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STATE-OF-THE-ART SATELLITE LASER RANGE MODELING FOR GEODETIC AND OCEANOGRAPHIC APPLICATIONS

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Abstract

Significant improvements have been made in the modeling and accuracy of Satellite Laser Range (SLR) data since the launch of LAGEOS in 1976. Some of these include; improved models of the static geopotential, solid-Earth and ocean tides, more advanced atmospheric drag models, and the adoption of the J2000 reference system with improved nutation and precession. Site positioning using SLR systems currently yield ~2 cm static and 5 mm/y kinematic descriptions of the geocentric location of these sites. Incorporation of a large set of observations from advanced Satellite Laser Ranging (SLR) tracking systems have directly made major contributions to the gravitational fields and in advancing the state-of-the-art in precision orbit determination. SLR is the baseline tracking system for the altimeter bearing TOPEX/Poseidon and ERS-1 satellites and thusly will play an important role in providing the Conventional Terrestrial Reference Frame for instantaneously locating the geocentric position of the ocean surface over time, in providing an unchanging range standard for altimeter range calibration and for improving the geoid models to separate gravitational from ocean circulation signals seen in the sea surface. Nevertheless, despite the unprecedented improvements in the accuracy of the models used to support orbit reduction of laser observations, there still remain systematic unmodeled effects which limit the full exploitation of modern SLR data.

1. INTRODUCTION

The analysis of Satellite Laser Ranging (SLR) data requires precise dynamic modeling of a rapidly moving near-Earth orbiting target. Through the application of the theory of motion for an orbiting object, both the satellite position and the SLR observing sites can be located in a common reference frame through the accurate determination of the satellite ephemerides. The principal model needed for the computation of a satellite's trajectory is that of the gravitational field which accurately reflects the inhomogeneous distribution of the Earth's mass, and the temporal changes in the field due to tidal and presently unmodeled climatological sources. Depending on the orbit of interest and the area-to-mass ratio of the satellite, non-gravitational forces arising from the effects of atmospheric drag and solar radiation are also important. Ground tracking systems provide an accurate means of sensing the perturbed motion of satellites. The primary advance in SLR geophysical applications comes through improvements in gravitational field modeling. By modeling the SLR measurements within global orbit solutions from many satellites, the broad features of the gravity field have been unambiguously determined. When combined with other less accurate forms of satellite tracking, satellite altimetry and surface gravimetry, the gravity field is sensed over an extensive spatial bandwidth. Using all these measurements has yielded comprehensive models of the Earth's gravity field in the form of spherical harmonic coefficients. These solutions describe the complex shape of the geoid as well as the resulting variation in the gravitational potential at altitude which perturbs the orbits of near-Earth artificial satellites.

SLR-based geodesy has benefitted from three achievements over the last 15 years. The first and certainly the most important is the advancement in laser tracking hardware. Since the launch of LAGEOS in 1976, laser systems have improved from 50 cm to centimeter level accuracies. With this rapid change in technology and an expanding global network, the laser data themselves were able to directly contribute to geophysical modeling. However, although great advances have been made, the SLR methodology has always been and continues to be geophysical and measurement model limited.

Laser systems are currently the most accurate and advanced means of precision satellite tracking. These ranging systems have substantially evolved, undergoing nearly a threefold improvement in system precision every five years during the last 15 years. The evolution of laser systems in monitoring the motion of near-Earth satellites has in turn resulted in much more stringent demands for geophysical models being used for representing the data to the sub-centimeter level.

Today the precision of existing SLR measurements is less than a cm for the best instruments. The process of forming laser normal points, a type of compressed data, effectively eliminates spurious observational noise of the current measurements. For all the laser data, there are systematic errors which are not eliminated in the normal point computation process. The effects of atmospheric propagation, especially horizontal gradients in the atmosphere which are not detectable by the surface meteorological measurements made at the laser sites, are the largest source of systematic error. Estimates of these errors are in the 0.5 to 2 cm range (Abshire and Gardner, 1985). Electronic errors, non-linearities in the tracking electronics as a function of signal strength, errors in the distance to the calibration targets, together with remaining spurious effects all result in a range system capable of 1-2 cm absolute accuracy for the current SLR data (Degnan, 1985) with further improvements in tracking hardware in progress.

