SLR Data

Analysis/Model Errors

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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		

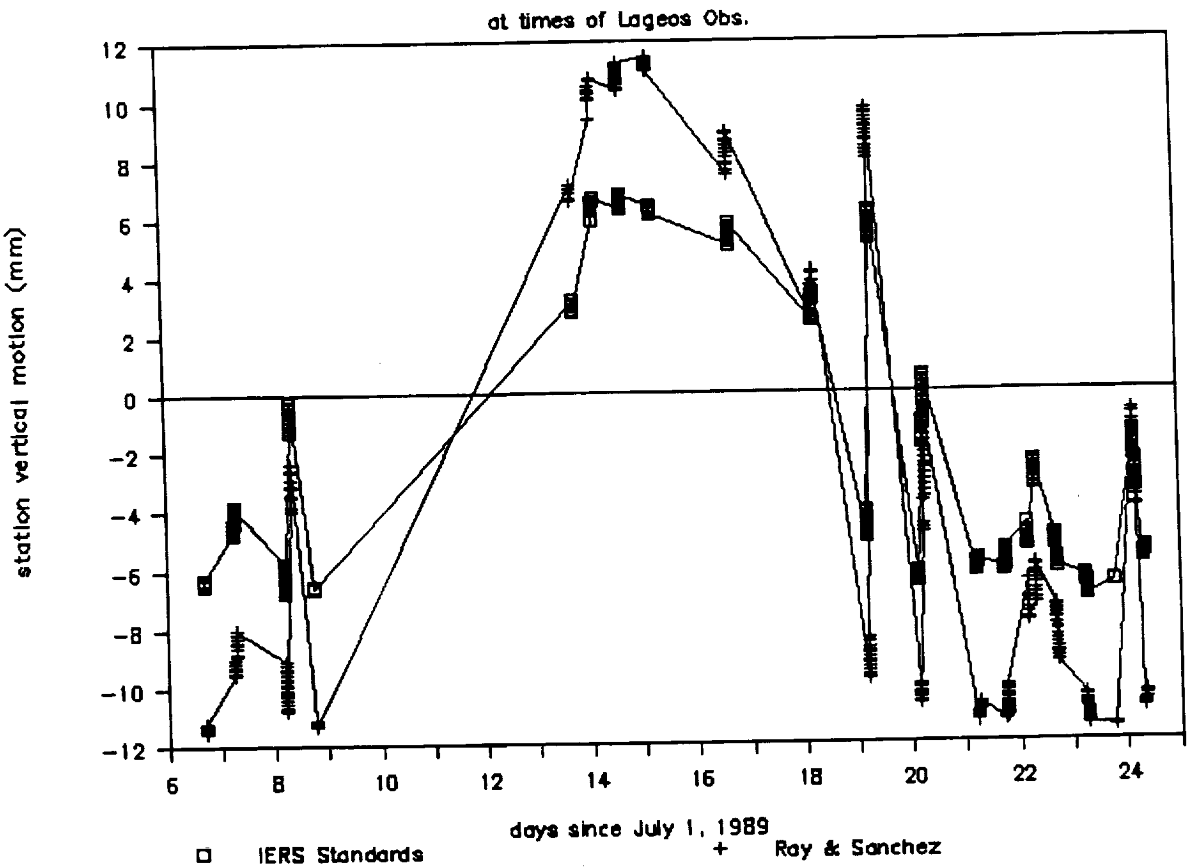
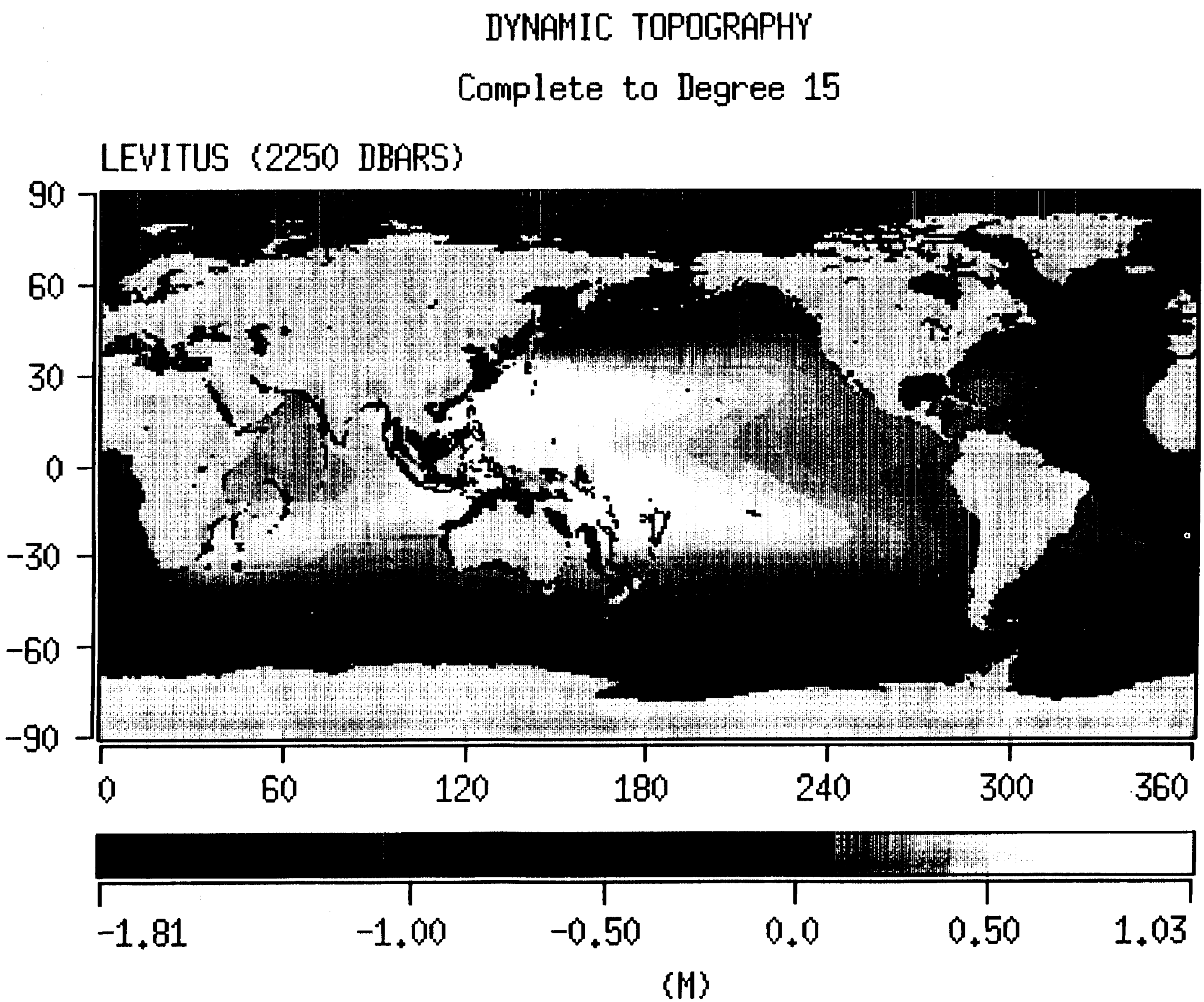


