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CHŌFU, TOKYO, JAPAN

Determination of Station Coordinates, Earth Rotation and Plate Motions from LAGEOS Laser Ranging: 1983-1986*

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ABSTRACT

This paper presents a summary of recent results of analyses of satellite laser ranging (SLR) data collected by the LAGEOS (Laser Geodynamics Satellite) for the 3.3-year period from September 1983 to December 1986. The LAGEOS data were analyzed to compute earth rotation parameters and a new global solution of the geocentric coordinates for 39 laser tracking stations. Laser station positioning was part of a simultaneous adjustment of parameters for the LAGEOS orbital elements, an along-track acceleration, a solar radiation pressure coefficient in 30-day arcs and earth rotation parameters in 5-day subarcs. The earth rotation series, computed at 5-day intervals, have an internal precision of better than 2 mas for polar motion components and 0.15 ms for the change in the length of day. For 15 selected laser stations, baseline and station coordinate changes have been investigated by successive determination of station positions using annual datasets covering the 3-year period beginning in January 1984. It is shown that laser observed rates of change in baseline lengths are in general agreement with the motions predicted by the Minster-Jordan AM1-2 model. Plate motions relative to Shimosato laser station have been observed for the first time using SLR data.

概　　要

測地衛星「ラジオス」に対して，世界のレーザ追跡局によって観測された衛星レーザ測距データの解析結果について述べる。データはNASA地殻力学プロジェクト提供の1983年９月～1986年12月のフルレートデータである。フルレートデータは極めて多量であるため，航技研において，３分間のデータから１個のノーマルポイント（正規点）を生成し，この圧縮したデータを解析に使用した。まず，全期間のラジオスデータを30日毎のアーク40個に分割する。各アークの元期における軌道要素，ラジオス抵抗係数，太陽輻射圧係数，地球回転パラメータ（極運動と世界時）を各アークに固有のパラメータとして，そして局位置座標を全アークに共通するパラメータとして，重み付き最小２乗法によって全データから唯一解として求めた。この局位置解は，レーザ追跡局（39局）の地球重心に関する３次元位置座標を表わし，航技研におけるレーザデータ解析の基準座標系を与える。各位置座標成分の精度は３～5cmである。また，５日平均の極運動シリーズの内部精度は2mas（1masは１秒角の1000分の１）以内，１日の長さの超過分（世界時の数値微分として求めた）の精度は0.15ミリ秒である。

次に局位置および基線長（局間距離）のプレート運動によると思われる時間変化を見るた

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めに，12アーク毎に局位置座標解（年平均解）を逐次決定した。ただし，1984年1月からの3年間連続して高精度データを観測した15局のみ考慮した。こうして，基線長について年度毎の観測値を求める。基線長の年変化から，この3年間の平均的な基線長変化率およびそのプレート毎の平均としてプレート運動の速度を観測した。一方，Minster & Jordan（1978年）はトランスフォーム断層の向き，震源スリップベクトルの方向，海洋底の地磁気縞模様等の地質学的データからおよそ300万年間の平均的なプレート運動を推定している。そこでレーザデータから求めた基線長変化率およびプレート運動を，地質学的モデルから予測される値と比較したところ，このデータ期間において一般に良く一致することが認められた。特に，本解析では日本唯一の第3世代レーザ測距装置である下里局（和歌山県那智勝浦町）のデータも同時処理しており，下里を基準点として，日本列島と太平洋プレート，インド・オーストラリアプレートとの相対運動の観測に衛星レーザ測距としては初めて成功している。

INTRODUCTION

Satellite laser ranging (SLR) has been playing an increasingly important role in the observation of global geodynamical phenomena from space. The earth rotation, geotectonics, and ocean dynamics are representative of research fields in which SLR technique has proven its ability. The nature of these studies requires acquisition of global observations, intensive data analyses, and interpretations of the results. The observation of global earth dynamics, therefore, has been carried out as the international cooperative programs.

The determination of the earth rotation was the principal objective in project MERIT, an IAU/IUGG international collaboration to monitor earth rotation and intercompare the techniques of observation and analysis [1]. The MERIT Main Campaign was conducted for the 14-month interval of September 1983 to October 1984, and during this period space techniques such as SLR, very long baseline interferometry (VLBI), lunar laser ranging (LLR) were used to collect observations for rotational dynamics of the earth. Intercomparisons of the analysis results by each technique including the conventional optial method have shown that space techniques have the capability to determine earth rotation parameters with the accuracies by an order of magnitude better than the conventional method [2]. The National Aerospace Laboratory (NAL) participated in the MERIT project as an analysis center for SLR technique and our MERIT solutions are reported in [3] ~ [5]. MERIT has been extended until January 1988 when a new organization for an international earth rotation service (IERS) based primarily on space techniques will become operational (MERIT extension). The MERIT extension has been performed under the NASA's Crustal Dynamics Project (CDP) [6].

According to plate tectonics, the upper surface of the earth consists of the crust and about 12 major lithospheres called "plates" with a depth of 70 ~ 100 km. Each plate with the overlying crust moves horizontally like a rigid body with no deformation. It is considered that relative plate motions at the plate boundaries are a cause of large earthquakes. The measurement of tectonic plate motion and deformation is of critical interest to verify hypothesis in geotectonics and to provide important input to the understanding of earthquake mechanism and prediction. This is the primary subject in the CDP which took place in 1979. Similarly, Wegener Mediterranean Laser campaign (WEGENER-MEDLAS) has been formed to detect plate motions in the Mediterranean areas using geodetic space techniques. Early results of observing plate motions obtained in these two projects using SLR technique are described in [7] ~ [10].

After the participation in project MERIT, NAL also has been involved in the CDP and performed analyses of SLR data for geodesy and geodynamics applications. Our latest results of analyses of 3.3 years of SLR data (September 1983 ~ December1986) to LAGEOS (Laser Geodynamics Satellite) are presented in this paper. The results include two major solutions: a new set of global station coordinates (NAL 8701) and the accompanying earth rotation sereis; and the sequence of annual station coordinates. The global station coordinates were determined as part of a simultaneous adjustment for orbit and earth rotation parameters using 40 thirty-day arcs, and provide solution for the geocentric positions for 39 laser sites tracked LAGEOS over the 3.3-year period. Note that this multi-year station solution averages out the effect of plate motions during this interval.

In SLR technique, plate motions are observed as the time-ordered change in baseline lengths. The rates of change in the baseline lengths have been derived from successively determined annual positions. Of special interest are the plate velocities relative to Shimosato laser station (SHO). SHO, located in the central part of the Main Island of Japan, is the only third generation laser system operated by the Hydrographic Department of the Maritime Safety Agency of Japan. The system has been operational since March 1982 [11]. It is stressed that the results presented herein are the first observations of plate motion around the Japan Islands which have been made in Japan using SLR technique.

DATA AND ANALYSIS METHOD

SLR data available at NAL are the "full-rate" data distributed from NASA Goddard Space Flight Center (GSFC). The full-rate data taken on LAGEOS are extremely large. In order to improve computational efficiency, these data were analyzed in the form of laser normal points at 3-minute intervals. The normal point procedure has another advantage that it imposes an equal weight on each pass, regardless of the pass length and the number of full-rate data included in the individual pass, during the adjustment process. For the 1983/1984 time frame, the 3-minute normal points computed by the University of Texas' Center for Space Research (UT/CSR) were used. The normal points for the 1985/1986 data period were generated by NAL, using an algorithm very close to Herstmonceux Standards [12].

Prior to the final analyses the quality of the NAL normal points was assessed by comparison with that of the UT/CSR normal points for the overlapped 5-month periods of January to May 1985. Both datasets, when applied to fit to the LAGEOS orbit, showed no significant difference in the estimation results. The small differences could be attributed to the use of different versions of the full-rate data tapes (we used the latest version for the normal point creation) and different data compression procedure. From these comparisons, it is concluded that the NAL normal points have the same quality as those of the UT/CSR [13].

An overview of the UT/CSR and NAL normal points used in this analysis for the entire 3.3 years is shown in Figs. 1 and 2. Fig. 1 shows a summary of the monthly LAGEOS observation status of laser tracking stations, indicating the total of 41 laser stations tracked LAGEOS during this interval. In the figure sites giving at least one normal point a month are barred. Fig. 2a shows the number of laser stations that provided normal points in each month and on the average 17.6 stations tracked LAGEOS. Fig. 2b shows the total number of normal points in each monthly frame. The average number of normal points contained in each 30-day arc is 3,430. In total, normal points of 139,838 including passes of 13,372 from 41 laser stations are constructed. The full-rate data precision is about 5 cm on the average, while the formal precision of normal points is usually better than 1 cm.