2. IMPROVED GEOPOTENTIAL MODELING

Since the launch of LAGEOS, the gravity model has been improved through the analysis of millions of laser ranges acquired on satellites which span a wide range of orbital inclinations. Knowledge of the geopotential field has improved in accuracy by an order of magnitude or more, especially for the longest wavelength portion of the field.

Closely coupled with the improvement in the gravity field was the development of ancillary force, environmental, and measurement models which enabled the exploitation of these data closer to their precision. Advanced solid Earth and ocean tidal models, descriptions of site motion due to various sources of loading, and improved realization of a geocentrically referenced Conventional Terrestrial Reference System all played an important role in the more accurate representation of SLR data in the orbit determination process. The very significant impact of the precise SLR data on the gravity solution was demonstrated when LAGEOS observations first were included in the GEM-L2 solution. This solution used 2.5 years of measurements acquired by third generation laser systems from 20 globally distributed stations. Given the stability of the LAGEOS orbit against the influences of solar radiation pressure and atmospheric drag, a well isolated gravitational signal was available for geopotential modeling. While complex non-conservative orbital effects are seen on the LAGEOS orbit leading to numerous important studies (e.g. Rubincam et al., [1987]; Rubincam, [1988,1990]; Afonso et al., [1985]; Scharroo et al., [1991]), these effects are far smaller and much better modeled than are the non-conservative effects on less stable lower orbiting satellites. For example, Starlette, like LAGEOS, is a small dense sphere. However, this satellite at its 800-1200 km altitude, it is subjected to atmospheric drag perturbations of several m/day^2 in the along track direction depending on atmospheric conditions whereas the along track "drag" (including thermal, neutral density and charged particle) on LAGEOS is approximately 2 cm/day^2. The GEM-L2 solution contained 630,000 laser measurements, about 70% of which were the high quality ranges to LAGEOS. During the time interval of 1979-1981 where the LAGEOS data used in GEM-L2 were taken, the best systems operated at single shot precision levels of approximately 5-cm. The LAGEOS range measurements were by far the most precise satellite observations used in GEM-L2 and the significant improvement seen in this model is directly attributable to LAGEOS' contribution.

In the mid-1980's, preparation for orbit determination support for the TOPEX/Poseidon Mission began in earnest with the goal being to achieve 10 cm RMS radial orbit modeling. This necessitated a complete reiteration of the GEM solutions requiring recomputation of all of the normal equations in order to benefit from modern constants and models. It was also essential to significantly increase the size of the gravity field to realize the full benefit of better modeling available at this time. Further improvements in laser tracking technologies (e.g. single photon tracking using more sensitive detection technologies with multi-channel plates), required consideration of force and measurement models addressing effects at the cm level. New models were introduced to meet advancing laser tracking precision. The recent GEM-T2 solution (Marsh et al., 1990) is an example of the new series of GEM solutions. It contained over two million observations from 1130 arcs spanning 31 satellite orbits. There was also a significant improvement in the laser data included in the GEM-T2 solution. Third generation SLR observations from Starlette, Ajisai, LAGEOS, BE-C, GEOS-1 and GEOS-3 were included. Second generation data sets included SEASAT and GEOS-2. Early laser data taken on BE-B, D1-C, D1-D and PEOLE were also used. GEM-T2 effectively exploited the available historical satellite tracking database available for geopotential recovery. GEM-T2 extended the truncation limits of the satellite solution for certain resonance and zonal orders to degree 50. The GEM-T3 solution (Lerch et al., [1992]), which combines satellite models with surface gravimetry and satellite altimetry from GEOS-3, SEASAT and GEOSAT, represents the most robust treatment of these diverse data sets within the GEM models.

