laser Ranging (SLR) to near-Earth satellites has revolutionized our understanding of the gravitational field and its temporal variations at its broadest scale. SLR has allowed a large number of the challenges for satellite geodesy, outlined in the Williamstown Report (*Kaula, 1970*) to be achieved. This includes the most accurate determination of the Earth's gravitational constant times its mass, GM, providing the most important data set for the recovery of low degree and order gravity harmonics, and providing highly accurate data for testing orbit models. This paper will provide an overview of the utilization for SLR ranging data in numerous investigative settings. There have been collateral gains seen in other disciplines fostered by the advances delivered through SLR. These include improved altimeter mapping of ocean circulation, improvements in non-SLR orbit applications, and geophysical modeling. As an example of these applications, a new approach will be discussed to obtain an inverse solution providing constraints on geophysical models describing post-glacial rebound and ice sheet mass balances. Preliminary results from a multiple satellite (Lageos-1, Lageos-2, Starlette, Stella, and Ajisai) obtained by our GSFC team and *Cheng et al, (1997)* will be combined with observed global sea level rise, and the secular polar motion rates to provide the observations for this inversion.

1. Introduction

Satellite Laser Ranging provides the most accurate and least ambiguous of all measurements used to track near-Earth satellites. By operating at optical wavelengths, the corrections needed for refractive delay modeling have been accurately known to the sub-cm level since the 1970s. The orbital constellation and characteristics of satellites useful for geodetic purposes carrying laser retroreflectors continues to expand. By tracking old, long abandoned satellites, (like the recent campaigns on the French D1-C and D1-D, and USA GEOS-3 satellites to improve the geopotential models), the passive tracking offered by SLR has been shown to be viable for at least decades if not centuries or longer. SLR tracking has also provided the means to accurately position ERS-1 and GFO when problems occurred with baseline, radiometric systems. Nevertheless, while having all of these strengths, SLR technology cannot deliver everything required to monitor geopotential changes in the Earth system, and GPS missions scheduled for launch in the coming few years will be used to significantly advance our current state-of-the-art. This paper will attempt to describe the contribution of SLR and provide some description of its limitations.

2. The Historic Role of SLR in Geopotential Modeling

The tracking technologies supplying data to contemporary gravitational modeling solutions virtually encompass all of the tracking system used since the start of the space program. The reason is that there has never been a dedicated geopotential mission, and the gravity field has to be inferred from the orbital behavior of a large number of satellites with different orbital characteristics. For example, EGM96, the recently released joint gravity modeling effort of Goddard Space Flight Center (GSFC), National Imagery and Mapping Agency (NIMA), and The Ohio State University, contains data from 40 satellites encompassing a myriad of tracking technologies described in Table 1. These data have varying strengths and weaknesses, which are briefly reviewed in this table.

Table 1. A Review of the Tracking Data Types Utilized in JGM and EGM96 Geopotential Solutions

Technology	Configuration: Observable: Types	Theoretical Precision	Typical Orbit Fit	Strengths	Weakness	Duration of Use
Camera: Baker-Nunn MOTS SPEOPT	satellite image against stars: right ascension and declination: passive and active (i.e. spaceborne flashing lamp) data types	1-2 arc sec (10-20m)	1-2 arc sec	first precision tracking systems	atmospheric shimmer: star catalogue errors: for passive data, tracking limited to satellite “dawn/dusk” geometry	1960- 1974
Satellite Laser Ranging	two-way range: our utilization restricted to satellites carrying retroreflectors	0.5 cm	2 cm (Lagoes); 5 cm (Starlette)	most precise absolute range: unbiased: excellent refrac modeling at optical wave- lengths	clouds obstruct obs: only 40-60% of passes acquired: early network limited in global distribution	1968- present
Radar: Ground- based	two-way range two-way range rate (S-band-> NASA C-band-> DoD)	1 m 0.3 cm/s	5 m 1 cm/s	first all-weather precision tracking system	single frequency results in large ionospheric error: meas biases	1972- present
TDRSS	two- and four-way (ground-sat-sat) range and range rate: operates at single freq w/ S- and K-band links	1 m-biased 0.4 mm/s	1.5 m 0.8 mm/s	excellent global coverage of user sats; high precision	single frequency: transponder delays: TDRS orbit accuracies	1983- present
OPNET/ TRANET (US Navy)	one-way range rate (sat-to-ground): dual frequency (150 and 400 Ghz)	0.2 cm/s	0.7 cm/s	good global network distribution	poor clocks: large third-order ionospheric refraction errors: 40% of data rejected	1965- 1995: TRANET being phased out
DORIS (France)	one-way range-rate (ground-to-sat): dual frequency (400 and 2000 Ghz)	0.4 mm/s	0.5 mm/s	high precision, all weather, excellent global coverage	sat tracks only one ground station at a time	1992- present
GPS (US Air Force)	pseudo- range/carrier phase (sat-to-sat)/(sat-to- ground)	1-2 cm	1-2 cm	3-D navigation of low satellites, unsurpassed coverage	controlled by DoD; current on-orbit receivers cannot cope with SA	1992- present
Altimetry	two-way range: (sat-to-ocean): both single and dual freq. altimeters flown	1-2 cm	7 cm	precise range to directly map ocean surface topography	limited by modeling of complex ocean surface signals	1975- present

Laser systems offer the most accurate range observations and have a long pedigree. These systems were first deployed in the late 1960s and were used for experimental orbit determination on NASA's BE-B, BE-C, GEOS-1 and GEOS-2 missions. By the early 1970s, the first international laser tracking campaign called ISAGEX was organized which produced meter-level ranging precision on 7 satellites (including those mentioned above along with the French D1-C, D1-D, and PEOLE satellites).