Figure 1. Comparison of models for ocean loading correction for the M2 tide at Maui, Hawaii

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)

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GEOMETRIC ANALYSIS OF SATELLITE LASER RANGING DATA

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The analysis of simultaneous laser data is investigated using the method of trilateration. Analysis of data from 1987 to 1992 is presented with selected baseline rates and station positions. The use of simultaneous Etalon data is simulated to demonstrate the additional global coverage these satellites provide. Trilateration has a great potential for regional deformation studies with monthly LAGEOS American solutions between 3 - 12 millimeters.

In the 1970s the precision of laser data was about 10 - 15 centimeters and the global distribution of satellite laser ranging stations was poor. Since that time the international laser ranging community has expanded and the precision of the data has improved substantially. Most laser ranging stations now produce data with a single shot precision on LAGEOS below 2 centimeters and much of that data has a single shot precision below 1 centimeter.

During the 1970s the mathematical methods to determine satellite positions using geometric data analysis were improved. The term used for that method is trilateration. The primary advantage of the trilateration technique is independent of orbit. It provides a means of analyzing station positions and data quality in such a way as to lower other outside influences such as satellite drag, radiation pressure, and gravity models that are used in the orbit determination methods. The major disadvantages to trilateration include the need for simultaneous ranging data, the difficulty in separating range biases from the station height, and the fact that the method does not allow for the extraction of the gravity field and other information that can be determined from an orbit determination process. Trilateration is also susceptible to low signal-to-noise ratio and low precision data.

Our method of trilateration requires simultaneous data from four or more laser ranging stations. There are several preprocessing steps that must occur to prepare the data for analysis. The process starts with a monthly LAGEOS fullrate release tape. Software selects the passes in which 4 or more stations have observations during the same timeframe. Once a timeframe has been found a polynomial is fit to the fullrate data for each pass. These polynomials, and other information such as the polynomial statistics and meteorological information, are written to an output file. The process continues through the entire data tape. After all of the polynomials have been determined, simultaneous data points are created at 30 second intervals from the pass polynomials. Poorly fitted passes are removed so that they don't corrupt the solution, although this rarely occurs. Any time intervals within the selected passes that have fewer than 4 stations are deleted. A summary output of the available stations and data yield is also produced at this step. Finally, the remaining LAGEOS tracking data is separated into two sections. One section is for Europe, North Africa, Commonwealth of Independent States. The other section is for the Americas, Easter Island, and Huahine.

To analyze the data geometrically, each section of LAGEOS ranging data is read in by the software. Apriori station positions and station velocities are used to compute each stations position at the middle of the month. The satellite position is determined for each observation so that angle dependent corrections are computed and applied to the data. Once all the data has been corrected an iterative process is started. The observed minus computed values (O-Cs) from each satellite position are determined for each epoch along with an average satellite position. The O-Cs are then edited using a 6-sigma editing criterion and the average satellite position is recomputed. A summary of each stations mean and rms are written to the run summary file along with the total number of observations per station and the number of edits. A sensitivity matrix is then generated. This is done by applying small offsets to each of the station position vector elements and determining what effect each offset has on the O-Cs for all of the epochs. This procedure is performed for each coordinate (ie. 12 times for 4 stations). A P transpose P matrix is generated and then inverted, where P is the matrix of partial derivatives of the O-Cs with respect to the adjusted station position. The O-Cs are then multiplied by the resulting partials and a matrix is then computed. These corrections are applied to the station positions and a new set of average satellite positions are computed and new O-Cs determined. Again these O-Cs are multiplied by the P matrix and reiterated. This iterative process is repeated until the delta rms of the O-Cs between consecutive iterations is less than one percent, or six iterations have been reached. The total change of the station position is determined for both x,y,z and latitude, longitude and height. The baseline lengths are determined for only the stations involved in the solution and saved in a database. This database also contains the month and the number of simultaneous observations between the two stations. A sample summary for a one month period for a European solution is shown in Figure 1. A by-product of the solution is the point distribution plot, a sample of which is shown in Figure 2. Baseline rates are generated from the baselines and a least-squares linear fit of each of the station combinations is computed by weighting the monthly baseline with the number of observations during that month. Some sample baseline rates are illustrated in Figures 3-5.

The method of trilateration also lends itself to doing long term solutions. In this method both the initial station position and the station velocities are determined. This method of analysis is still under development.

The requirement for simultaneous ranging data from 4 stations requires geographic coverage over a broad area, which in turn requires high altitude satellites. The Etalon satellites offer great potential because of their high altitude and visibility to a larger number of stations at one time. However, the Etalon satellites have had a low global ranging priority so they are rarely ranged by more than two stations at any one time. An intense Etalon campaign was performed during May and June of 1992 to determine how well these satellites can be used for Crustal Dynamics research and geometric data analysis. Unfortunately, because of the low Etalon priorities, the campaign yielded no simultaneous ranging data sets from 4 stations and only 1 data set where 3 station ranged simultaneously. LAGEOS 2, scheduled for launch in October 1992, offers the next best opportunity to obtain a large simultaneous ranging data set. In addition, at an inclination of about 65 degrees, there will be an opportunity to obtain simultaneous trans-atlantic data sets on a high priority SLR satellite.

In the future, we expect that simultaneous geometric analysis of data from LAGEOS, LAGEOS2, and Etalon1 and Etalon 2, spread over a period of a few days, will accurately determine baselines and velocities. Future modifications to the geometric analysis software are expected to include the additional determination of range and time biases from individual data sets.