2.1 IMPROVEMENTS IN SUPPORTING GEOPHYSICAL MODELS

Additional model improvements have significantly contributed to improved representation of the SLR data within orbital solutions. These improvements fall mutually into two categories. The first entails improvement of the other geophysical models effecting orbit determination and the time-dependent positioning of the observer within a well defined Conventional Terrestrial Reference System (CTRS). The second category concerns model optimization, and the ability to extract the best signal from the diverse observational data set available for geopotential recovery. The first category will be reviewed below.

SLR-geodesy is based on the exploitation of the functional relationships between very precise observations and the underlying model parameters. These parameters are either part of a model used to environmentally correct the data or are part of the physical models which describe the perturbations acting on a satellite and observer-to-satellite positioning. Model parameters are classified in two groups; *arc parameters* which are orbit-specific including the initial satellite state-vector, atmospheric drag coefficients, solar radiation modelling parameters, measurement related parameters such as measurement biases etc.; and *common parameters* which are satellite-invariant including tracking station positions and their motions (tectonic and environmental), reference frame parameters including polar motion and Earth rotation, nutation and planetary ephemerides, and the geophysical force models representing the static and time-dependent gravitational field.

Improved modeling of satellite tracking data over the years has progressively contributed to the accuracy of SLR solutions. Table 1 shows that recent GEM models have significantly increased the number and complexity of the models used to compute orbital motion due to temporal gravitational effects and those used to position an Earth-fixed observer. This development parallels that used at GSFC in the overall analysis of SLR. These models are required to support cm-level geodesy which has resulted in large increases in the size of various models. By increasing the number of harmonic coefficients in both the static and tidal gravity models, the truncation effect on low orbiting satellites is reduced. For example, based on the evaluation of the TOPEX orbit by Casotto (1989), the ocean tide model required for TOPEX to reduce omission effects below the one cm RMS radial error has required us to develop and employ ocean tide models containing more than 7000 terms spanning 96 discrete tidal lines. Along with improved and more complete models of tidal changes in the geopotential fields, reliance on space-based determinations of Earth orientation parameters, creation of SLR normal points, and improved accommodation of non-conservative force model effects have all made significant contributions to recent solutions.

These supporting models were not available for earlier studies or for the supporting site positioning and Earth orientation recovery. The attendant model error created systematic errors in both the orbits and the recovered parameters over a large range of spatial and temporal scales. To reduce these errors, temporal averaging was extensively applied. For example, early GSFC site positioning solutions focused on annual solutions

(Christodoulidis et al., 1985). Earth orientation parameters were recovered using 5-day averaging. With the current level of supporting models, less averaging is needed. Recent GSFC solutions (Robbins et al., 1992) now yield monthly station positions and daily values of Earth pole and length of day variations. Also, the improved stability of the long period reference frame has permitted direct recovery of horizontal site velocities which are much less distorted by the former neglect of some important long period force modeling effects which cause a drift in the orbital frame with respect to Conventional Terrestrial Reference Frame.

The importance of these models are quantified by mapping them into the space of the laser observations on Starlette and LAGEOS (Table 2). The contribution to the variance of the range residuals of numerous models which have been introduced into the analysis of the SLR observations are tabulated. The level of modeling has been systematically stepped back to that which was used to develop GEM-L2. Simulated laser ranging from a global network was generated using all of the current TOPEX standard models (Wakker, 1991). These models were then eliminated to demonstrate the sensitivity of the satellite ranging to each model in turn. These two satellites are at widely separated altitudes largely spanning the geodetic orbits currently available. While cm-level modeling is still a goal, Table 2 demonstrates that a great many effects must be considered when this level of modeling is required. Since many of these effects are similar to the signal arising from the static gravitational field, some aliasing will occur within geopotential solutions due to the limitation and/or neglect of these and other supporting models. Developing models which support mm level ranging will require further advances in the understanding of the geophysical response of the Earth. For example, Figure 1 presents a comparison of the laser site motion due to ocean loading using two independent models (Ray and Sanchez, 1989 vs IERS Standards, 1990) for the largest M2 constituent at the Maui, Hawaii site. While these models are suitable to support cm level geodesy, mm level data precision is rapidly approaching and will require extensive (especially environmental) modeling improvements.