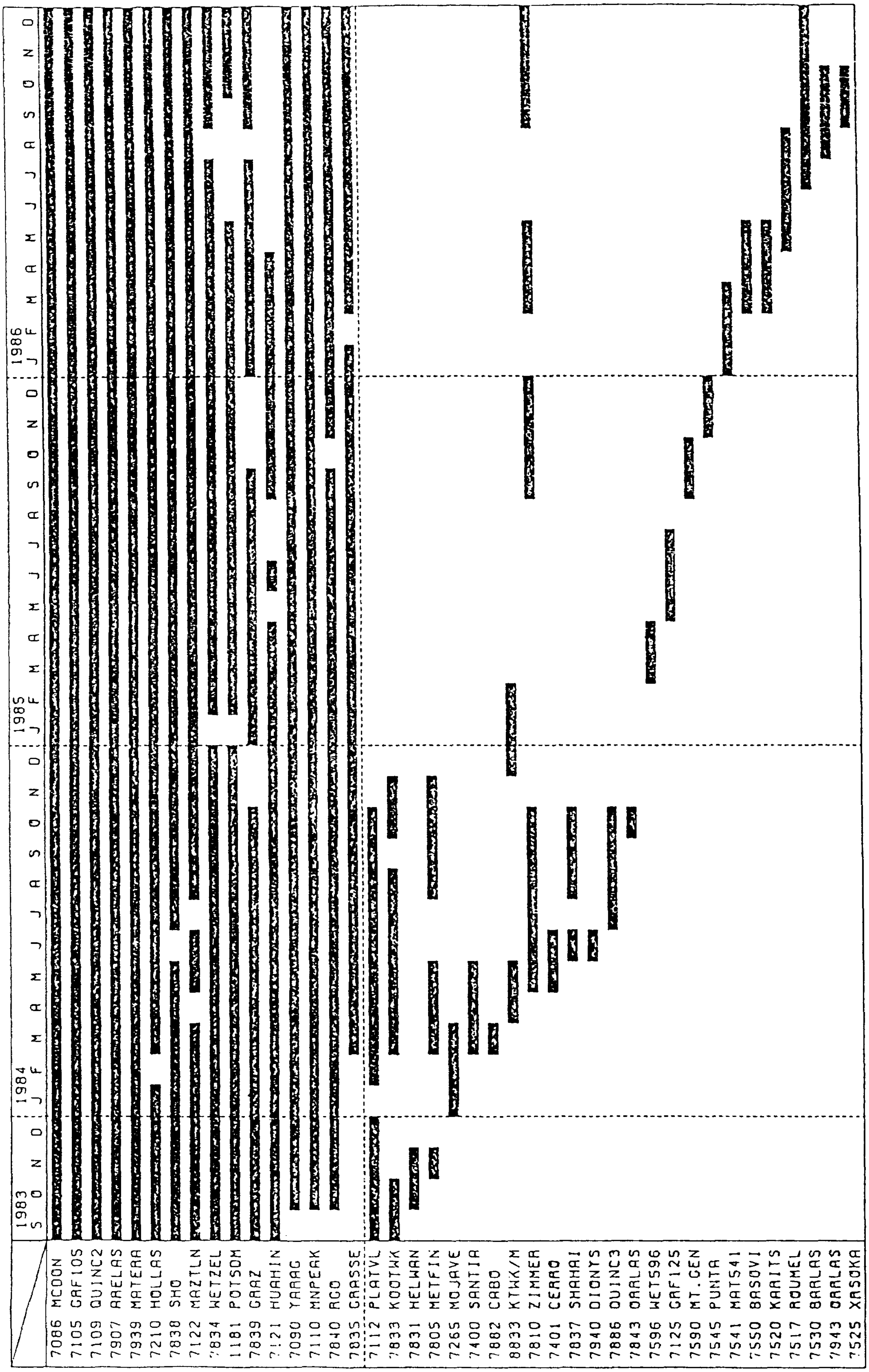


Fig. 1 Overview of Monthly LAGEOS Observation Status in the 1983/1986 Data Period

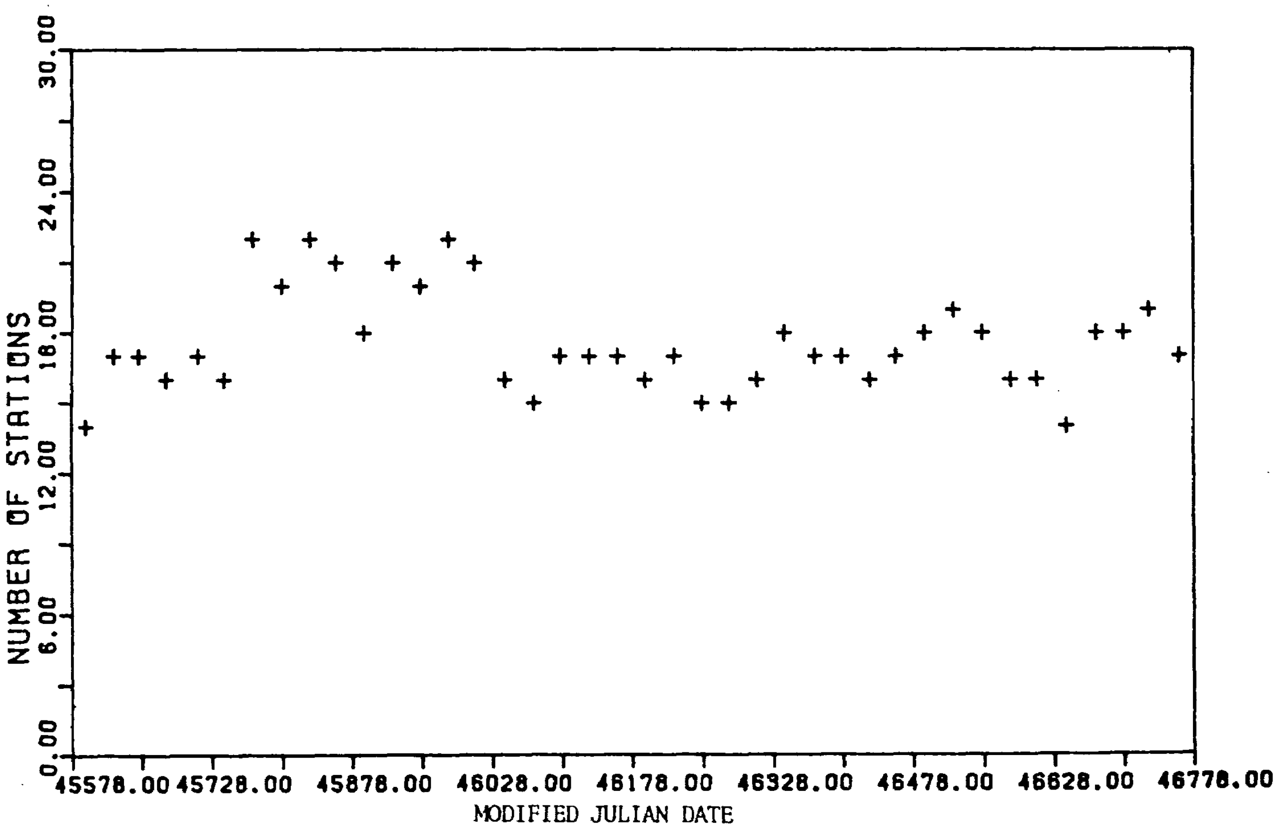


Fig. 2a Number of Laser Stations Tracked in Each Monthly Interval

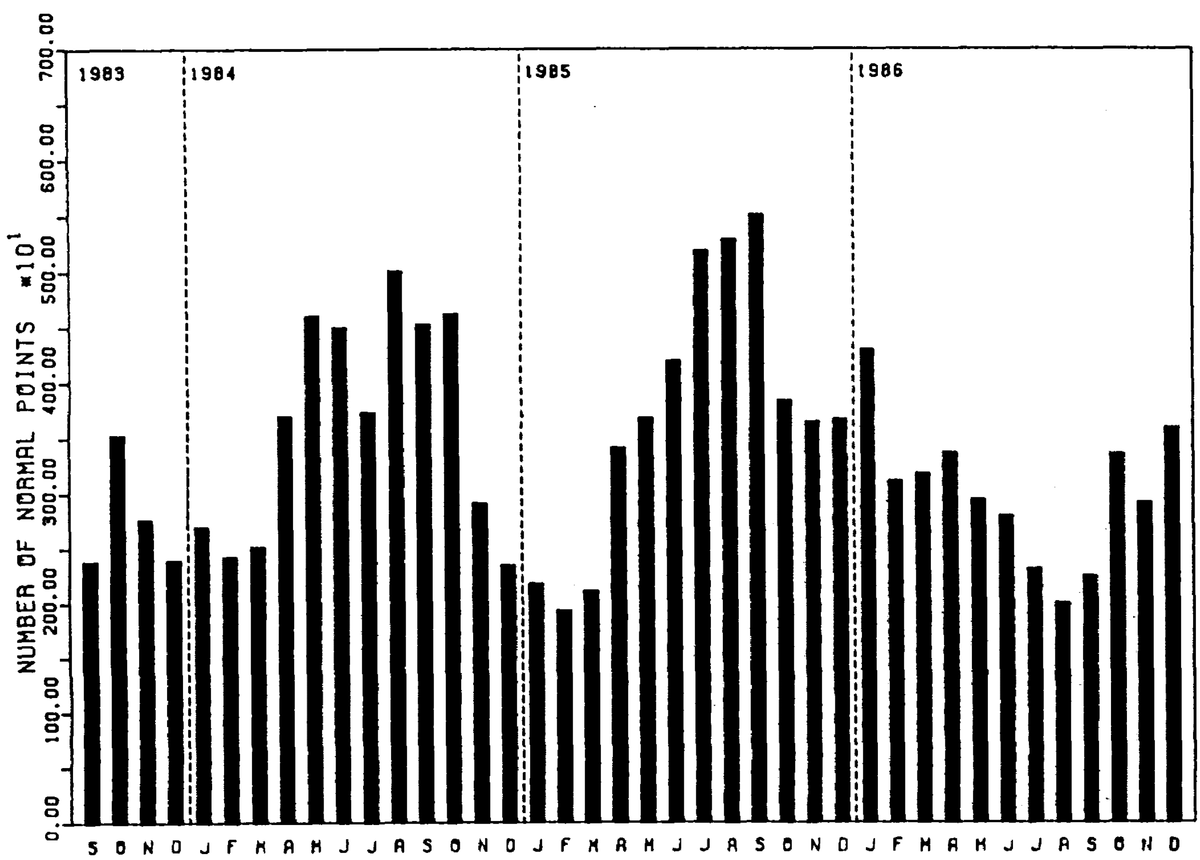


Fig. 2b Number of Normal Points in Each of Monthly Intervals

NAL orbit processor (for instance, see [14]) has been used in data analysis. Parameter estimation is based on a weighted least squares adjustment of tracking observations to a satellite orbit using a numerical integration method. It possesses the multi-arc processing capability. That is, a single simultaneous solution for station coordinates, earth rotation parameters, orbit and dynamical parameters is determined from multiple arcs of data. All the astronomical constants, kinematical models, perturbational force models, and measurement correction models adopted for LAGEOS data reduction software closely follow the MERIT Standards [15] and are summarized in Table I.