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SOLUTION FOR  5/90 VERSION 3.1
THE STATIONS BEING SOLVED FOR ARE   7835  7839  7840  7834  7939  7810  1181  1884
THE TOTAL NUMBER OF THIRTY SECOND POINTS =  547
ITERATION  1 MEAN =   0.0005 RMS =  0.0381 M EDITS =   82
7835 POINTS =  243 EDITS = 19 MEAN =   0.61(CM) RMS =  2.79(CM) GRASSE,FRANCE
7839 POINTS =  308 EDITS = 14 MEAN =  -2.14(CM) RMS =  4.98(CM) GRAZ,AUSTRIA
7840 POINTS =  401 EDITS = 25 MEAN =   1.04(CM) RMS =  2.49(CM) ROYAL GREENWICH OBSERVATORY,ENGLAND
7834 POINTS =  251 EDITS =  2 MEAN =  -3.53(CM) RMS =  4.06(CM) WETTZELL,GERMANY
7939 POINTS =  433 EDITS = 15 MEAN =   1.58(CM) RMS =  2.98(CM) MATERA,ITALY
7810 POINTS =  407 EDITS =  7 MEAN =  -0.23(CM) RMS =  3.21(CM) ZIMMERWALD,SWITZERLAND
1181 POINTS =   97 EDITS =  0 MEAN =  -0.02(CM) RMS =  3.86(CM) POTSDAM,GERMANY
1884 POINTS =  258 EDITS =  0 MEAN =   2.01(CM) RMS =  2.77(CM) RIGA,LATVIA
ITERATION  2 MEAN =   0.0003 RMS =  0.0294 M EDITS =   83
ITERATION  3 MEAN =   0.0001 RMS =  0.0260 M EDITS =   83
ITERATION  4 MEAN =  -0.0001 RMS =  0.0238 M EDITS =   79
ITERATION  5 MEAN =   0.0001 RMS =  0.0221 M EDITS =   81
ITERATION  6 MEAN =  -0.0001 RMS =  0.0220 M EDITS =   78
ITERATION  7 MEAN =   0.0000 RMS =  0.0211 M EDITS =   78
ITERATION  8 MEAN =   0.0000 RMS =  0.0209 M EDITS =   74
ITERATION  9 MEAN =   0.0002 RMS =  0.0214 M EDITS =   68
7835 POINTS =  243 EDITS = 15 MEAN =   0.18(CM) RMS =  2.36(CM)
7839 POINTS =  308 EDITS = 14 MEAN =  -0.08(CM) RMS =  2.20(CM)
7840 POINTS =  401 EDITS = 17 MEAN =   0.04(CM) RMS =  1.22(CM)
7834 POINTS =  251 EDITS =  7 MEAN =  -0.09(CM) RMS =  3.26(CM)
7939 POINTS =  433 EDITS =  8 MEAN =   0.05(CM) RMS =  1.36(CM)
7810 POINTS =  407 EDITS =  7 MEAN =  -0.02(CM) RMS =  2.05(CM)
1181 POINTS =   97 EDITS =  0 MEAN =  -0.10(CM) RMS =  3.77(CM)
1884 POINTS =  258 EDITS =  0 MEAN =   0.09(CM) RMS =  1.91(CM)

 7835 OFFSET IN CENTIMETERS   -0.8250  -4.5956   2.2171
 7839 OFFSET IN CENTIMETERS  -12.5536   1.6383  -3.0958
 7840 OFFSET IN CENTIMETERS    3.7155   2.1842   0.9769
 7834 OFFSET IN CENTIMETERS  -15.0631 -10.3012  -3.5499
 7939 OFFSET IN CENTIMETERS    6.5119   0.9027   2.9142
 7810 OFFSET IN CENTIMETERS    1.1438  -0.5387  -0.6604
 1181 OFFSET IN CENTIMETERS   11.1416  -0.7329  -5.1856
 1884 OFFSET IN CENTIMETERS    3.4161  -0.6365   3.8376

STATION 7835 TO STATION 7839 =   764437.0501 M # OF 30 SECOND PTS =   91
STATION 7835 TO STATION 7840 =   932884.7705 M # OF 30 SECOND PTS =  142
STATION 7834 TO STATION 7835 =   753159.1604 M # OF 30 SECOND PTS =  124
STATION 7835 TO STATION 7939 =   877290.0126 M # OF 30 SECOND PTS =  225
STATION 7810 TO STATION 7835 =   349661.2268 M # OF 30 SECOND PTS =  119
STATION 1181 TO STATION 7835 =  1060757.9395 M # OF 30 SECOND PTS =   11
STATION 1884 TO STATION 7835 =  1890491.9961 M # OF 30 SECOND PTS =   87
STATION 7839 TO STATION 7840 =  1183242.7342 M # OF 30 SECOND PTS =  218
STATION 7834 TO STATION 7839 =   302138.4442 M # OF 30 SECOND PTS =  137
STATION 7839 TO STATION 7939 =   719404.9253 M # OF 30 SECOND PTS =  205
STATION 7810 TO STATION 7839 =   610840.0036 M # OF 30 SECOND PTS =  238
STATION 1181 TO STATION 7839 =   616033.6433 M # OF 30 SECOND PTS =    0
STATION 1884 TO STATION 7839 =  1242790.6872 M # OF 30 SECOND PTS =  166
STATION 7834 TO STATION 7840 =   917334.0128 M # OF 30 SECOND PTS =  188
STATION 7840 TO STATION 7939 =  1694490.9600 M # OF 30 SECOND PTS =  311
STATION 7810 TO STATION 7840 =   685045.3282 M # OF 30 SECOND PTS =  299
STATION 1181 TO STATION 7840 =   895488.7178 M # OF 30 SECOND PTS =   96
STATION 1884 TO STATION 7840 =  1683599.7109 M # OF 30 SECOND PTS =  152
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Fig. 1