The current gravity models cannot be expected to yield orbit errors at the overall accuracy level of the laser data themselves. The projections from solution covariances reflect instead, our overall ability to fit these data *a posteriori* as reviewed in Table 3. This limitation in our ability to model the laser ranges is a vexing problem for there are many unmodeled error sources which contribute to the post-solution data fits. Among likely candidates, we have some evidence that the error attributable to the static or tidal gravitational field is no longer the major contributing factor to the observation residuals. This conclusion is reached by taking individual satellite data sets like the laser data acquired on Ajisai and giving these data extremely high weight in test solutions. When such solutions are then tested, there is little improvement in the Ajisai orbital fit. This indicates that other effects are playing a significant role. Yet this inability to fit the data at their noise levels has important consequences.

It has long been observed that precise SLR observation residuals from orbit solutions exhibit systematic behavior within each pass, even after adjustment of the gravity field. An analysis of 600 passes of Starlette SLR data reveal that over 90% had apparent biases of 3 cm or more. This residual characterization is dominated by orbit modeling rather than observation shortcomings. As a result of large (as compared to SLR nominal data accuracy) unmodeled effects in the residuals, their variance is much higher than that of a random effect. Thus, not all of the geodetic information can be extracted from these precise data. For example, gravitational signals which would otherwise be detectable at the cm level are obscured. If these data could be fully modeled with their gravity signal exhausted, there would be a considerable improvement in the accuracy of the SLR geodetic products produced using these data.

From the previous discussion, gravitational and orbit positioning solutions based upon near-continuous inter-satellite tracking have certain advantages. They largely eliminate the need to make complex media corrections to the observations since they are made above the atmosphere. Of course, force modeling errors effecting the orbit arising from solar radiation pressure and atmospheric drag still require further improvement. However, a word of caution is warranted. While continuous high precision tracking above the atmosphere like GPS tracking of TOPEX will eliminate many sources of systematic modeling error, the basic parameterization of the gravity field as a static and tidally varying physical system may itself have significant shortcomings. Only now are we coming to realize that there are a great number of environmental sources of mass redistribution arising from meteorological sources, such as variations of the atmospheric pressure field (Chao and Au, 1991) and continental water storage (Chao and O'Connor, 1988) which require much more attention in current orbit determination processes. These meteorological fluctuations, although having strong seasonality, are rather erratic in nature on shorter time scales. A recent report by Nerem et al., (1992) shows significant changes in the LAGEOS sensed zonal harmonics of the gravitational field related to atmospheric mass redistribution within monthly solutions. Evidence is mounting that these sources of unaccommodated signal are being sensed well above the noise level exhibited by modern SLR/GPS tracking systems. Treatment of these effects will require extensive evaluation of in situ data sources many of which are currently insufficient for the modern needs of precision orbit modeling. Neglect of these effects can limit the detection of signals of great general interest, such as the changes in the geopotential field due to post-glacial rebound, tectonic movement, and core activities.

3. SLR SUPPORT OF OCEAN APPLICATIONS

Satellite Laser Ranging will be used to support oceanographic science through the tracking support provided on recent satellite altimeter missions. Both TOPEX/Poseidon (launched in August 1992) and ERS-1 (launched in July 1991) are heavily dependent on SLR data for precise orbit determination. The accuracy of the orbital reference provided by SLR directly impacts the ability of these missions to geocentrically monitor the ocean surface over time needed for studying global ocean circulation.