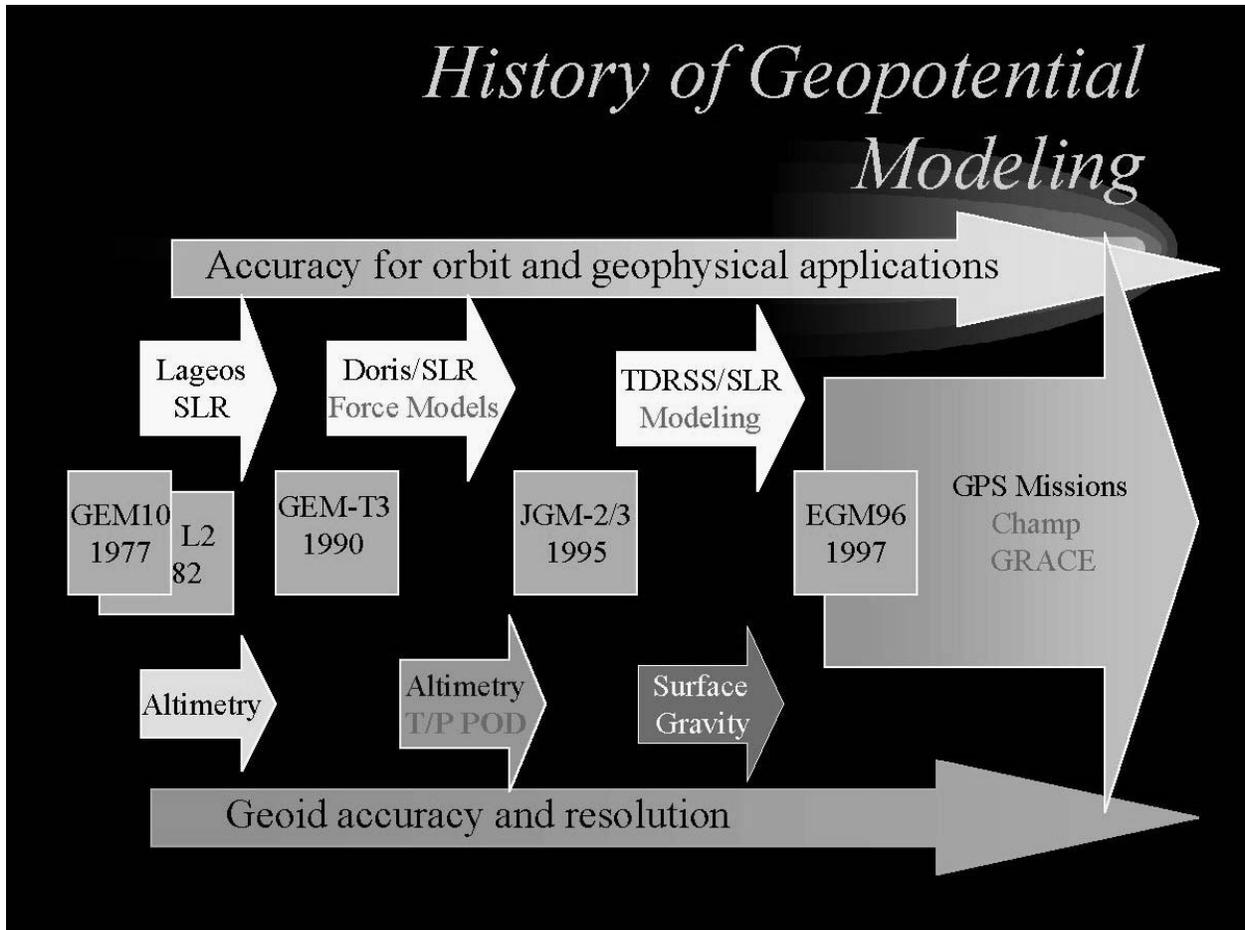
Laser systems have substantially evolved and have undergone over a five-hundred-fold improvement in system precision from the middle 1970s through the mid-1990s. This evolution buttressed the progress made for monitoring the motion of near-Earth satellites and has resulted in much more stringent demands for geopotential models capable of exploiting these data to their cm accuracy level. The major limitation found with lasers are their susceptibility to weather and the finite number of satellites which carry corner cubes enabling them to be tracked by these systems. Nevertheless, these data are largely responsible for the advances seen in gravity models, especially after the middle 1970s with the launch of very clean laser targets found with the Starlette and LAGEOS satellites, (1975 and 1976 respectively). *Lerch et al*, (1993) describes the contribution of SLR within GSFC geopotential solutions emphasizing the contribution of Starlette and LAGEOS, which given their complementary high and low altitudes (800 and 5600 km perigee heights), provided the means to accurately separate long from middle wavelength geopotential terms.