JUNE 1988 LAGEOS POINTS

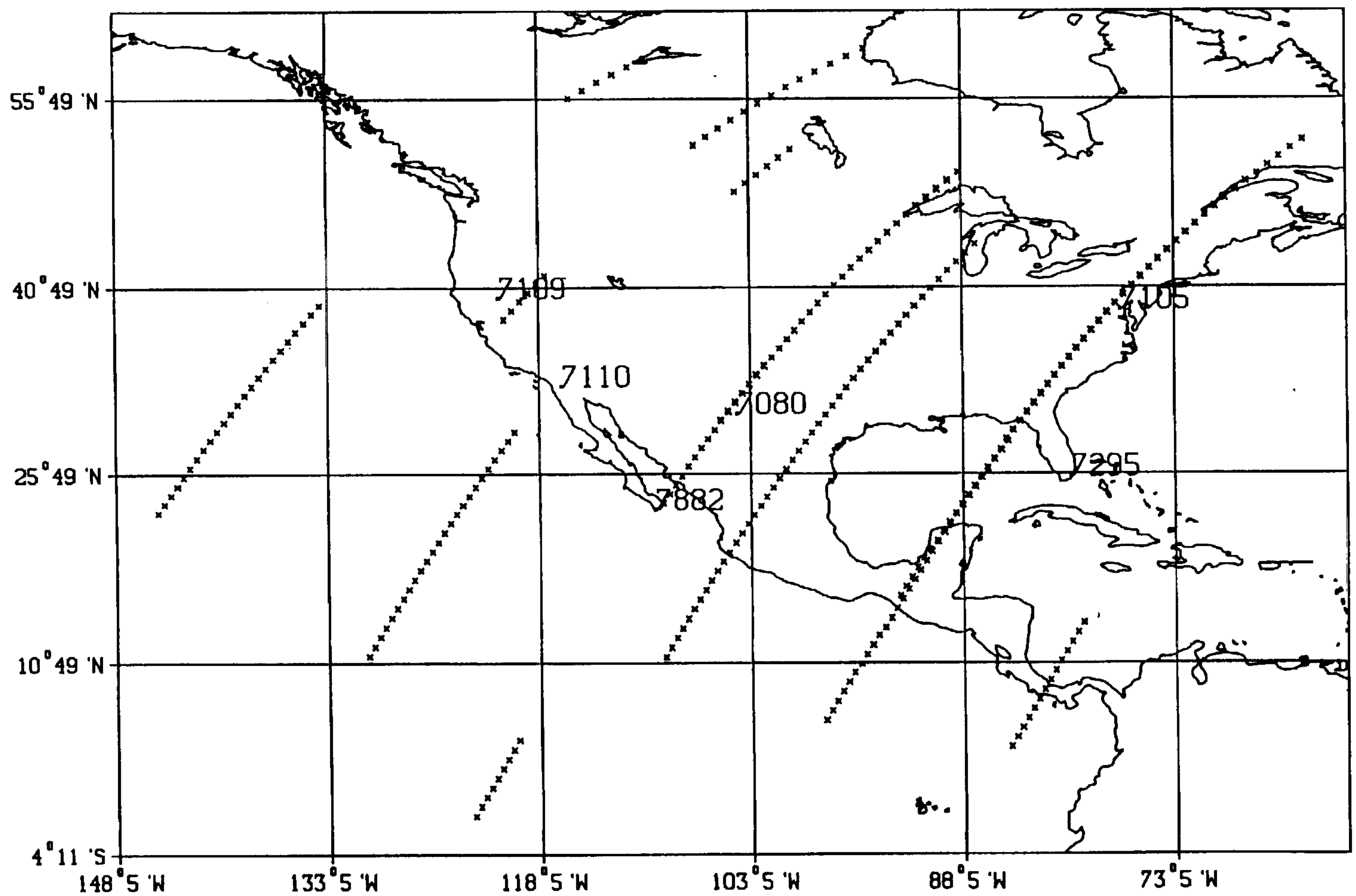

Fig. 2

GREENBELT - MONUMENT PEAK DATES 7/87 - 12/90
BASELINE = 3559741 (M) RATE = -2. (MM/YR)

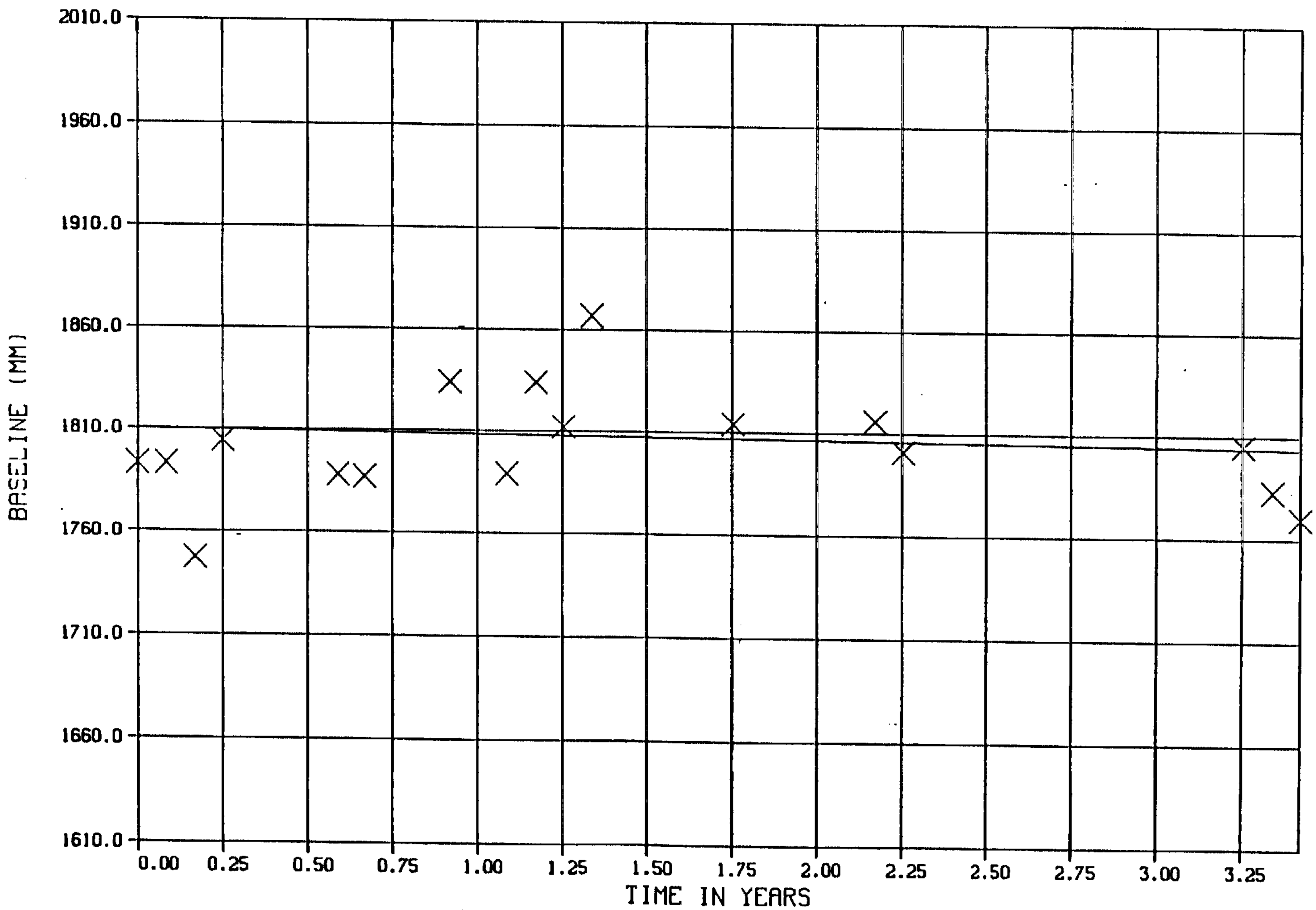

Fig 3

QUINCY - MONUMENT PEAK DATES 7/87 - 12/90
BASELINE = 883601 (M) RATE = -33. (MM/YR)