From the analysis of the climatological models, the sea surface is known to depart significantly (±70 cm) from the geoid, and is offset in its center of figure with respect to the earth's center of gravity by as much as 25 cm. The absence of perfect symmetry of the dynamic height field with respect to the geocenter gives rise to non-zero degree one terms in the spherical harmonic expansion of the ocean topographic field (see Figure 2). The degree one terms in the absolute ocean height models are essential for understanding long term changes in the character of the dynamic height field. C,S (1,1) describe the east-to-west slope of the ocean topography across the major ocean basins. The C(1,0) has implications for understanding the seasonal thermal expansion of the oceans. Each of these terms has an important physical basis. The values for the first degree terms from climatology imply that on average over the past 70 years, the southern oceans are more dense than their northern counterparts, and that the western portion of the major gyres are more energetic than that of the east; each of these observations are seen in the in situ data record. It is therefore important to verify that these terms are accurately determined within the satellite analyses. These terms are of special concern for they are of the 1 CPR spatial scale of the dominant orbit error.

The orbital motion of a an altimeter satellite exhibits an integrated response to the forces generated by the inhomogeneous mass distribution on and within the Earth, the density of the atmospheric medium it traverses, by the size and orientation of the satellite surfaces exposed to the Sun and Earth and the response of these surfaces to this incident radiation. There are many additional, although less significant, forces acting on the satellite which require consideration. It is important to characterize the likely errors in these models, and their effect on the radial position over time of an orbiting altimeter satellite. Through this assessment, significant insight can be gained into the role of highly accurate SLR tracking in the recovery of satellite's orbital ephemerides and by inference, in the recovery of the ocean's dynamic height.

Much of the orbit error signal is at or near to 1 Cycle Per Revolution (CPR). At longer periods, principally errors in the odd zonal geopotential harmonics and errors in modeling satellite surface forces are capable of producing a modulation of the 1 CPR error over the orbital arc length. This is the so called "bow-tie" error effect. Moreover, there are important ocean topographic signals on the spatial scale of the 1 CPR orbit errors. The only hope for separating these signals from those of the 1 CPR orbit errors, is through the dense, global distribution of highly accurate tracking data which allows parameters in the orbit determination process to eliminate these errors. Again, TOPEX/Poseidon, with simultaneous tracking provided by satellite laser ranging and DORIS, offers the promise that this separation of signals can effectively be accomplished. The complete spatial correlation of the orbit and oceanographic effects at 1 CPR and the existence of weak tracking data sets supporting previous altimeter missions has limited the understanding of the change in ocean topography on this spatial scale to date.

Secondly, the best "standard" in existence for precise ranging is provided by SLR. Both of these altimeter satellites will overfly ocean/sea oil platforms allowing simultaneous tracking from the SLR and altimeter systems. The SLR ranges will be used to position the satellite with respect to the platform location (using GPS ties). Through tide gauges on the platform, the satellite altimeter is accurately located with respect to the instantaneous ocean surface based on the absolute scale provided by SLR. The altimeter range is calibrated through this method. In this way, the altimeter measurements can be assessed and monitored over the course of these missions to prevent instrument drift being confused with long period sea level changes.

4. SUMMARY

Since the launch of LAGEOS, our ability to model the range data to this and other satellites has improved by more than an order of magnitude. The accuracy and precision of the existing SLR systems has made an enormous contribution to the modeling of the static and tidal geopotential fields. Primarily, through the employment of millions of laser ranges, great progress was seen in the modeling of the gravity field at GSFC as well as at UT/CSR and DGFI/GRGS. These data are capable of detecting the gravity and tidal signals to unprecedented accuracy levels. However, with data of this precision, the further need for supporting geophysical and environmental models of improved accuracy is evident. These underlying models are themselves of considerable scientific interest. Currently, given *a posteriori* data fits which are inferior to the accuracy of SLR, the accuracy of SLR systems are yet to be fully exploited in current solutions, and geodetic signals otherwise detectable at the cm-level, are being obscured by these modeling shortcomings. With improvement, SLR data will be better able to detect temporal changes in many physical systems, like that of the geopotential field. This is important for example, for monitoring mean eustatic conditions apart from postglacial crustal rebounding.