In the first solution to be discussed, the entire

Table I. Summary of Computation Models Adopted for LAGEOS Analysis.

Force model

Gravitational

Earth; GEM-L2 complete to degree and order 20 (Lerch et al., 1985 [16])
Sun, Moon, Venus through Saturn; JPL DE200/LE200 (Standish, 1982 [17])
Solid earth tides; Wahr (1981a) model [18] using the earth model 1066A of Gilbert and Dziewonski (1975) [19]
Ocean tides; Schwiderski (1980) model [20]

Nongravitational

Drag; Along-track acceleration on Lageos
Solar radiation pressure; Direct solar eclipse by the earth and moon using conical shadow model
Special and general relativistic effects are not applied.

Earth orientation

IAU 1976 Precession (Lieske et al., 1977 [21])
IAU 1980 Nutation (Wahr, 1981b [22])
Definition of UT (Aoki et al., 1981 [23])
Periodic UT1 (Yoder et al., 1981 [24])
Earth rotation and polar motion; solved-for parameters

Equations of motion

Mean equator and equinox of J2000.0 nonrotating reference frame

Measurement model

Laser station coordinates; solved-for parameters by global adjustment
Tropospheric refraction; Marini and Murray (1973) [25]
Solid tides; Wahr (1981a) [18] using the 1066A earth model
Ocean loading site displacements (Schwiderski, 1980 [20]) are not applied.
Centre-of-mass offset correction
Time-tag correction; referred to UTC(BIH)
3-minute NAL/CSR normal points

Data span

September 1983 to December 1986

Software

NAL orbit processing system [14]

data span was used to determine a single set of the geocentric coordinates of the laser stations, simultaneously with orbit and earth rotation parameters (polar motion and universal time UT1). As implemented in the orbit processor, the difference between UT1 and the International Atomic Time (TAI), (UT1-TAI), is adjusted. In the orbital analysis, LAGEOS orbital elements at arc epoch, LAGEOS-drag, solar radiation pressure coefficient, 5-day averaged polar motion, and values of (UT1-TAI) at 5-day subarc epochs are estimated as arc-dependent parameters in each of 30-day data arcs, and station coordinates are adjusted uniquely as arc-independent or common parameters from all 40 thirty-day arcs. To remove the longitude singularity and ill-conditioning in the z-axis orientation, we fixed the longitude and latitude of GRF105 (7105) and the latitude of SHO (7838). Furthermore, to eliminate the singularity between the satellite's nodal longitude and the earth's longitude, we fixed in each 30-day arc the first value of (UT1-TAI) at the smoothed value of the Bureau International de l'Heure (BIH) Circular D publications, and each of the remaining (UT1-TAI) values was adjusted. In the solution process each normal point was weighted by the noise level of 50 cm for all stations. This solution for global station coordinates forms the basis for an initial definition of the terrestrial reference frame (as realized by the set of tracking stations through their coordinates). It should be noted, however, that the station coordinates and the corresponding baselines obtained in this way represent the mean values in which the plate motions and deformations during the 3.3-year interval are averaged out.

In the second solution for observing tectonic plate motions from SLR data, station positions were adjusted using consecutive annual data intervals beginning in January 1984. For this investigation, 15 laser stations are selected which,

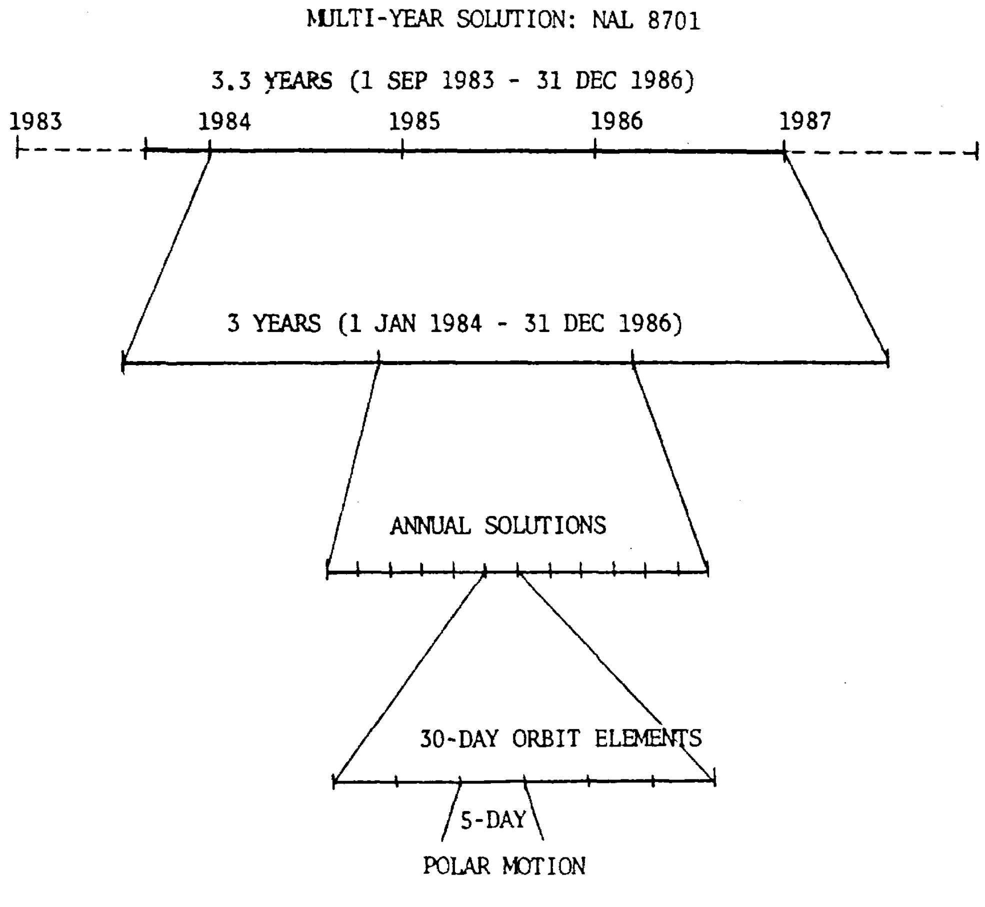


Fig. 3 LAGEOS Data Analysis Overview

in view of Fig. 1, tracked LAGEOS in the three-year interval. The Potsdam (1181) laser was excluded because of a less accurate older generation system. To establish a stable terrestrial reference frame, we fixed the latitude of GRF105 and SHO and the longitude of Yaragadee at the values of the multi-year station coordinates (NAL 8701). Other than these, the solution procedure was exactly the same as that used for 3.3-year analysis. Fig. 3 summarizes the aforementioned solution approach for plate motion identification. On the basis of these annually determined coordinate solutions, the rates of change in baseline lengths are computed and compared to the rates predicted by a model of geologic tectonic plate motions of Minster and Jordan [26].

RESULTS AND DISCUSSION

Global Station Coordinates and Earth Rotation

As shown in Fig. 1, LAGEOS SLR data for this 3.3-year interval have been obtained by more than 40 laser stations which include some sites visited for only a few months by the transportable systems of NASA and European MTLRS. For the solution of global station coordinates, TLRS-1 occupation at Quincy (7886) and MTLRS-1 occupation at Kootwijk (8833) were unadjusted due to site anomalies, and in total 39 sites are considered. Table II summarizes the final results of station coordinates, which are referred to as the NAL 8701 system or SSC (NAL) 87 L 01 in the BIH designation. The NAL 8701 system defines the terrestrial reference coordinate system used for all geodetic studies at NAL. In this table, sites with an asterisk are shown in the geodetic marker. The standard deviations for each of the cartesian coordinates represent formal uncertainties associated with data weight assigned and the number of normal points in the fit period and no scaling has been applied. The coordinates given in Table II must be regarded as the time-averaged positions of the stations during the 3.3-year interval, so that the mean epoch for each station coordinate was assigned to indicate the average date of all normal points from the respective site. Note also that the solution was determined using 398,600.448 km^3/s^2 for the earth's gravitational parameter (GM), and 299,792,458 m/s for the speed of light. These values are consistent with the recommended values in the MERIT Standards.

The 5-day averaged values of the pole position in the X_p and Y_p coordinates and the change in the length of day are shown in Figs. 4a and 4b and Fig. 5, respectively. The solid curves in Fig. 4 show the Vondrak-smoothed curves using $\epsilon = 10^{-4}$ (half amplitude at about 30 days) for each of the polar motion series. The rms fit of the series to the smoothed curve was 1.7 mas for X_p component and 1.3 mas for Y_p component. The change in the length of day DR was computed through numerical differentiation of the (UT1R-TAI), the time series with the effects of tides removed [24]. The formal uncertainties in the polar coordinates are better than 2 mas and the precision of the length of day is estimated to be below 0.15 ms.

Estimates of an along-track acceleration and solar radiation reflectivity coefficient in the LAGEOS orbit were obtained as part of the simultaneous adjustment in the NAL 8701 solution. Figs. 6 and 7 show values of the recovered along-track acceleration and solar radiation coefficient over each 30-day arc, respectively. The average along-track acceleration computed from these values was -3.524×10^{-12} m/s^2, while the average value of the estimated solar radiation coefficient was about 1.121.

Fig. 8 presents a summary of the overall rms of laser range residuals associated with the NAL 8701 solution. The results indicate that 30-day orbits are fitting the LAGEOS normal points to about 11 cm on the average. It seems, however, that an rms of fit of residuals for the UT/CSR normal points (first 16 monthly arcs) is slightly large as compared to those of the rms of fit

Table II. The NAL 8701 Laser Station Coordinates.