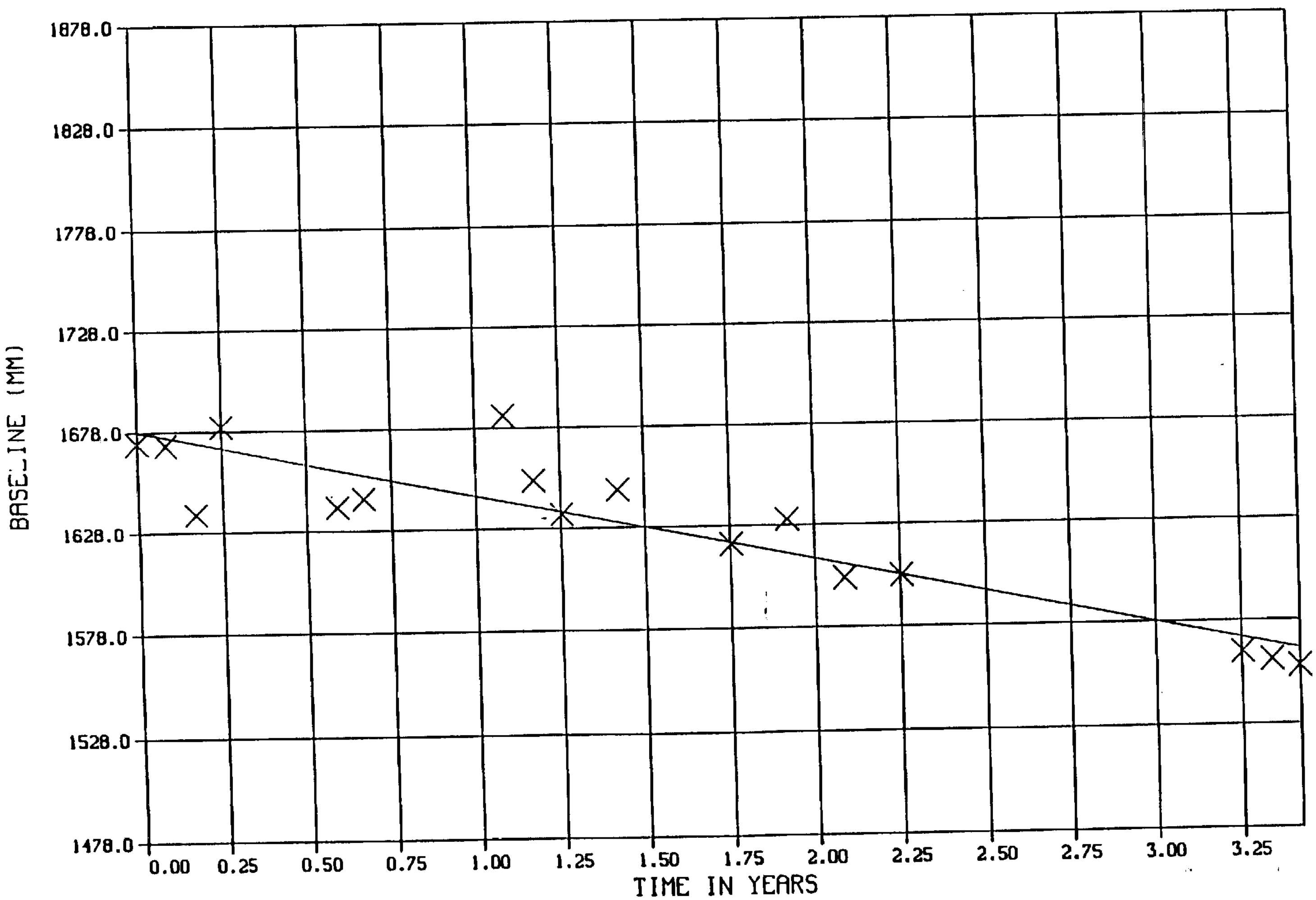

Fig 4

DIONYSOS - HERSTMONCEUX DATES 7/87 - 1/90
BASELINE = 22324305 (M) RATE = 21. (MM/YR)