Focus on improving underlying geophysical models, improving data treatment and incorporation of in situ data bases to describe short-term and erratic meteorological sources of mass transport are required objectives for future SLR geodetic investigations.

The SLR observations are also playing an increasingly important role in supporting satellite-based oceanography. Through the tracking support being provided to ERS-1 and TOPEX/Poseidon, these data and their supporting models, will be the basis for defining the absolute geocentric location of the instantaneous ocean surface to better understand the Earth's climatological system and ocean circulation. The SLR data will also be invaluable in the continuous calibration of the altimeter instruments over the lifetime of these and other altimeter missions.

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Table 1. Chronological parameterization of GEM models

NAME (DATE)/ NO. OF SATS	FIELD	MOST RECENT SLR DATA:*	REF SYS/ NUTATIONS	SOLID TIDES	OCEAN TIDES	CTRS	DRAG
GEM-9/10(1977) /30	20x20	76S	1950/Wollard no relativity	None	None	CIO	J71 w/24 hr Ap
GEM-L2(1983) /30	20x20	81L,S	↓	k_2=0.29 e_2=2.018^0 h_2=0.60 l_2=0.075	None	↓	↓
GEM-T1(1987) /17	36x36	84L,S	J2000/Wahr no relativity	k_2=.30 e_2=o^0 h_2=.609 l_2=.0852 Frequency dependence	32 lines (600 coef)	"zero-mean"	↓
GEM-T2(1990) /31	36x36	87L,S,A	↓	↓	↓	↓	+ DTM w/3 hr kp
GEM-T3(1991) /31 T3S	50x50	89L,S,A	↓	↓	↓	↓	↓
Pre-Launch TOPEX Model (1992)/34	70x70	90L,S,A 91E,R_1,R_2	J2000/ Wahr w/relativity	↓	96 lines (6000+coef)	IERS with dynamic polar motion	+ MSIS w/3 hr kp

* L LAGEOS
S Starlette
A Ajisai
E ERS-1
R1, R2: Etalon (USSR) -1 and -2

Key for CTRS: CIO - mean figure axis referenced to the Conventional International Origin; "zero-mean" - mean figure axis reference obtained from the LAGEOS polar motion series; IERS - new international standard definition of the Conventional Terrestrial Reference System (McCarthy, 1989).
Key for Drag: DTM - Barlier et al., (1987); MSIS - Hedin (1986); J71 - Jacchia (1971); 3 hr kp - model uses 3 hour values of the kp magnetic index; 24 hr Ap - model uses daily values of the Ap magnetic index.

Table 2. Estimated contribution of geophysical models to SLR range signal

FORCE MODELS	STARLETTE RMS (cm) Residual: 6^d arc		LAGEOS RMS (cm) Residual 30^d arc
• rotational deformation/ dynamic polar motion	4.9		0.2
• ocean tides:[1] extensive sideband, non-resonance tidal terms	5.8		3.2
• ocean tides	21.8		13.3
• frequency dependency[2] of solid Earth tides	21.6		5.0
• Earth albedo/IR reradiation	4.8		3.3
• Earth tides[3]	150.7		213.7
• GEMT3 v. GEML2 static gravitational model	206.1		7.0
meas. models			
pole tide		0.2	
ocean loading		0.5	
solid Earth tides (geometric)		6.5	

(1) sideband contribution from over 80 tidal lines using linear admittances to scale dominant tide line.

(2) from Wahr (1979): departure of K_2 from .30 within principally semi-diurnal band.

(3) using K_2 = .30 for frequency invariant model.