Other tracking technologies made contributions which were increasingly more important for EGM-96. A capability was developed at NASA using globally deployed S-Band radars. The Unified S-Band Network along with the SLR provided tracking flexibility within NASA's operational environment. The laser tracking supported high precision orbit determination needs whereas the S-Band Network tracked a large constellation of NASA satellites having less stringent orbit determination requirements. The radar tracking approach has progressed to yield today's Tracking Data and Relay Satellite System (TDRSS) consisting of a constellation of geostationary satellites which are used to track lower orbiting user satellites equipped with similar transponders to those tracked by the S-Band Network. TDRSS was designed to largely replace the S-Band Network while also providing satellite communication capabilities. TDRSS data were a major new data type first employed in EGM-96.

Concurrent with SLR developments, the US Navy developed and deployed a robust tracking network of their own supported by ground beacons and spaceborne transponders. The TRANET Doppler network consisted of a large number of global stations in operation from the middle 1960s onward. This network supported precision orbit determination needs within the US Department of Defense. The dual frequency TRANET network provided a large volume of 1 to 4 cm/s range-rate observations.

More recently, the French Space Agency, CNES, has developed a robust radiometric tracking technology which is similar in principal to TRANET, but with the ground stations transmitting a dual-frequency signal captured by an on-board satellite receiver. This system, DORIS, uses solid state electronics, operates at higher frequencies than TRANET, and is capable of an order of magnitude improvement over TRANET noise characteristics. DORIS observations are also much freer of residual ionospheric refraction effects (mostly third order) which plague the TRANET data.

The US Air Force has deployed the Global Positioning System (GPS), an active constellation of 24 12-hour satellites launched into six orbital planes inclined by 55° , with on-orbit spares. GPS is the most robust of all tracking systems, providing 3-D direct navigational capability to any Earth based or near-Earth orbiting observer. GPS data were another major resource first used in JGM-3 and EGM-96. GPS technologies form the basis for future dedicated geopotential missions which will provide major improvements in both gravity modeling accuracy at all wavelengths and the model's resolution provided by studying orbital behavior.



The above cartoon portrays the author's sense of the driving events, technologies, and capabilities that have produced the phenomenal improvement in geopotential knowledge over the last 25 years. The challenges attached to the gravity field problem are of two types, most easily discussed as a function of spatial bandwidths in the models:

- long wavelength modeling (to approximately degree and order 36):

This long wavelength portion of the model is essential for accurate orbit determination and for various geophysical and oceanographic applications.

- mid to high degree modeling (current models have now been determined to degree and order 460):

Geoid accuracy and resolution has been essential for many mapping, navigational, and geophysical applications.

2.1 SLR Contributions to Long Wavelength Geopotential Recovery

SLR is the principal technology responsible for the improvements we have seen in the long wavelength field. SLR data acquired on LAGEOS-1 after its launch in 1976 provided a unique opportunity for model development. Given the attenuation of the shorter wavelength geopotential signals at its 5,600 km

altitude, LAGEOS analyses permitted the isolation of the long wavelength geopotential signals within gravity solutions. LAGEOS is relatively insensitive to the gravity field above degree 10 and senses none of the geopotential at detectable levels even with today's improved tracking systems above degree 20. Coupled with Starlette, whose eccentric 800 to 1,200 km orbit sensed much more of the higher frequency field, SLR data supported significant model advancement and provided the foundation for all model recovery to the present. Even in EGM96, these satellites contribute data that receive the highest relative weight in the solution. By being designed solely as SLR targets, the clean, dense, uncomplicated spheres forming these satellites allowed for much improved isolation of the gravitational signals apart from atmospheric drag, solar radiation and spacecraft thermal imbalance effects. LAGEOS and Starlette allowed cm to decimeter overall orbit accuracy to be achieved without confronting many daunting, less well understood non-conservative force modeling issues prevalent in satellites which were designed for purposes beyond being passive laser targets.

The JGM-1 and JGM-2 solutions utilized data from 31 satellites described in *Nerem et al, (1994)*. The utilization of these data extend back to many previous solutions in most cases and are documented in the GEM-T1, GEM-T2, GEM-T3 and JGM-1&2 papers found in the *Journal of Geophysical Research* (*Marsh et al, 1988; Marsh et al, 1990; Lerch et al, 1994; Nerem et al, 1994* respectively). A complete discussion of all of the common orbital analysis approaches and results, which for EGM96 are a reiteration of these previous efforts, is beyond the scope of this paper.

There is a major difference in the JGM-1&2 solutions and EGM96. In JGM-1&2, there are only four or five satellite tracking data sets that are strongly weighted. This includes the laser data from LAGEOS-1, Starlette, and Ajisai, the DORIS data from SPOT-2, and the tracking data incorporated into JGM-2 from TOPEX/Poseidon (SLR and DORIS data). Basically, all other data are utilized to condition the model and break the correlation to take the "lumped" perturbations sensed by these satellites and ascribe the signal to the individual spherical harmonic coefficients forming the gravity field. Especially given the incremental build up to these solutions, and the earlier iteration of the model that produced GEM-T3, this process was both well understood, and largely a reiteration on earlier analyses.