ID STATION	CARTESIAN COORDINATES X (m)	σx (m)	Y (m)	σY (m)	Z (m)	σZ (m)	MEAN EPOCH
1181 POTSDM	3800621.188	0.058	882005.293	0.037	5028859.921	0.048	46104.4
7086 MCDON*	-1330125.315	0.024	-5328526.738	0.024	3236150.355	0.024	46283.5
7090 YARAG*	-2389006.393	0.020	5043329.349	0.012	-3078525.446	0.018	46223.2
7105 GRF105*	1130719.764	0.002	-4831350.659	0.008	3994106.666	0.007	46181.0
7109 QUINC2*	-2517234.788	0.015	-4198556.378	0.033	4076569.751	0.027	46171.6
7110 MNPEAK*	-2386277.932	0.018	-4802354.548	0.030	3444881.439	0.028	46204.3
7112 PLATVL*	-1240678.229	0.035	-4720463.392	0.037	4094480.673	0.028	45781.1
7121 HUAHIN*	-5345865.104	0.038	-2958246.928	0.039	-1824624.004	0.046	45996.7
7122 MAZTLN*	-1660089.292	0.027	-5619100.520	0.022	2511637.896	0.027	46205.6
7210 HOLLAS*	-5466006.562	0.012	-2404428.211	0.047	2242187.332	0.040	46088.9
7805 METFIN	2892594.944	0.167	1311808.222	0.146	5512610.265	0.107	45875.1
7810 ZIMMER	4331283.446	0.054	567549.464	0.040	4633140.360	0.051	46290.1
7833 KOOTWK	3899224.144	0.075	396742.818	0.052	5015074.213	0.050	45823.0
7834 WETZEL	4075529.969	0.047	931781.303	0.023	4801618.596	0.046	46115.7
7835 GRASSE	4581691.702	0.042	556159.404	0.026	4389359.759	0.048	46294.3
7838 SHO	-3822388.551	0.048	3699363.359	0.046	3507573.188	0.006	46254.3
7839 GRAZ	4194426.535	0.049	1162693.879	0.025	4647246.788	0.048	46137.2
7840 RGO	4033463.713	0.040	23662.323	0.019	4924305.356	0.041	46259.0
7907 ARELAS	1942792.144	0.055	-5804077.738	0.022	-1796919.214	0.015	46113.3
7939 MATERA	4641964.980	0.043	1393069.930	0.021	4133262.578	0.051	46196.8
7265 MOJAVE*	-2356475.767	0.055	-4646618.415	0.066	3668424.743	0.047	45734.7
7400 SNTAGO*	1769699.984	0.095	-5044612.985	0.054	-3468259.916	0.061	45804.6
7401 CERTOL*	1815517.411	0.075	-5213464.865	0.044	-3187999.330	0.043	45854.2
7530 BARGIY	4443968.324	0.073	3121946.878	0.062	3334695.818	0.084	46730.0
7831 HELWAN	4728283.264	1.759	2879669.072	1.197	3156895.316	1.088	45646.4
7837 SHAHAI	-2831087.775	0.085	4676203.479	0.069	3275172.955	0.053	45973.8
7843 NATMAP	-4446476.798	0.070	2678127.234	0.075	-3696252.085	0.057	45988.0
7882 CABO*	-1997241.591	0.164	-5528041.067	0.129	2468355.056	0.130	45761.7
7940 DIONYS	4595217.250	1.901	2039464.395	0.715	3912613.440	0.517	45865.6
7596 WETZEL MTLRS-2	4075585.202	0.169	931837.973	0.542	4801559.516	0.424	46145.3
7520 KARITSA	4596044.920	0.057	1733477.730	0.055	4055720.197	0.037	46536.1
7541 MATERA MTLRS-2	4641992.867	0.048	1393042.974	0.051	4133231.074	0.034	46458.8
7550 BASOVIZZA	4336741.090	0.074	1071272.620	0.095	4537911.318	0.061	46556.2
7517 ROUMELLI	4728697.401	0.041	2174374.687	0.050	3674572.452	0.046	46637.0
7525 XRSOKALARIA	4745952.379	0.069	1905707.116	0.083	3799168.569	0.072	46694.5
7943 UNKNOWN	-4446476.549	0.035	2678126.941	0.039	-3696251.753	0.035	46685.0
7125 GRF125 MTLRS-1	1130744.038	0.063	-4831369.839	0.052	3994077.821	0.042	46230.9
7590 MT.GENEROSO	4390312.279	0.042	696751.884	0.049	4560835.488	0.032	46341.2
7545 PUNTA SA MENTA	4893400.628	0.054	772673.861	0.071	4004140.187	0.047	46386.5

*The stations marked with an asterisk are monument coordinates.