Table 3. Typical satellite laser ranging orbital fits in cm from various GEM solutions

Gravity model	Lageos	Ajisai	Starlette
GEM-9	33.3	95.1	116.0
GEM-L2	19.9	79.7	100.0
GEM-T1	5.5	12.3	21.2
GEM-T2	5.3	9.4	13.3
GEM-T3	5.2	9.0	11.8
Overall laser ranging precision	3.8		

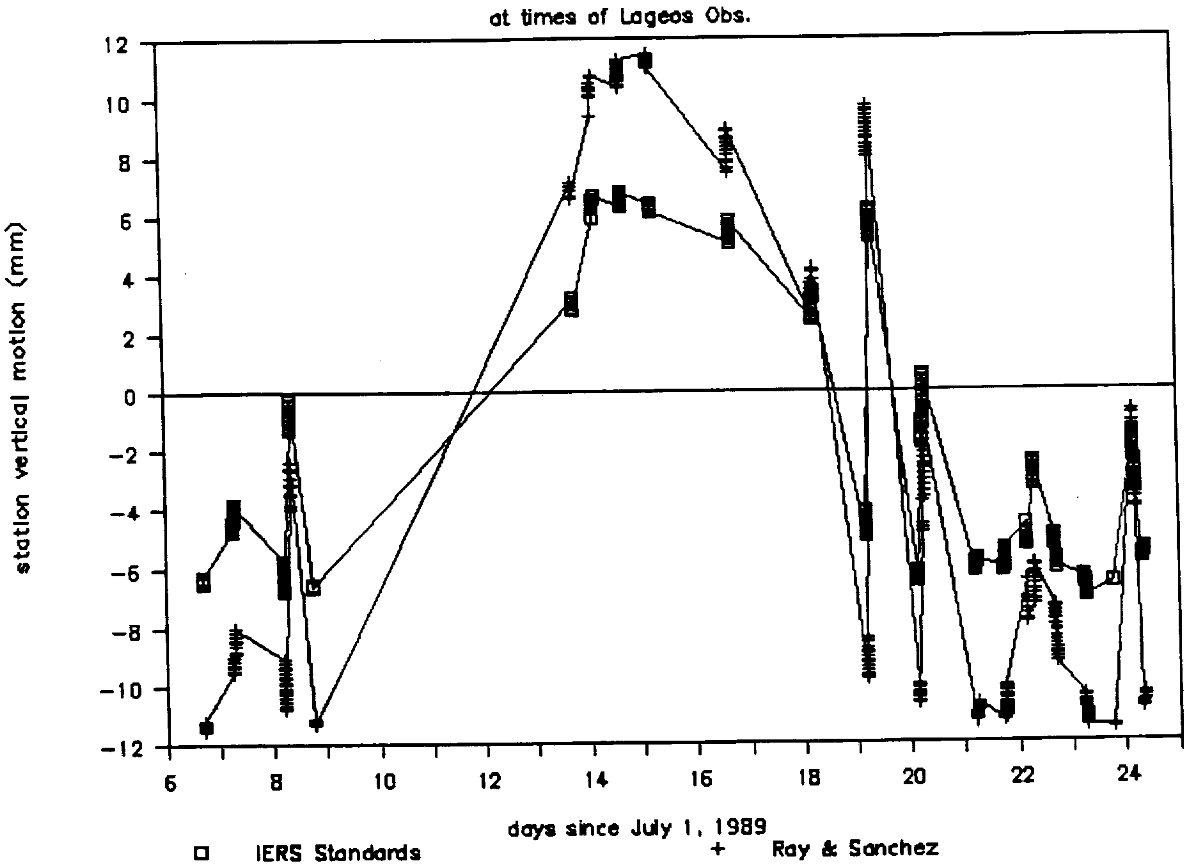