With the data set analyzed for EGM96, the number of highly weighted data sets more than doubled. Several strong SLR data sets were newly available (e.g. LAGEOS-2 and Stella). New continuous tracking data types were also available and contributed strong information. Given this advance, and the added complexity of using TDRSS and GPS data types for the first time, data weighting strategies and field optimization approaches were reinitialized and required a revisitation of these issues. These new data types significantly contributed to model improvements within the longer wavelengths.

SLR is still one of the strongest data types available to recover long-wavelength geopotential coefficients, and is currently the only technology that is accurate enough to monitor temporal changes in any part of the field. However, radiometric techniques providing complete orbital tracking coverage are increasingly important and will have an increasingly prominent role for these purposes within future dedicated gravity recovery missions.

2.2 Geoid Resolution and Recovery

There have been recent developments that have dramatically enhanced our ability to model the shorter wavelengths within the gravity field. These are: (a) satellite radar altimetry, which has provided a synoptic mapping of the ocean surface topography, and (b) changes in the world's political climate which has caused the release of previously withheld surface gravimetric data sets for improved continental modeling. SLR has been an important technology that has helped maximize the information yield from both of these sources.

With improved geopotential modeling, the orbit accuracy for TOPEX/Poseidon (T/P) was a direct beneficiary. Coincident SLR and DORIS tracking on T/P allowed for much more detailed thermal and radiative force modeling to complete the orbit determination challenges for this mission. This altimeter mission has revolutionized sea surface topographic recovery utilizing space-based radar altimeter platforms. Significant improvements to the ocean geoid and the long wavelength modeling of dynamic sea surface topography is a direct result of the unprecedented orbital accuracy achieved for T/P.

A second major contribution to improved geoid accuracy and spatial resolution comes with the availability of surface gravimetry over most continental areas. Prior to the EGM-96, accurate surface data was not available over much of north central Asia, the former Soviet Union, and China. Changing world politics have greatly improved this situation and new technologies, like airborne gravimetry, have also provided data over several remote areas covered by the ice sheets. The strength of the SLR data for describing the long wavelength geoid has supported inclusion of the surface gravity into recent gravity solutions with data weights that are much closer to realistic. This has been achieved by simultaneously solving for long wavelength "errors" arising within surface gravimetry from their reference systems, discontinuities at country borders, and other sources of long wavelength errors when these data are included in the model. This approach is described in *Lemoine et al., (1997)* for EGM-96. Essentially, this approach references the long wavelengths in the surface gravimetry to an SLR determined geoid.

2.3 SLR Limitations for Geopotential Field Recovery

While a dedicated geopotential recovery mission has not yet reached orbit, a significant data set has been assembled which supports geopotential recovery. However, to understand the solution it is desirable to review the strength of the geopotential signal contained in tracking data. This then gives insight into the limitations of SLR for geopotential field recovery.

From linear orbit theory (*Kaula, 1966*), it is shown that a given satellite samples the geopotential in a systematic and characteristic fashion. Satellites of geodetic interest are generally found in stable orbits and at altitudes largely above 700 km to mitigate against significant atmospheric drag effects. For the purposes herein, we can assume that geodetic orbits have a stable semi-major axis, eccentricity and inclination. This gives rise to a systematic geographic sampling of the gravity field.

Orbital perturbations arise from this sampling of the Earth's inhomogeneous distribution of mass. When the geopotential model is represented in spherical harmonics, the terms combine by order to produce a perturbative frequency spectrum. Applying linear theory (*Kaula, 1966*), the gravitational field produces perturbations which are periodic at frequencies:

$$\dot{\Psi} = (n - 2p + q)(\dot{M} + \dot{\omega}) - q\dot{\omega} + m(\dot{\Omega} - \dot{\theta}) \quad (\text{Eq. 1})$$

where:

n	is the degree of the Stokes harmonic
m	is the order of the Stokes harmonic
p	is a subscript in the inclination function
q	is a subscript in the eccentricity function
$\dot{\omega}$	is the mean rate of the argument of perigee
$\dot{\Omega}$	is the mean node rate
\dot{M}	is the mean anomalistic motion rate
$\dot{\theta}$	is the mean rotation rate of the Earth

For geodetic orbits, the range of subscripts of concern are: n from 2 to 70; m from 0 to 70; q = 0, ±1, ±2; and p ranges from 1 to n. Allowing k = (n - 2p + q), the dominant perturbations from the gravity field have frequencies of:

$$k \text{ cycles/revolution} + m \text{ cycles/day} \quad (\text{Eq. 2})$$

The gravitational field produces a complicated perturbation spectrum with a large signal occurring at or near one cycle-per-revolution (1cpr). These perturbations can be separated into the following classes described in Table 3.