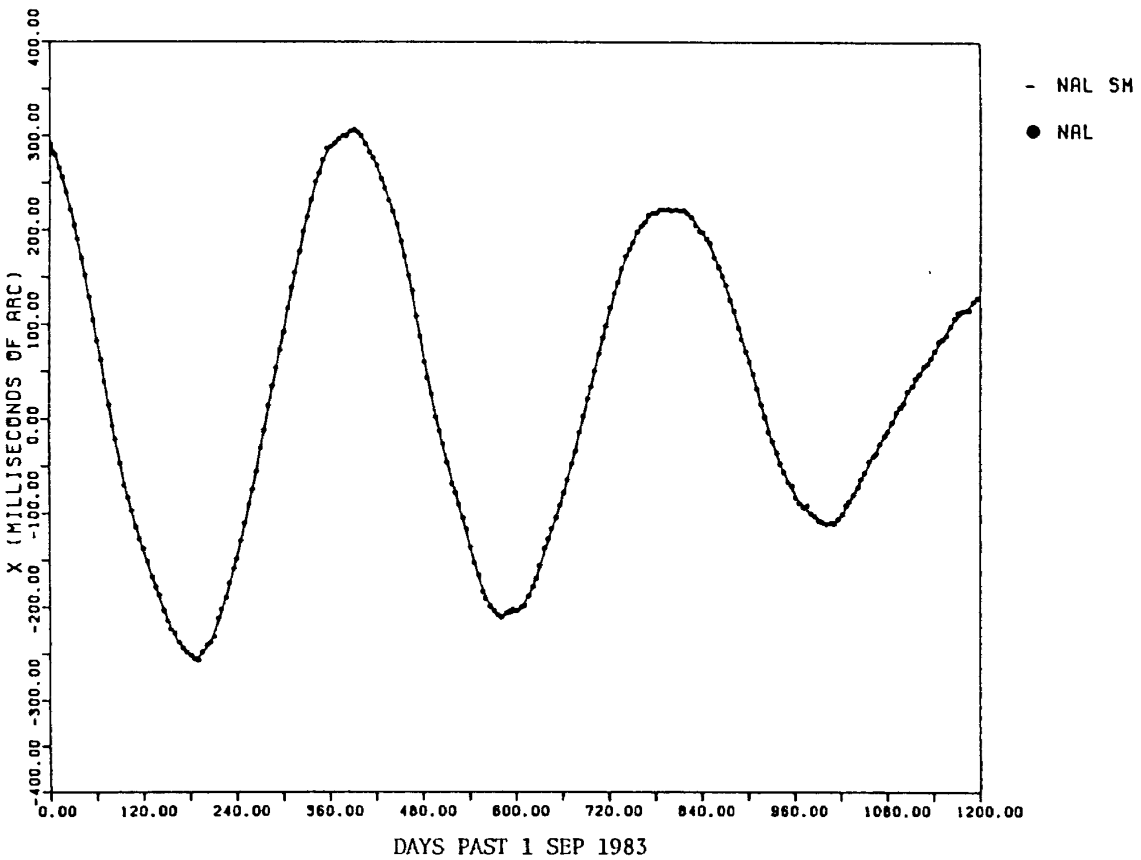


Fig. 4a Polar Motion, X-Component

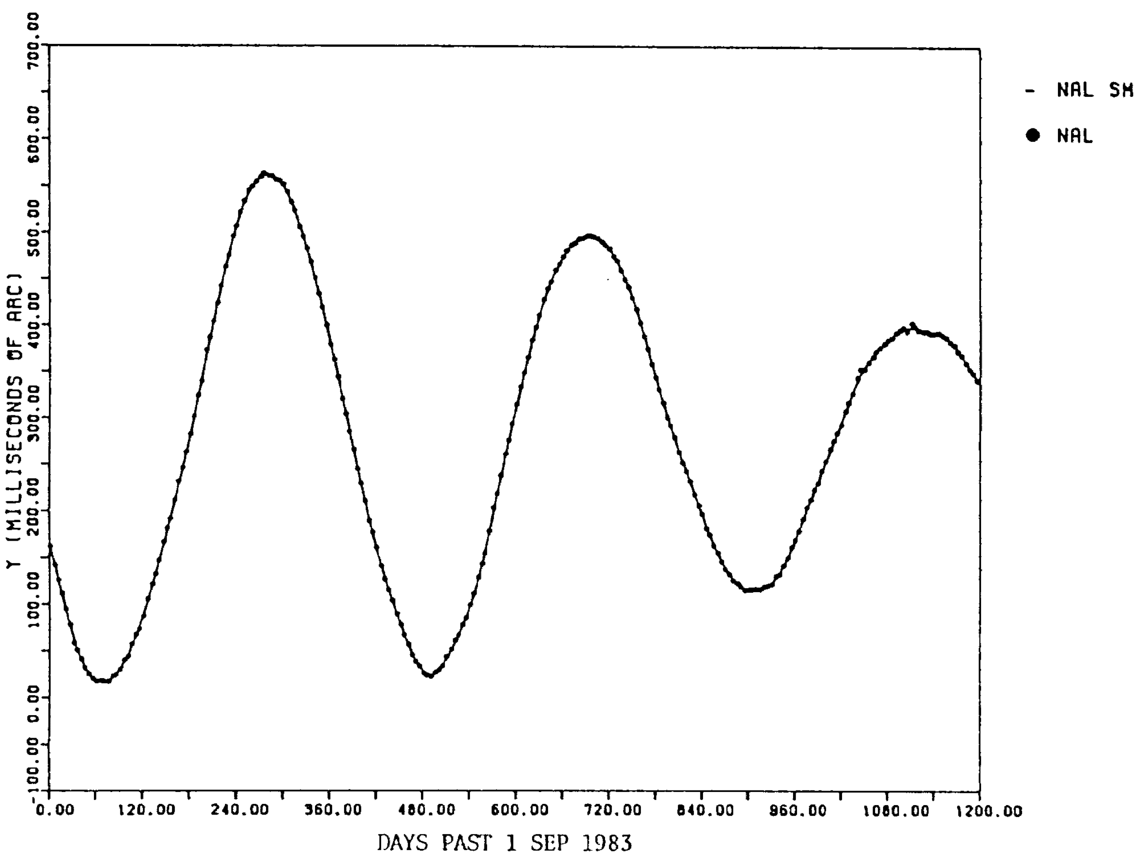


Fig. 4b Polar Motion, Y-Component

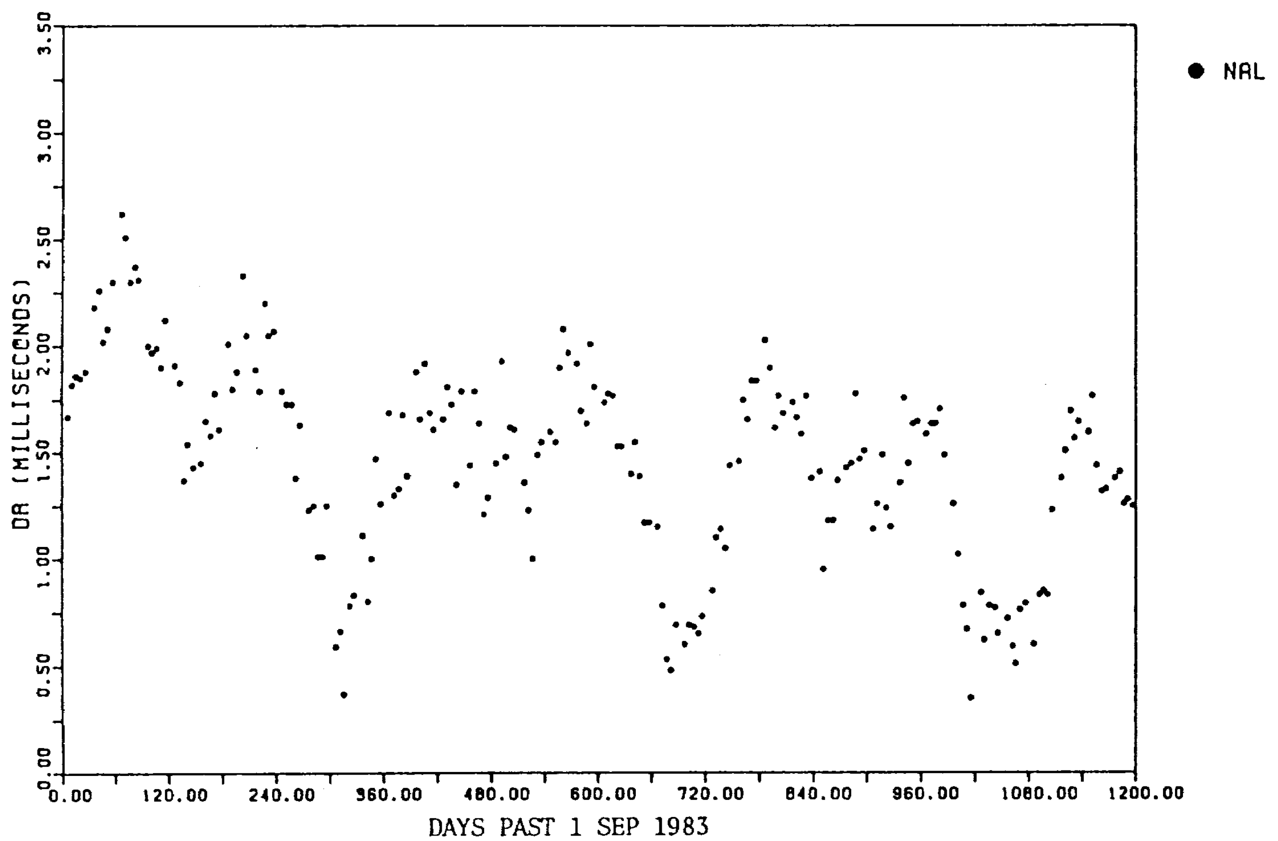


Fig. 5 The Excess Length of Day

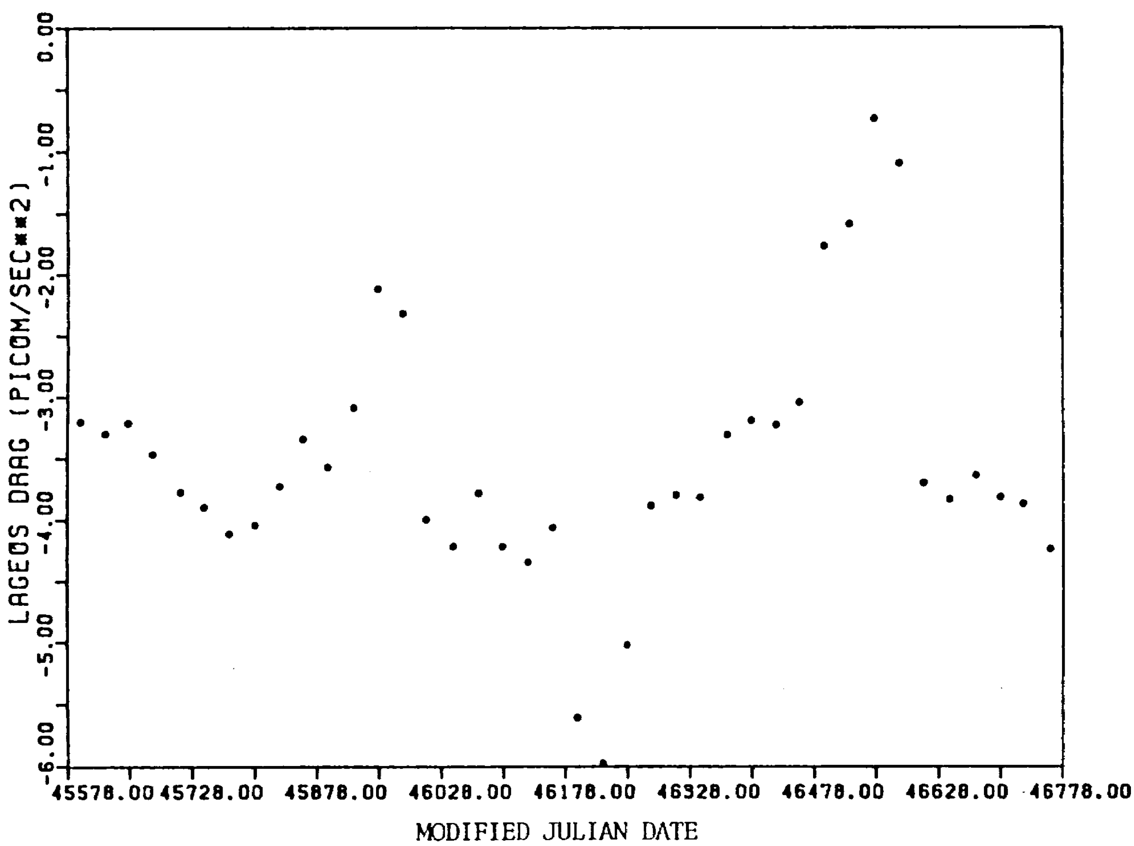


Fig. 6 Estimate of Along-Track Acceleration

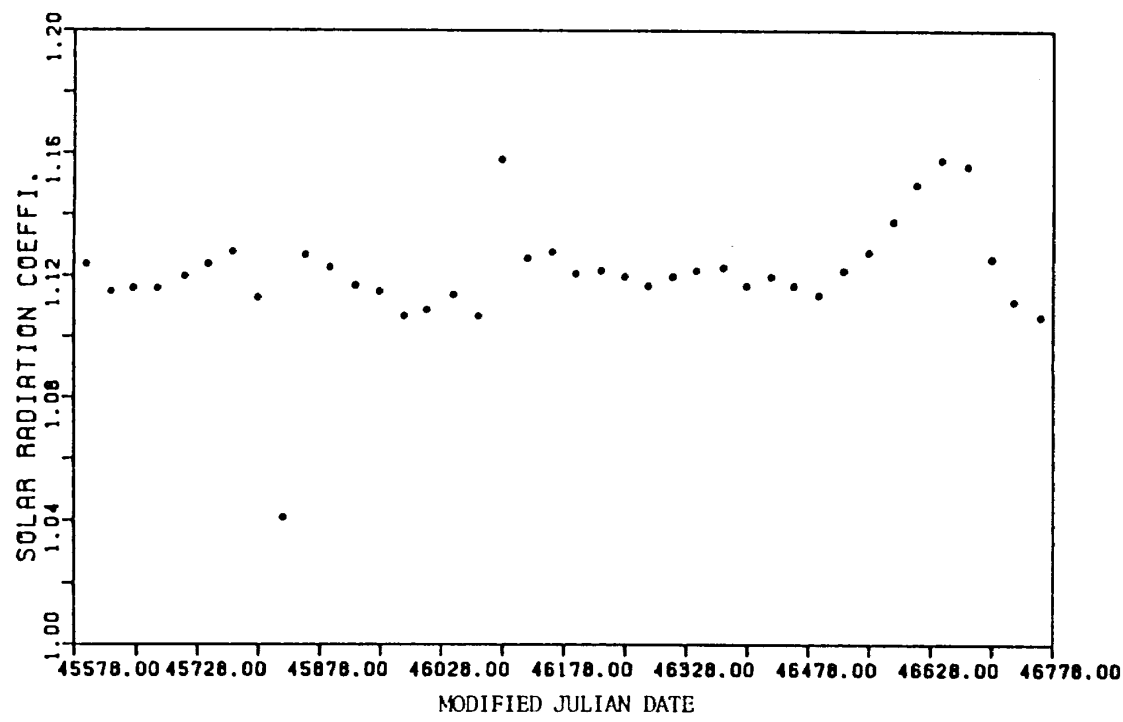


Fig. 7 Estimate of Solar Radiation Reflectivity Coefficient

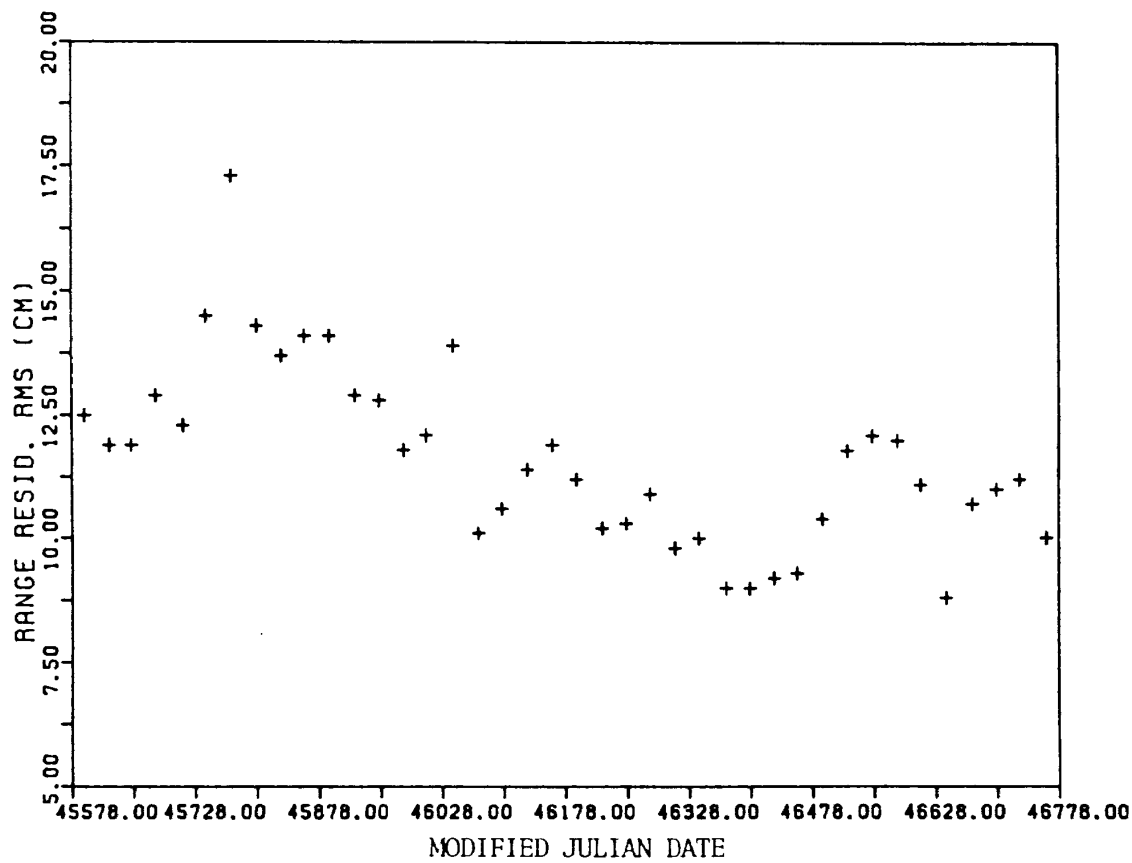


Fig. 8 The RMS of Overall Range Residuals

values for the NAL normal points. This decreasing trend in the rms of fit values seems to reflect the gradual improvement of the quality of the laser systems that contributed to the solutions. Of interest here is the effect on LAGEOS orbit of solar eclipse by the moon as seen from LAGEOS. Such phenomena lasting for the time longer than 10 minutes occurred at least 15 times during the 3.3-year interval. Of course, the total length of the eclipse is important for the magnitude of the orbital perturbations. The longest eclipse occurred on April 9, 1986, and lasted for about 67 minutes and during that period about 80 percent of the sun was shadowed by the moon at maximum. For this particular 30-day arc the rms of fit increased up to 27.7 cm with no accounting for the eclipse, and proper modeling of the eclipse in the analysis software reduced it to 11.8 cm. The effect of the eclipse on LAGEOS orbit is discussed in more detail in Noomen et al. [27].

SLR-Observed Tectonic Plate Motions