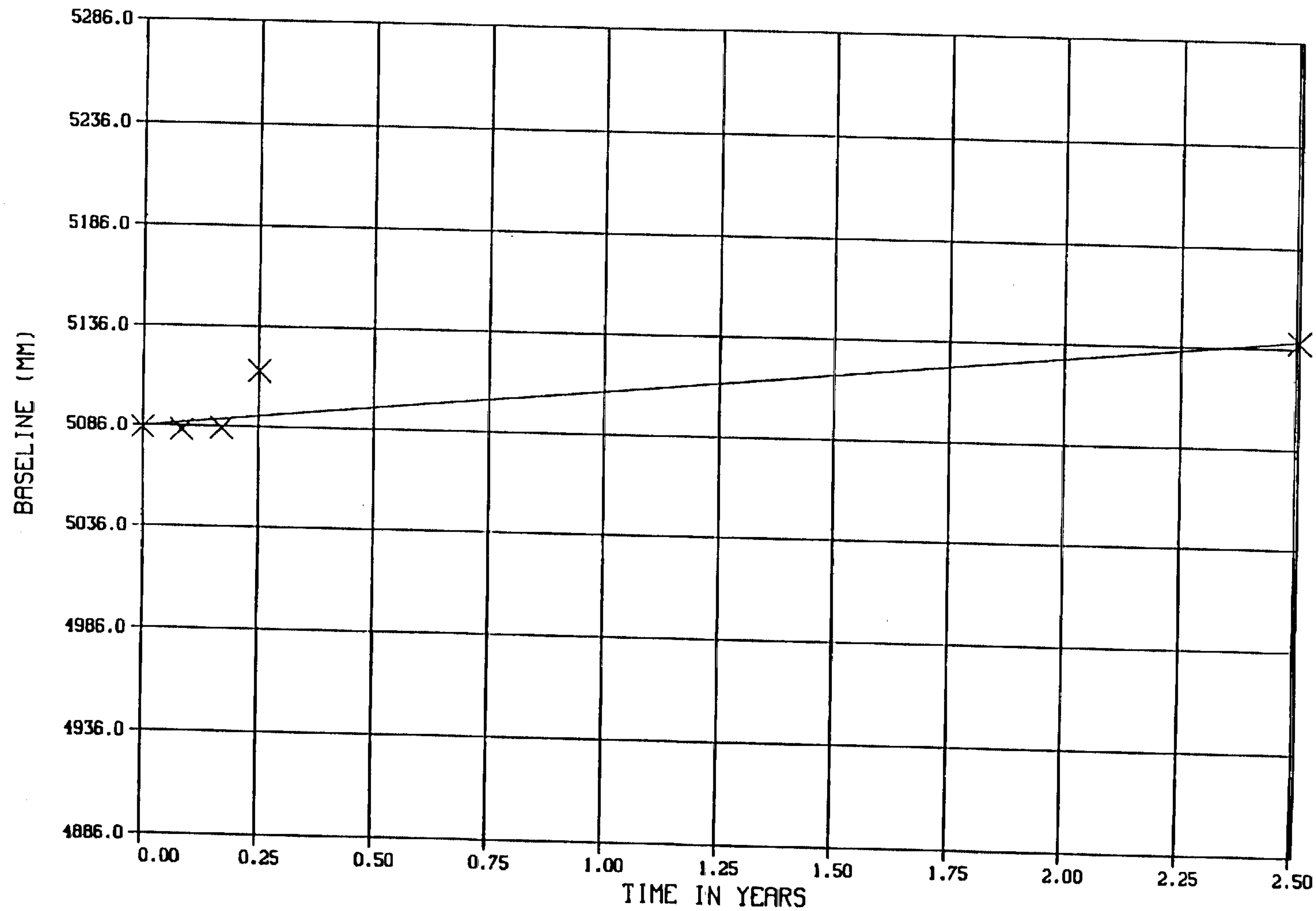

Fig. 5

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IMPROVEMENT OF SLR ACCURACY, A POSSIBLE NEW STEP

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Abstract

The SLR technology experienced a large number of technical improvements since the early 1970ies, leading now to a millimetric instrumental accuracy. Presently it appears as useless to increase these instrumental performances as long as the atmospheric propagation delay suffers its actual imprecision. It has been proposed since many years to work in multiwavelength mode, but up to now the considerable technological difficulties of subpicosecond timing have seriously delayed such an approach.

Then a new possibility is proposed, using a device which is not optimized now for SLR but has already given good results in the lower troposphere for wind measurement: the association of a radar and a sodar. While waiting for the 2-λ methodology, this one could provide an atmospheric propagation delay at the millimetre level during a few years with only little technological investment.

I/ INTRODUCTION

It has been pointed out since a long time that all space geodesy techniques have to deal with the same general problem, i. e. the crossing of the atmosphere to reach either an artificial satellite, or the moon, or a star, or a quasar, etc...

Nevertheless, if it is the same atmosphere for every techniques, the effect is known to be quite different for radiowave and for optical methodologies, the first ones suffering more than the other ones from the crossing of ionosphere (but this is corrected classically by two-frequencies methods) and from the troposphere transit (because of the atmospheric water vapor content which is quite unpredictable and has a strong impact on propagation of radio waves and not on optical ones). Considering these aspects, the general advantages of radio techniques compared with optical ones in geodesy are their all-weather capabilities, and their drawbacks are linked with their poor tropospheric correction quality.

As long as the instrumental accuracies were at a few centimeters level, this meteorological aspects were of secondary concern. This is no longer the case since many years with VLBI, who had to use costly water vapor radiometers to upgrade the tropospheric correction to an excellent level (and since this period, VLBI has got the best positioning precision among all space geodesy techniques). Since a few years too it is no longer the case with satellite laser ranging, which is able of an internal instrumental precision of a few millimeters, to be compared with the final positioning accuracy of 2–3 cm. Of course the tropospheric corrections are not the only problems biasing the results (consider for example the poor world coverage of SLR stations), but significant improvements of this parameter must be researched. Many teams have pointed out that multiwavelength methodology could provide this required amelioration. Anyway it is quite clear that this will ask for a tremendous technological effort and will probably not be operational since some years. For that reason we have looked for a new solution, able to give better tropospheric correction with up-to-date techniques, even if probably not as efficient as 2-colour method, but immediately available.

II/ THE ATMOSPHERIC CORRECTION FOR SLR

If **n** is the index of refraction, $\mathbf{n} = \mathbf{c_0} / \mathbf{c}$ ($\mathbf{c_0}$ is the light celerity in vacuum and **c** in the atmosphere).

Classically we define the co-index of refraction as

$$\mathbf{N} = (\mathbf{n} - 1).10^6$$

and for optical wavelengths, using for example Essen's formula:

$$\mathbf{N} = \mathbf{A}_\lambda (\mathbf{P_a} / \mathbf{T}).\{ 1 + (\mathbf{a} - \mathbf{b.t}).\mathbf{P_a} \} - \mathbf{B}_\lambda (\mathbf{P_v} / \mathbf{T})$$

where $\mathbf{P_a}$ is the atmospheric pressure, $\mathbf{P_v}$ is the water vapor pressure, **T** is the absolute temperature and **t** is the centigrade temperature. $\mathbf{A}_\lambda$ and $\mathbf{B}_\lambda$ are λ-dependant parameters, and **a** and **b** are constants. With a 10^{-7} precision it is acceptable to use the simplified formulation:

$$\mathbf{N} = \mathbf{A'}_\lambda (\mathbf{P_a} / \mathbf{T}) - \mathbf{B}_\lambda (\mathbf{P_v} / \mathbf{T})$$