Table 3: Gravity Field Induced Orbit Perturbations

Major Characteristic	Rate Arguments	Typical Orbital Frequency (cyc-per-rev) (cyc-per-day)	Classification
k ≠ 0	$k\dot{M} \neq m\dot{\theta}$	≥ cpr	short period
k = 0	$\dot{\Psi} \approx m\dot{\theta}$	m = 1 to n cpd	"m-daily"
m = 0	$\dot{\Psi} \approx m\dot{\omega}$	≥ 0.02 cpd	long-period
k = 1, 2, 3	$k\dot{M} \neq m\dot{\theta}$	0.05 to 0.5 cpd	resonant

As noted above, each of these perturbation families yield "lumped" harmonics which are the linear sum of contributions of terms of the same order having the same dominant frequency, and include terms with long period modulation (with -qω) about the main frequency. Therefore

$$\dot{\Psi}_{m,0,k} = k(\dot{M} + \dot{\omega}) + m(\dot{\Omega} - \dot{\theta}) \quad (\text{Eq. 3})$$

is the dominant frequency, and the complete family includes all terms with

$$\dot{\Psi} = \dot{\Psi}_{m,q,k} = -q\dot{\omega} + \dot{\Psi}_{m,0,k} \quad (\text{Eq. 4})$$

This gives rise to an odd/even degree parity for the lumped harmonics within each order (cf. *Wagner and Klosko, 1975*) which segregates the main and modulating terms. For the low eccentricity orbits used in our geopotential solutions, we find terms being significant with q having a range of values from -2 to +2 with q=0 representing the dominant term.

From the orbit perturbations they produce, adjacent coefficients of the same order and same odd/even degree parity are only distinguishable from one another given that the higher degree term introduces a shorter period perturbation which is not found in the perturbations arising from the adjacent lower degree term. These short period perturbations are lumped with still higher degree coefficients of the same parity and order. For example, (2,2) and (4,2) share common orbital frequencies except for a shorter period

perturbation arising from (4,2). (6,2) shares all of the perturbation frequencies of (4,2) and (2,2) but has an additional short period term absent with (4,2). Likewise for (8,2) w.r.t. (6,2) and so on.

Therefore, for a given orbit, short period sensitivity in the tracking data is needed to separate terms having the same order and odd/even degree parity when recovering the gravity field. If the data cannot resolve short period effects, many satellites with different sensitivity to the terms contributing to the sum are needed to separate these signals into their associated recovered individual harmonics and correlation in the recovered model shows where this separation is lacking. This fairly describes the current state of geopotential modeling. On the other hand, dedicated geopotential missions are designed to yield extensive perturbation mapping continuously over each orbital revolution thereby allowing a single satellite to recover a "complete" model up to some degree and order limits through the separation afforded by mapping all short period perturbations within a specified band.

For the conventional data sets used in JGM-1, all are capable of resolving long period zonal and strong resonance perturbations (which produce orbital perturbations which range in period from several days to secular). Only the strongest data sets like SLR are capable of sensing a significant subset of the m-daily perturbations which are generally smaller in magnitude than resonance and long period zonal effects. However, given the rather sparse temporal tracking coverage provided by SLR and the high noise of TRANET/OPNET Doppler systems, none of the data sets available before 1992 were capable of observing the large number of short period orbital perturbations which are generally much smaller than the m-daily perturbations.

To illustrate this point and the limitations of the SLR data for geopotential recovery, we take Starlette as an example. From the normal equations truncated to degree and order 36 computed from the Starlette tracking data used in EGM96, we present the range of coefficient sensitivity vs the set of eigenvalues from this part of the geopotential field. This comparison is shown in Figure 2. The Starlette data is sensitive to nearly all terms in the 36x36 field, reflecting a linear theory's estimate of orbital perturbations (ranging from a few mm to a few km). The eigenvalues show that the recovery of individual terms is not well supported across the 36x36 field despite this sensitivity. The eigenvalues span more than 12 orders of magnitude. Starlette therefore only contributes a few hundred unique lumped harmonics to the recovery of the gravity field while it has sensitivity to over three times as many individual geopotential terms. Without sampling the short period orbital perturbations, despite this sensitivity, SLR lacks a means to separate this signal into individual gravity harmonics. The temporally discontinuous SLR tracking limits the geopotential recovery obtainable from an individual SLR satellite data set.

Geopotential recovery missions like GRACE and CHAMP are designed to exploit systems that continuously track near-Earth satellites with high precision. Both of these missions are based on the 3-D tracking offered by the GPS constellation. With GPS data, the short period gravity perturbations will be directly and continuously mapped. GRACE and CHAMP will also orbit at lower altitudes than the geodetic SLR satellites, thereby experience less attenuation of the geopotential signal, and offer recovery of complete higher degree and order fields to some truncation limit. Because of the lumped perturbation effect discussed above, recovery strategies for CHAMP and GRACE will require modeling of terms beyond the truncation limits of the adjusted fields so that higher degree coefficient *errors* and not their *full perturbation* are aliasing sources in these solutions.

However, while the current or contemplated constellation of SLR satellites do not support complete model recovery like these dedicated geopotential missions, SLR currently yields the most accurate "lumped" harmonics and is the only existing tracking technology which supports study of the non-tidal variation in the gravity field. Also the time interval of SLR tracking now extends for a long enough time interval that separation of long period lunar tides (18.6 and 9.3 year periods) from secular effects is emerging in several analyses (*Cheng et al., 1997; Eanes, 1995*). SLR therefore is supporting the