In an attempt to detect tectonic plate motion from SLR data, the individual annual solutions for tracking station coordinates were determined. For this purpose, fifteen sites with continuous data records over the 3.3-year interval are chosen. Table III lists the selected laser stations for observing plate motions, and their geographic distribution is shown in Fig. 9.

Table IV presents a summary of successively determined annual solutions of the station coordinates for the 1984/1986 time frame. From these annual solutions baseline length (hereafter referred to as simply baseline) can be determined as the magnitude of the vector difference between two stations. The baseline changes of most interest tectonically are those due to motion in the horizontal directions. Therefore, in

Table III. LAGEOS Laser Tracking Stations Selected for Observing Plate Motions.

ID	SYSTEM	LOCATION	PLATE
7090	MOBLAS-5	YARAGADEE, AUSTRALIA	INDIA
7907	SAO-2	AREQUIPA, PERU	SOUTH AMERICA
7210	HALEAKALA	HALEAKALA, HALEAKALA	PACIFIC
7121	MOBLAS-1	HUAHINE, FRENCH POLYNESIA	PACIFIC
7110	MOBLAS-4	MONUMENT PEAK, USA	PACIFIC
7105	MOBLAS-7	GREENBELT, USA	NORTH AMERICA
7109	MOBLAS-8	QUINCY, USA	NORTH AMERICA
7086	MLRS	McDONALD, USA	NORTH AMERICA
7122	MOBLAS-6	MAZATLAN, MEXICO	NORTH AMERICA
7838	SHO FIXED	SHIMOSATO, JAPAN	EURASIA
7835	FRA. FIXED	GRASSE, FRANCE	EURASIA
7834	GER. FIXED	WETTZELL, FRG	EURASIA
7839	GRAZ FIXED	GRAZ, AUSTRIA	EURASIA
7840	RGO FIXED	HERSTMONCEUX, UK	EURASIA
7939	SAO-1	MATERA, ITALY	EURASIA

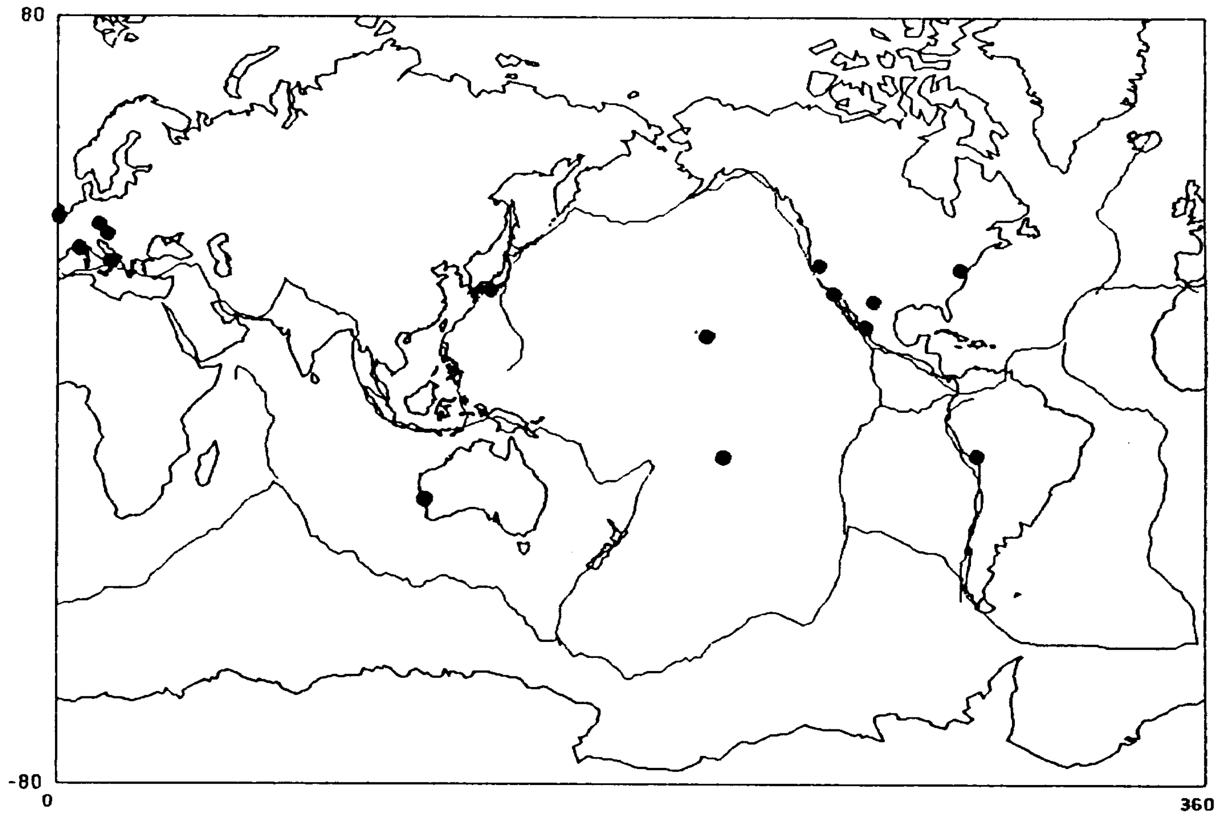


Fig. 9 LAGEOS SLR Network for Plate Motion

the computation of baselines, the height component of the individual annual station coordinates was suppressed with the average values taken from the NAL 8701 system.