We define also the geometric length of the optical ray $\mathbf{L_g}$, the optical path $\mathbf{L_o}$, and the geometric distance **L** between two points $\mathbf{s_0}$ and $\mathbf{s_1}$ being one at the ground level and the other beyond the atmosphere, at the satellite level:

$$L_g = \int_{s_0}^{s_1} ds \qquad\qquad L_o = \int_{s_0}^{s_1} n(s).ds$$

If we call $\Delta\mathbf{L} = \mathbf{L_0} - \mathbf{L}$, it is a function of the angle α between the vertical and the direction of the satellite. We notice that:

$$\Delta\mathbf{L} = (\mathbf{L_0} - \mathbf{L_g}) + (\mathbf{L_g} - \mathbf{L})$$

As the curvature of the ray path is low, and as this curvature is experienced only on a small range (a few tens of kilometers), the difference $\mathbf{L_g} - \mathbf{L}$ is generally considered as negligible. On another hand, $\Delta\mathbf{L}$ can be expressed as:

$$\Delta\mathbf{L} = \mathbf{f}(\alpha) \,.\, \Delta\mathbf{L}_{\mathbf{vertical}}$$

And the function $f(\alpha)$ may be found in (Berrada-Baby *et al.*, 1987 or Akhundov et Stoskii, 1992). We have now to deal with ΔL for $\alpha = 0$. h_0 being the elevation of the SLR station above "sea level",

$$\Delta L = \int_{h_0}^{\infty} N(h).dh$$

Considering the very low dependance of the result regarding the water vapor for these optical wavelengths, we will focus on the "dry" part of this expression ΔL_d :

$$\Delta L_d = \int_{h_0}^{\infty} A \frac{P_a}{T}.dh$$

And, $\rho(h)$ being the air density, $T(h)$ the absolute temperature, $P(h)$ the atmospheric pressure and $g(h)$ the acceleration of the pesanteur at the elevation h, with $R = 287$ J.kg/°K

* $P_a = \rho(h) . R . T(h)$

* $d P(h) = \rho(h) . g(h) . dh$

so that,

$$\Delta L_d = \int_{h_0}^{\infty} \frac{dP(h)}{g(h)}.A.R$$

At this level we may have different assumptions:

1st hyp. $g(h) = g_0$ = constant. Then $\Delta L_d = A.R.P_0 \ / \ g_0$

2nd hyp. $g(h) = g_0 \ / \ (1 + 2.h/r_0)$ closer to the reality. We find then:

$$\Delta L_d = \frac{A.R.P_0}{g_0}\left(1 + \frac{2R\beta}{r_0.\frac{\beta}{T_0}(g_0 + R.\beta) - 2.g_0}\right)$$

(β is the gradient of T). For P_0 = 1000 mbar, we find $\Delta L_d \doteq 2,3$ meters

And the difference between these two models is below 1 cm : various studies show (Berrada-Baby, 1987) that this discrepancy is around 5 mm, and is quite stable and thus easy to model. On another hand, the differences between the second model and real data deduced from (Cira 1965) campaigns are quite small (1 mm typically).

So we conclude that it is extremely important to measure $\mathbf{P_0}$ with an excellent precision (1 mbar of error induces 2.3 mm on the atmospheric correction). And one must take into account the fact that the function $\mathbf{f}(\alpha)$ (that is the air-mass number) will multiply these values by numbers up to 2.5 in operationnal SLR measurements.

If the temperature is measured in the first 5 kilometers, looking at fig. 1 and fig. 2, we observe that half the total correction is already acquired (fig. 1), and that the upper layers are quite well defined by the profile in the troposphere. If we compare these facts with the abovementionned value of 5 mm, whose noise is around 1-2 mm, multiplied by the air-mass value (1 to 2.5), i. e. less than 5 mm, it is clear that any temperature profile of good precision acquired in the troposphere will leave a residual error on the atmospheric correction at the millimeter level.

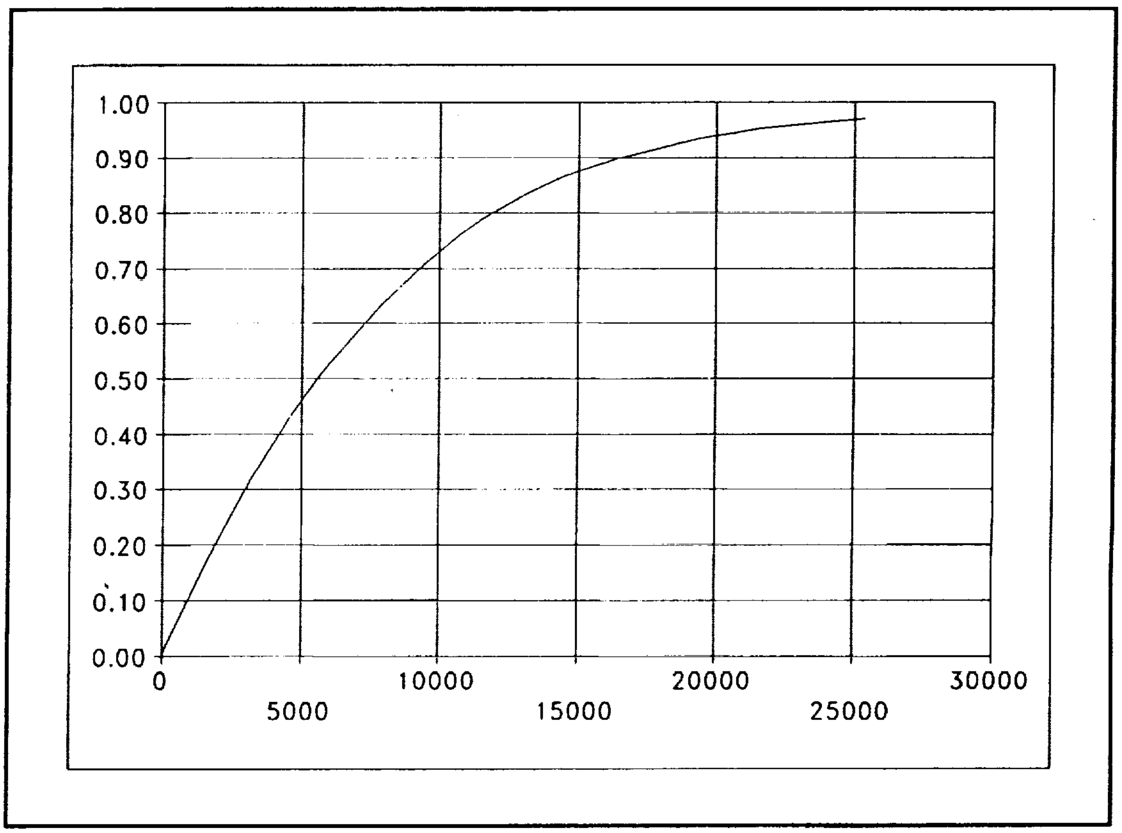

Fig. 1: Fraction (Y-axis) of the total atmospheric correction for a vertical transit of a laser pulse, from the ground level up to a given altitude (X-axis, in meters). Computed from an observed radio-profile in Greece, 1990.