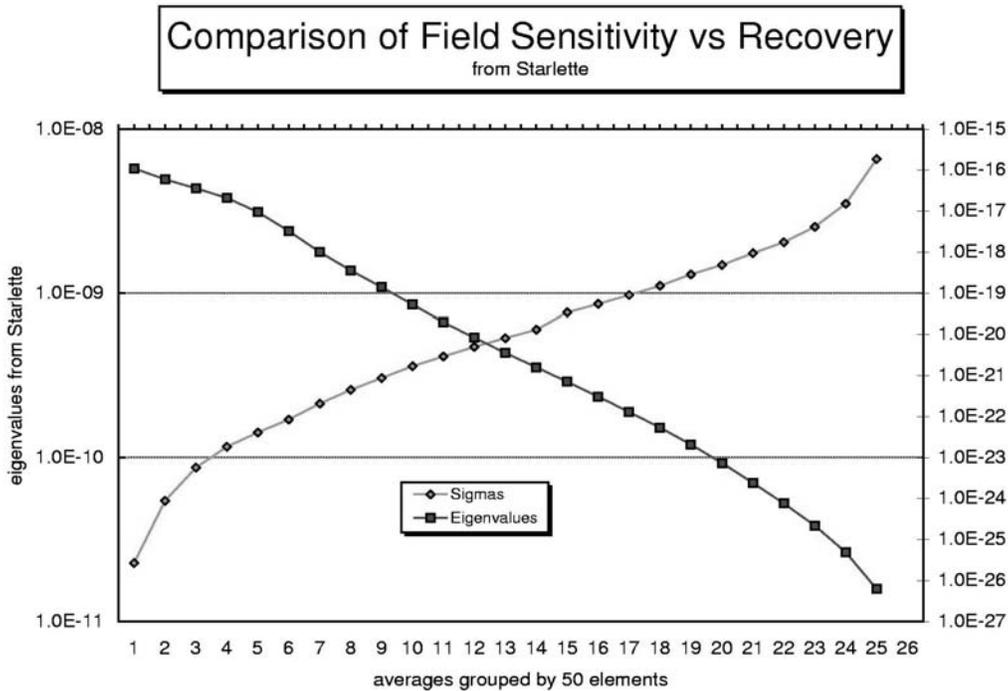


Figure 2. Comparison of STARLETTE Standard Deviations and Eigenvalues

monitoring of the time dependence of some long wavelength geopotential terms which contributes to our understanding of several important geophysical processes.

3.0 SLR Applications for Investigating Mass Transport in the Solid Earth/Ocean/Atmospheric Systems

Various authors have evaluated SLR data to recover:

- secular changes in some of the low degree zonal harmonics,
- time series of a more restricted set of zonal recoveries which can be compared to external models, like Atmospheric and Ocean Circulation Models (ACM and OCM) from which mass transport can be inferred
- preliminary estimates of the ordinary low degree and order tesserial harmonic time series (e.g. $C(2,2)$ and $S(2,2)$) having similar underlying physical bases.

There is an increased interest in this activity as the time scale of SLR data continues to lengthen. Table 4 compares some of the recent solutions for secular even zonal rates. Table 5 compares the odd zonal rates that have been estimated by several groups.

Table 4. Comparison of Even Secular Zonal Rates Determined by SLR (Units: $10^{-11}/y$)

Authors	Secular Change in J_2	Secular Change in J_4	Secular Change in J_6
<i>Rubincam [1984]</i>	-2.6 ± 0.6		
<i>Cheng et al [1989]</i>	-2.5 ± 0.3	0.3 ± 0.6	
<i>Geogout & Cazenave [1993]</i>	-2.8 ± 0.4		
<i>Nerem & Klosko [1996]</i>	-2.8 ± 0.3	0.2 ± 1.5	
<i>Cazenave et al [1996]</i>	-3.0 ± 0.5	-0.8 ± 1.5	
<i>Cheng et al [1997]</i>	-2.7 ± 0.4	-1.4 ± 1.0	0.3 ± 0.7
<i>Devoti et al [1998]</i>	-3.3 ± 0.3	1.7 ± 0.8	0.6 ± 1.2

Table 5. Comparison of Odd Secular Zonal Rates Determined by SLR (Units: $10^{-11}/y$)

Authors	Secular Change in J_3 & J_5	Secular Change in J_{odd} using Nerem & Klosko constraint: $J_{\text{odd}} = J_3 + 0.837 J_5$	Secular Change in J_{odd} using Devoti et al constraint: $J_{\text{odd}} = J_3 + 0.9 J_5$
<i>Cheng et al [1989]</i>	-0.1 ± 0.3 & ---		
<i>Nerem & Klosko [1996]</i>	only lumped term	1.6 ± 0.4	
<i>Cazenave et al [1996]</i>	-1.7 ± 0.1 & ---		
<i>Cheng et al [1997]</i>	-1.3 ± 0.5 & 2.1 ± 0.6	0.5 (inferred from J_3 and J_5)	0.6 (inferred from J_3 and J_5)
<i>Devoti et al [1998]</i>	only lumped term		-1.1 ± 0.3

Table 6. Inverse solution using secular rates to constrain climate and geophysical models (from *Klosko and Chao, 1998*)

Secular Zonal Harmonic Rate Solution Employed:	Viscosity contrast of lower mantle (Pa-sec assuming upper mantle has a value of 10^{21})	Antarctica mass imbalance contribution to GSL (mm/y)	Greenland mass imbalance contribution to GSL (mm/y)	Weighted RMS (fit to secular rates)
<i>Nerem & Klosko (1996)</i>	7.2×10^{22}	-0.12	-0.08	0.67
<i>Cheng et al, (1997)</i>	1.0×10^{22}	0.21	-0.17	0.59
<i>IPCC estimate (Warrick et al, 1996)</i>		-1.4 to 1.4	-0.5 to 0.5	