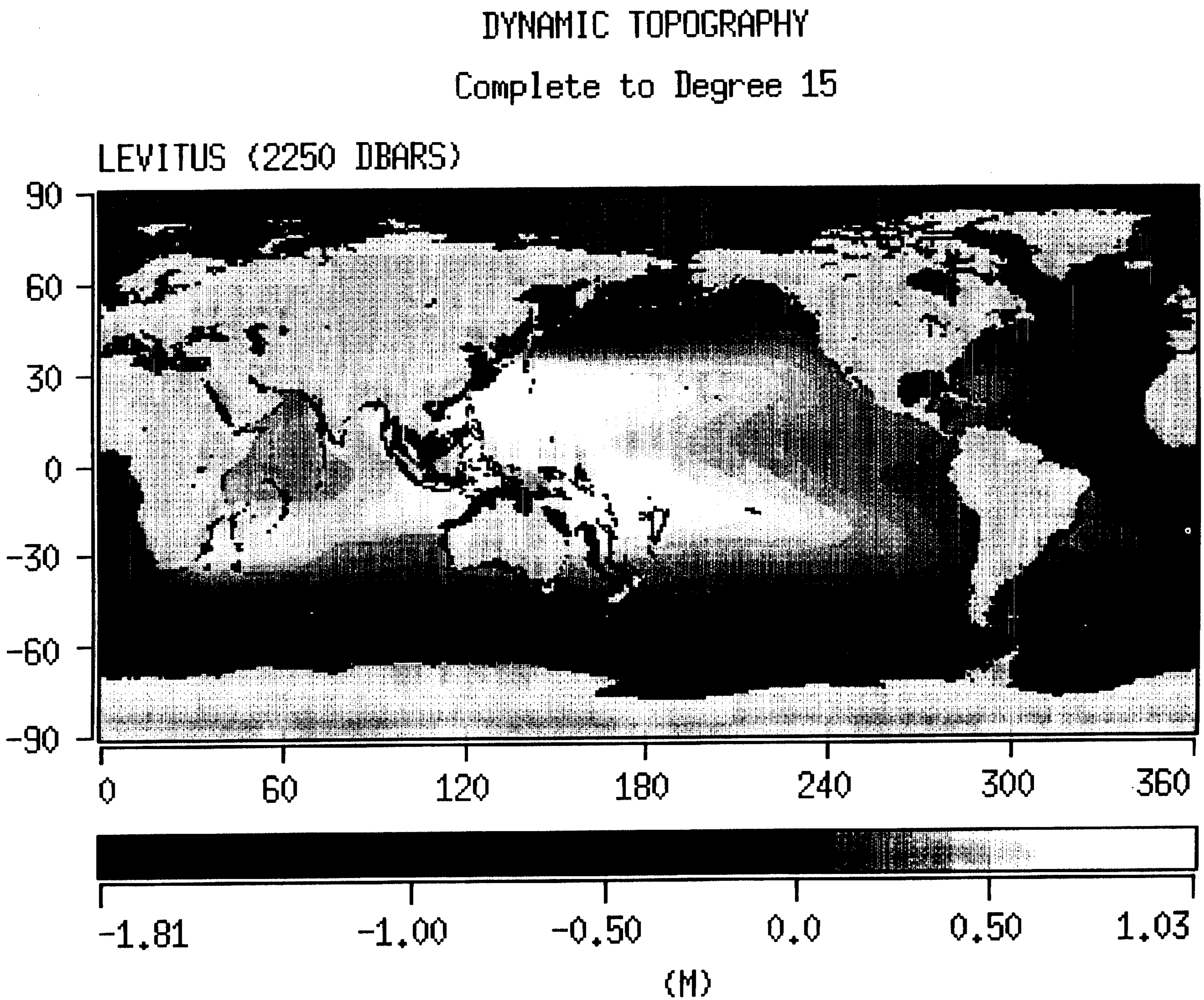


Figure 1. Comparison of models for ocean loading correction for the M2 tide at Maui, Hawaii

Figure 2.


DYNAMIC TOPOGRAPHY
Complete to Degree 15
LEVITUS (2250 DBARS)
90
60
30
0
-30
-60
-90
0
60
120
180
240
300
360
-1.81
-1.00
-0.50
0.0
0.50
1.03
(M)