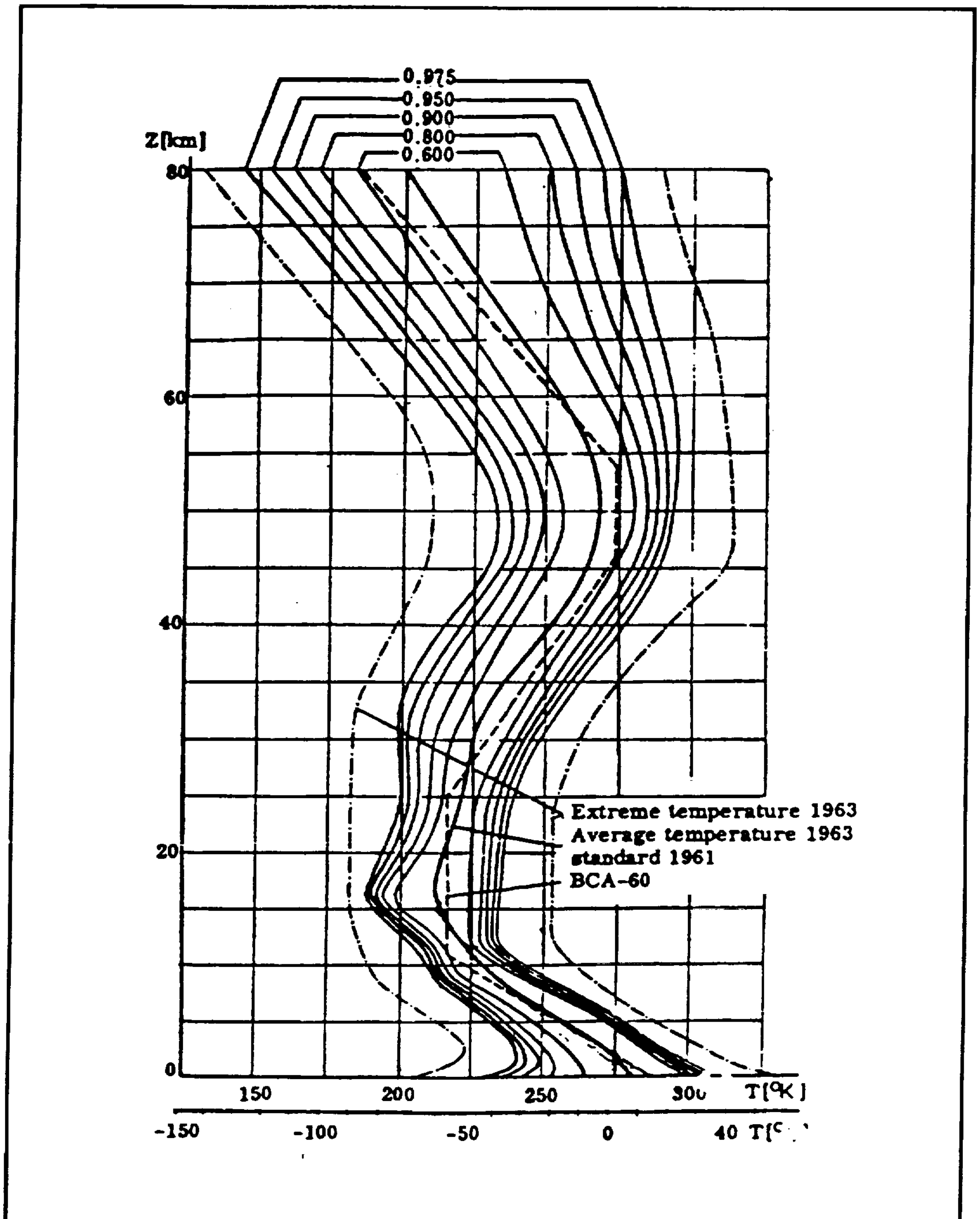

Fig. 2: Typical temperature profiles (from CIRA 1965). If the possible variations are quite large, it is also noticeable that the profiles have the same topological aspects and are quite "parallel", with no intersection from one to another.

III/ PROPOSITIONS

The first one is obviously to measure P_0 quite carefully. It is necessary to calibrate often the barometers employed, to measure preferably the pressure close to the level of the axes intersection of the telescope (it is generally the case). *It must be possible to measure the pressure with an absolute precision < 0.2 mbar.*

Considering the efficiency of barometric levelling, whose precision may reach one meter, we observe that it means that constant pressure surfaces are quite horizontal, so that it is useless to measure the horizontal gradient of P_0 in order to correct its effect in the direction of the sight, provided the weather is reasonably quiet.

Anyway, it seems mostly advisable to improve the correction by a good measurement of **T(h)** in the direction of the satellite, at the 0.1°C level, up to an elevation of 3 to 10 km.

In these conditions, one may be sure to get an atmospheric correction better than 1 mm. It is easy to notice that such a precision with 2-wavelength SLR will require a 20 times better precision on the differential time-of-flight measurement between the two colors (i. e. 0.5 picosecond), which is quite uneasy to reach.

The solution we propose for an easy measurement of the temperature profile along the line of sight is a SODAR (Acoustic LIDAR) associated with a RADAR, the acoustic and the radio wave having the same wavelength. The radar is used to track the acoustic wave, so it allows to measure the speed of the sound in the atmosphere, which in turn provides an excellent temperature profile (at the 0.1 °C level). Such instruments (e. g. Remtech) are now used close to airports, in order to measure winds and wind shears, and this technology is already available. The common ranges are 3 to 5 km, but large instruments may reach 10 km.

IV/ CONCLUSIONS

We propose that an experiment be carried with a radar/sodar equipment close to an up-to-date SLR station in order to check the possible improvements that such data could provide to the laser data. This solution is probably an excellent alternative allowing to wait for the 2-wavelength generation of SLR stations.

On another hand, we insist on the necessity to check quite carefully the barometric equipments used in SLR stations, as the $\mathbf{P_s}$ parameter is by far the most important to perform a good atmospheric correction.

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