The secular zonal harmonic rates are extremely useful parameters for constraining the character and magnitude of various geophysical and long period environmental processes within the solid Earth and its fluid envelop. The observed secular change in the Earth's polar motion (which in itself is due to a secular change in the $C(2,1)$ and $S(2,1)$ geopotential coefficients) and the global rise in sea level can also be used for these purposes although all of these observed secular rates are limited in spatial resolution. Nevertheless, although limited, these observed effects provide insight into ongoing very long period and

subtle effects. *Klosko and Chao* (1998) have recently reported results which used this set of observed rates, forward modeled the long period geopotential zonal contributions of global water entrapment in reservoirs and observed mass change in the mountain glacier system, and estimated the mantle viscosity contrast used for Post Glacial Rebound modeling, and the secular mass change over the Greenland and Antarctica ice sheets. Each of these solved for effects are important for they are either climate sensitive or are needed, as in the case of PGR modeling, to unambiguously understand the century old time series provided by tide gauges (c.f. *Douglas*, 1997). An example of the results obtained from the *Klosko and Chao* analysis using the secular zonal rates from *Cheng et al*, (1997) and *Nerem and Klosko* (1996) are shown in Table 6. The results for mass balance over the ice sheets are compared to the Intergovernmental Panel on Climate Change report which indicates that the net mass flux from these sources into the oceans is not well known. The SLR estimates show very little secular mass imbalance from either source.

4. Summary

SLR has allowed a large number of the challenges for satellite to be achieved including the most accurate determination of the Earth's gravitational constant times its mass, GM, providing the most important data set for the recovery of low degree and order gravity harmonics, and providing a highly accurate data set for testing orbit models. The utilization for SLR ranging data includes gravity field recovery, precision orbit determination, and gaining insights into processes underway that continuously redistribute the Earth's mass. There have been collateral gains seen in other disciplines enabled by the advances delivered through SLR. This includes improved altimeter mapping of ocean circulation, improvements in non-SLR orbit applications, and geophysical modeling. However, the role played by SLR is likely to change with the launch and availability of GPS-based data sets supporting dedicated geopotential missions. CHAMP and GRACE are scheduled for launch in the next few years. These mission concepts are designed to exploit the continuous 3-D tracking offered by GPS and will map all short period orbit perturbations within specific bandwidths. These mission will significantly improve our ability to model the geopotential field and will diminish SLR's contribution as a result. Nevertheless, SLR will continue to provide the best data set for evaluation of long period and secular changes in the low degree portion of the field which is important for places bounds on the mass transport ongoing in the Earth's system.