Figs. 10a and 10b show the evolutions of baseline length differences from the nominal values between SHO (7838), Japan, on the Eurasian plate (EURA), and Haleakala (7210), Hawaii, on the Pacific plate (PCFC) and Yaragadee (7090), Australia, on the Austro-Indian plate (INDI), respectively. The error bars attached to the individual data denote the one-sigma formal errors in the annual baseline solutions. Also shown in these figures are straight lines which fit, in a weighted least squares sense, to the annually observed SLR baselines. The slope of the "best fit" line for SHO to Haleakala is −94 (±19) mm/yr and represents the estimated change rate of baseline between the two stations. The positive and negative values imply expansion and contraction, respectively, in baseline length between two points on the crust. The weighted rms of fit about the straight line is 13 mm. On the other hand, as shown in Fig. 10a, the rate predicted by a geological model by Minster and Jordan in 1978, called AM1-2 model, is −85 mm/yr. Note that the Minster and Jordan model predicts the average rates over a few millions of years. The SLR rate, however, is in good agreement with that predicted by the AM1-2 model. Similarly, Fig. 10b plots the results for the SHO-Yaragadee line. The slope computed by fitting a line to these points is −65 (±15) mm/yr, while the rate implied by the Minster-Jordan model is −65 mm/yr. The rms of fit about the straight line is only 6 mm. Again, we see very nice agreement with the Minster and Jordan rate. The standard deviations of the rate estimates given in Fig. 10 and in the figures below are either formal or scaled uncertainties and do not always account for all the effects of systematic errors.

Using the same procedure, we can compute the rates of change of baselines for all the combinations from 15 stations, in total, 105 baselines.

Table IV. The Annually Determined Station Coordinates.

ID	Location	Plate	Year	Longitude E DDD MM SS.SSSS	(σ)	Latitude N DD MM SS.SSSS	(σ)	Height M	(σ) M
7105	GRF105	NOAM	1984	283 10 20.3075	(0.0015)	39 1 14.1795*		22.519	(0.022)
			1985	283 10 20.3074	(0.0013)	39 1 14.1795*		22.499	(0.019)
			1986	283 10 20.3032	(0.0014)	39 1 14.1795*		22.517	(0.020)
7086	MCDON	NOAM	1984	255 59 2.8421	(0.0017)	30 40 37.1402	(0.0020)	1963.616	(0.030)
			1985	255 59 2.8367	(0.0012)	30 40 37.1425	(0.0016)	1963.616	(0.020)
			1986	255 59 2.8349	(0.0013)	30 40 37.1403	(0.0018)	1963.633	(0.021)
7109	QUINC2	NOAM	1984	239 3 19.0943	(0.0012)	39 58 30.0038	(0.0025)	1109.648	(0.017)
			1985	239 3 19.0888	(0.0010)	39 58 30.0094	(0.0021)	1109.630	(0.017)
			1986	239 3 19.0872	(0.0013)	39 58 30.0052	(0.0024)	1109.654	(0.019)
7122	MAZTLN	NOAM	1984	253 32 27.3077	(0.0014)	23 20 34.2544	(0.0020)	34.115	(0.019)
			1985	253 32 27.3039	(0.0012)	23 20 34.2590	(0.0016)	34.161	(0.017)
			1986	253 32 27.3034	(0.0014)	23 20 34.2566	(0.0019)	34.185	(0.018)
7210	HOLLAS	PCFC	1984	203 44 38.7502	(0.0023)	20 42 25.9915	(0.0029)	3068.469	(0.016)
			1985	203 44 38.7407	(0.0020)	20 42 25.9989	(0.0024)	3068.483	(0.017)
			1986	203 44 38.7401	(0.0023)	20 42 25.9965	(0.0027)	3068.478	(0.020)
7121	HUAHIN	PCFC	1984	208 57 31.9411	(0.0024)	-16 44 0.6796	(0.0030)	47.307	(0.024)
			1985	208 57 31.9335	(0.0026)	-16 44 0.6732	(0.0030)	47.332	(0.038)
			1986	208 57 31.9321	(0.0029)	-16 44 0.6744	(0.0033)	47.413	(0.042)
7110	MNPEAK	PCFC	1984	243 34 38.4052	(0.0012)	32 53 30.2481	(0.0023)	1842.329	(0.017)
			1985	243 34 38.3991	(0.0011)	32 53 30.2541	(0.0019)	1842.348	(0.016)
			1986	243 34 38.3972	(0.0013)	32 53 30.2514	(0.0022)	1842.369	(0.018)
7090	YARAG	INDI	1984	115 20 48.2685*		-29 2 47.4149	(0.0012)	244.608	(0.017)
			1985	115 20 48.2685*		-29 2 47.4152	(0.0010)	244.639	(0.015)
			1986	115 20 48.2685*		-29 2 47.4116	(0.0012)	244.583	(0.016)
7907	ARELAS	SOAM	1984	288 30 24.7690	(0.0030)	-16 27 56.6757	(0.0010)	2492.369	(0.016)
			1985	288 30 24.7569	(0.0027)	-16 27 56.6745	(0.0009)	2492.360	(0.016)
			1986	288 30 24.7631	(0.0030)	-16 27 56.6737	(0.0010)	2492.342	(0.017)
7838	SHO	EURA	1984	135 56 13.3514	(0.0044)	33 34 39.6993*		101.614	(0.023)
			1985	135 56 13.3433	(0.0036)	33 34 39.6993*		101.661	(0.017)
			1986	135 56 13.3461	(0.0042)	33 34 39.6993*		101.684	(0.019)
7834	WETZEL	EURA	1984	12 52 41.1406	(0.0020)	49 08 41.7871	(0.0040)	661.380	(0.022)
			1985	12 52 41.1465	(0.0019)	49 08 41.7779	(0.0035)	661.338	(0.023)
			1986	12 52 41.1414	(0.0023)	49 08 41.7843	(0.0039)	661.310	(0.026)
7835	GRASSE	EURA	1984	6 55 16.0339	(0.0024)	43 45 16.8945	(0.0041)	1323.025	(0.032)
			1985	6 55 16.0379	(0.0014)	43 45 16.8859	(0.0034)	1323.027	(0.020)
			1986	6 55 16.0311	(0.0021)	43 45 16.8948	(0.0039)	1323.036	(0.034)
7840	RGO	EURA	1984	20 10.0374	(0.0016)	50 52 2.5750	(0.0037)	75.532	(0.020)
			1985	20 10.0414	(0.0014)	50 52 2.5673	(0.0032)	75.541	(0.020)
			1986	20 10.0366	(0.0013)	50 52 2.5752	(0.0035)	75.580	(0.019)
7939	MATERA	EURA	1984	16 42 16.8637	(0.0018)	40 38 55.8023	(0.0040)	535.999	(0.019)
			1985	16 42 16.8638	(0.0015)	40 38 55.7934	(0.0035)	535.961	(0.017)
			1986	16 42 16.8608	(0.0017)	40 38 55.8011	(0.0039)	536.004	(0.020)

*Station component held unadjusted.

equatorial radius : 6378137.0 M
flattening : 1/298.257

The results for the inter-plate baselines are summarized in Table V and for the intra-plate baselines in Table VI. Also shown in both tables are interstation motions expected from the Minster-Jordan AM1-2 model. Table VII summarizes the "plate-averaged" rates of change of baselines observed by SLR. The results were obtained using the LAGEOS rates in Table V. The sigma of each average rate of change was computed as the standard deviation of the average. Note that many, but not all, are in general qualitative agreement with the rates implied by the AM1-2 model. However, the close examination of the numerical results reveals the following. In general, the

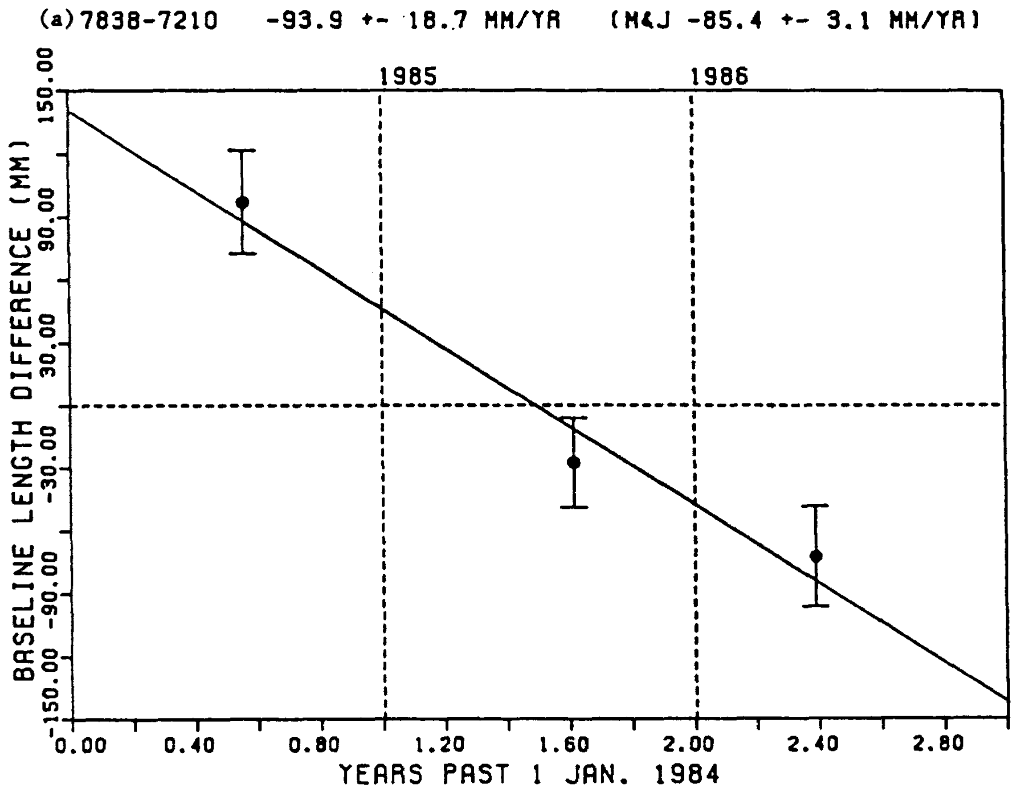


Fig. 10a Baseline Length Differences from the Nominal Value between Shimosato and Haleakala