References

- Cazenave, A.A., Gegout, P., Ferhat, G. and Biancale, R. (1996) *Temporal Variations of the Gravity Field from Lageos 1 and Lageos 2 Observations*, in "Global Gravity Field and Its Temporal Variations," R.H. Rapp, A.A. Cazenave and R.S. Nerem, eds., IAG Symposia 116, Springer Verlag, Berlin-New York.
- Cheng, M.K., Eanes, R.J., Shum, C.K., Schutz, B.E. and Tapley, B.D. (1989) *Temporal Variations in Low-Degree Zonal Harmonics from Starlette Orbit Analysis*, Geophys. Res. Lett., 16(5), 393-396.
- Cheng, M.K., Shum, C.K. and Tapley, B.D. (1997) *Determination of long-term changes in the Earth's gravity field from satellite laser ranging observations*, J. Geophys. Res., 102, 22, 377-22, 390.
- Devoti, R., Luceri, V., Rutigliano, P., Sciarretta, C. and Bianco, G. (in press, 1999) *Time series of low degree zonals obtained analyzing different geodetic satellites*.
- Douglas, B.C. (1997) *Global sea level rise: a redetermination*, Surv. in Geophys., 18, 2-3, 279-292.
- Eanes, R., (1995) *A study of temporal variations in Earth's gravitational field using Lageos-1 laser range observations*, CSR Report 95-8, The University of Texas at Austin.
- Gegout, P., and Cazenave, A. (1993) *Temporal variations of the Earth's gravity field for 1985-1989 from Lageos*, Geophys J. Int., 114, 347-359.
- Kaula, Wm. (1970) *The Terrestrial Environment: Solid-Earth and Ocean Physics*, NASA Contractor Report CR-1579, Massachusetts Inst. of Technology, Cambridge, MS 147, pp.
- Kaula, Wm. (1966) *Theory of Satellite Geodesy*, Blaisdell, Waltham, MA.
- Klosko, S. and Chao, B. (1998) *Secular Variations of the Zonal Gravity Field, Global Sea Level and Polar Motion as Geophysical Constraints* Phys. Chem. Earth, Vol. 23, No. 9-10, pp. 1091-1102.
- Lemoine, F.G., Kenyon, S.C., Factor, J.K., Trimmer, R.G., Pavlis, N.K., Chinn, D.S., Cox, C.M., Klosko, S.M., Luthcke, S.B., Torrence, M.H., Wang, Y.M., Williamson, R.G., Pavlis, E.C., Rapp, R.H., and Olson, T.R. (1998) *The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96*, NASA Technical Report 206861.
- Lerch, F.J., Klosko, S.M., and Patel, G.B. (1982) *Gravity Model Development from Lageos*, Geophys. Res. Letter, 9, (11), pp. 1263-1266.
- Lerch, F.J., Marsh, J.G., Klosko, S.M., Patel, G.B., Chinn, D.S., Pavlis, E.C., and Wagner, C.A. (1991) *An Improved Error Assessment for the GEM-T1 Gravitational Model*, J. Geophys. Res., 96, 20023-20040.
- Lerch, F.J., Nerem, R.S., Putney, B.H., Felsentreger, T.L., Sanchez, B.V., Marshall, J.A., Klosko, S.M., Patel, G.B., Williamson, R.G., Chinn, D.S., Chan, J.C., Rachlin, K.E., Chandler, N.L., McCarthy, J.J., Luthcke, S.B., Pavlis, N.K., Pavlis, D.E., Robbins, J.W., Kapoor, S., and Pavlis, E.C. (1994) *Geopotential models from satellite tracking, altimeter, and surface gravity data: GEM-T3 and GEM-T3S*, J. Geophys. Res., 99, 2815-2839.
- Lerch, F.J., Nerem, R.S., Putney, B.H., Klosko, S.M., Patel, G.B., Williamson, R.G., Iz, H.B., Chan, J.C., and Pavlis, E.C. (1993) *Improvements in the Accuracy of Goddard Earth Models (GEM)*, Contributions of Space Geodesy to Geodynamics: Earth Dynamics/Geodynamics 24, AGU Monograph, D.E. Smith and D.L. Turcotte, eds.
- Lerch, F.J., Putney, B.H., Wagner, C.A., and Klosko, S.M. (1981) *Goddard Earth Models for Oceanographic Applications (GEM 10B and 10C)*, Marine Geodesy, 5, 2.
- Marsh, J.G., Lerch, F.J., Putney, B.H., Christodoulidis, D.C., Smith, D.E., Felsentreger, T.L., Sanchez, B.V., Klosko, S.M., Pavlis, E.C., Martin, T.V., Robbins, J.R., Williamson, R.G., Colombo, O.L., Rowlands, D.D., Eddy, W.F., Chandler, N.L., Rachlin, K.E., Patel, G.B., Bhati, S. and Chinn, D.S. (1988) *A new gravitational model for the Earth from satellite tracking data: GEM-T1*, J. Geophys. Res. 93, 6169-6215.
- Marsh, J.G., Lerch, F.J., Putney, B.H., Felsentreger, T.L., Sanchez, B.V., Klosko, S.M., Patel, G.B., Robbins, J.R., Williamson, R.G., Engelis, T.E., Eddy, W.F., Chandler, N.L., Chinn, D.S., Kapoor, S., Rachlin, K.E., Braatz, L.E., and Pavlis, E.C. (1990) *the GEM-T2 Gravitational Model*, J. Geophys. Res., 95, B13, 22043-22070.
- Nerem, R.S. and Klosko, S.M. (1996) *Secular variations of the Zonal Harmonics and polar Motion as Geophysical Constraints*, in "Global Gravity Field and Its Temporal Variations," R.H. Rapp, A.A. Cazenave and R.S. Nerem, eds. IAG Symposia 116, Springer Verlag, Berlin-New York.

Nerem, R.S., Lerch, Marshall, J.A., Pavlis, E.C., Putney, B.H., Tapley, B.D., Eanes, R.J., Ries, J.C., Schutz, B.E., Shum, C.K., Watkins, M.M., Klosko, S.M., Chan, J.C., Luthcke, S.B., Patel, G.B., Pavlis, N.K., Williamson, R.G., Rapp, R.H., Biancle, R., and Nouel, F. (1994b.) *Gravity Model Development for TOPEX/POSEIDON: Joint Gravity Models 1 and 2*, J. Geophys. Res., 24421-24447.

Nerem, R.S., Lerch, F.J., Williamson, R.G, Klosko, S.M., Robbins, J.W. and Patel, G.B. (1994a.) *Gravity model improvement using the DORIS tracking system on the SPOT-2 satellite*, J. Geophys. Res., 99, 2791-2813.

Rubincam, D.P., (1984) *Postglacial rebound observed by Lageos and the effective viscosity of the lower mantle*, J. Geophys. Res., 89, 1077-1087.

Tapley, B.D., Watkins, M.M., Ries, J.C., Davis, G.W., Eanes, R.J., Poole, S.R. Rim, H.J., Schutz, B.E., Shum, C.K., Nerem, R.S., Lerch, F.J., Marshall, J.A., Klosko, S.M., Pavlis, N.K. and Williamson, R.G. (1996) *The Joint Gravity Model-3*, J. Geophys. Res., 101 (B12), 28029-28049.

Wagner, C.A., and Klosko, S.M. (1977) *Gravitational harmonics from shallow resonance orbits*, Celestial Mechanics, 16.

Warrick, R, Oerlemans, J., Woodworth, P., Meier, M., and Provost, C. (1996) "Sea level change," in IPCC Second Scientific Assessment of Climate Change, Cambridge University Press, Cambridge.