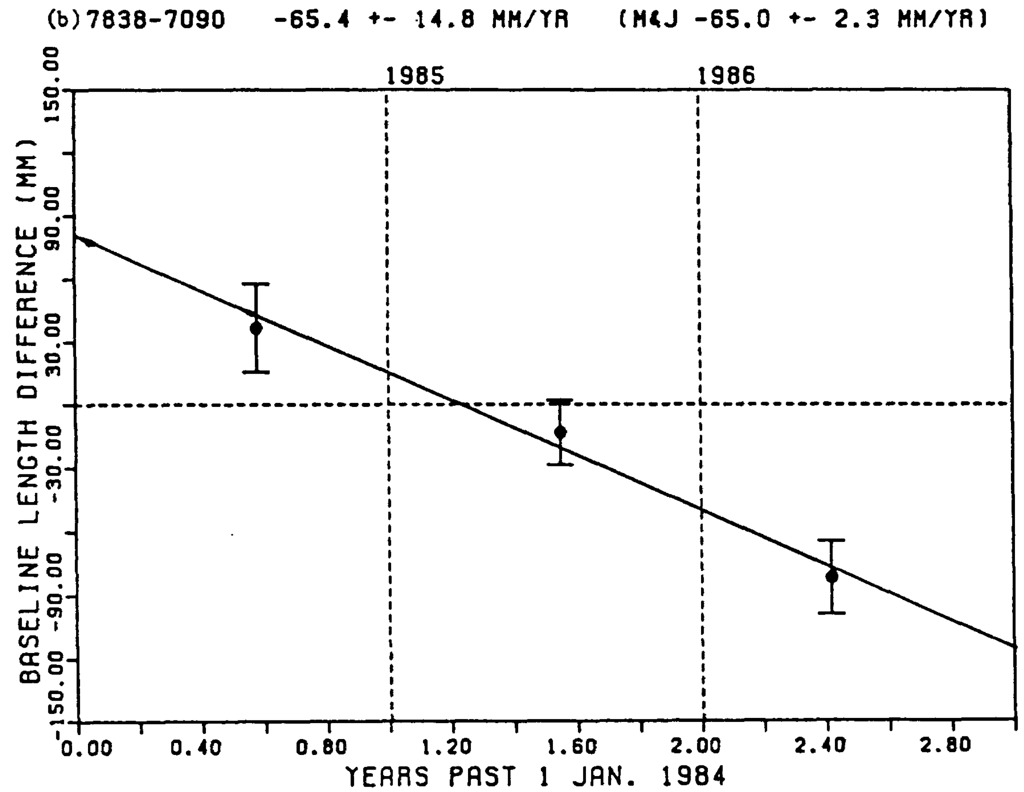


Fig. 10b Baseline Length Differences from the Nominal Value between Shimosato and Yaragadee

scatters for the straight line fit to baselines with the end sites connected by one of the 5 European stations are large as compared to those associated with the Circum-Pacific baselines, resulting in the rate estimates which are relatively large departures from those expected by the Minster-Jordan model. These observations and the linear regression analysis described below suggest that European sites have been unstable tectonically during this interval. For the intra-plate motions illustrated in Table VI, we see that some of the SLR-observed rates seem to be much removed

Table V. SLR-Observed Rates of Change for the Inter-Plate Baselines and the Corresponding Rates Implied by the Minster-Jordan AM1-2 Model.

Baseline	AM1-2 Rate, mm/yr	LAGEOS Rate,* mm/yr	Scatters: WRMS,** mm	Scatters: NRMS***
North American to Eurasian				
7086 - 7834	16	84 ± 90	69	4.20
7086 - 7835	17	22 ± 129	89	5.65
7086 - 7838	-7	-16 ± 20	9	0.67
7086 - 7839	15	39 ± 89	70	4.15
7086 - 7840	17	39 ± 63	63	4.50
7086 - 7939	15	42 ± 80	57	4.42
7105 - 7834	18	68 ± 86	69	4.17
7105 - 7835	20	-1 ± 114	82	5.15
7105 - 7838	-4	3 ± 34	26	1.88
7105 - 7839	18	19 ± 78	67	3.79
7105 - 7840	19	24 ± 66	52	3.84
7105 - 7939	19	24 ± 68	52	4.06
7109 - 7834	14	57 ± 64	52	3.34
7109 - 7835	15	2 ± 96	71	4.75
7109 - 7838	-9	-25 ± 18	5	0.37
7109 - 7839	14	19 ± 66	55	3.31
7109 - 7840	15	16 ± 64	51	3.89
7109 - 7939	13	21 ± 57	44	3.54
7122 - 7834	15	39 ± 71	56	3.74
7122 - 7835	16	-16 ± 97	70	4.83
7122 - 7838	-8	-10 ± 17	3	0.25
7122 - 7839	15	-1 ± 68	56	3.56
7122 - 7840	16	-1 ± 60	46	3.59
7122 - 7939	15	3 ± 58	44	3.73
North American to Pacific				
7086 - 7110	41	16 ± 19	5	0.34
7086 - 7121	5	-38 ± 28	1	0.07
7086 - 7210	31	8 ± 21	5	0.35
7105 - 7110	16	22 ± 30	24	1.96
7105 - 7121	10	4 ± 22	12	0.78
7105 - 7210	14	23 ± 35	27	2.07
7109 - 7110	-53	-32 ± 11	5	0.54
7109 - 7121	-20	-32 ± 24	14	0.85
7109 - 7210	8	-7 ± 15	7	0.61
7122 - 7110	54	44 ± 14	10	0.93
7122 - 7121	12	24 ± 26	8	0.47
7122 - 7210	44	59 ± 17	13	1.03

Table V. SLR-Observed Rates of Change for the Inter-Plate Baselines and the Corresponding Rates Implied by the Minster-Jordan AM1-2 Model. (Continued)

Baseline	AM1-2 Rate, mm/yr	LAGEOS Rate,* mm/yr	Scatters	
			WRMS,** mm	NRMS***
North American to South American				
7086 - 7907	-10	-9 ± 42	31	2.64
7105 - 7907	-5	-28 ± 19	15	1.46
7109 - 7907	-9	-2 ± 18	15	1.73
7122 - 7907	-11	-12 ± 42	33	3.04
North American to Austro-Indian				
7086 - 7090	-20	-33 ± 6	2	0.49
7105 - 7090	-11	-10 ± 6	5	2.61
7109 - 7090	-33	-43 ± 5	1	0.25
7122 - 7090	-19	-17 ± 5	2	0.43
Pacific to Eurasian				
7110 - 7834	1	44 ± 70	57	3.74
7110 - 7835	6	-9 ± 100	74	5.03
7110 - 7838	-48	-46 ± 17	3	0.25
7110 - 7839	1	6 ± 69	58	3.61
7110 - 7840	5	5 ± 65	52	4.07
7110 - 7939	3	10 ± 60	47	3.89
7121 - 7834	-5	13 ± 34	25	2.88
7121 - 7835	1	-2 ± 44	32	3.84
7121 - 7838	-78	-80 ± 24	0	0.01
7121 - 7839	-6	-2 ± 34	26	2.99
7121 - 7840	-0	1 ± 39	28	3.06
7121 - 7939	-3	1 ± 25	18	2.93
7210 - 7834	-23	1 ± 45	35	2.47
7210 - 7835	-17	-31 ± 66	48	3.54
7210 - 7838	-85	-94 ± 19	13	0.97
7210 - 7839	-24	-20 ± 49	40	2.63
7210 - 7840	-17	-25 ± 55	42	3.21
7210 - 7939	-22	-20 ± 42	32	2.74
Pacific to South American				
7110 - 7907	36	25 ± 25	20	2.28
7121 - 7907	58	41 ± 65	46	2.73
7210 - 7907	46	44 ± 37	29	3.41
Pacific to Austro-Indian				
7110 - 7090	-39	-43 ± 5	3	0.81
7121 - 7090	-51	-59 ± 23	13	0.79
7210 - 7090	-67	-77 ± 11	6	0.78

Table V. SLR-Observed Rates of Change for the Inter-Plate Baselines and the Corresponding Rates Implied by the Minster-Jordan AM1-2 Model. (Continued)

Baseline	AM1-2 Rate, mm/yr	LAGEOS Rate,* mm/yr	Scatters: WRMS,** mm	Scatters: NRMS***
Eurasian to South American				
7834 - 7907	13	35 ± 84	67	6.12
7835 - 7907	15	-13 ± 104	72	6.34
7838 - 7907	-7	-7 ± 16	11	2.54
7839 - 7907	14	1 ± 70	60	5.00
7840 - 7907	13	13 ± 55	45	4.81
7939 - 7907	16	14 ± 71	56	7.31
Eurasian to Austro-Indian				
7834 - 7090	-13	-33 ± 33	26	3.19
7835 - 7090	-8	8 ± 47	32	4.12
7838 - 7090	-65	-65 ± 15	6	0.62
7839 - 7090	-12	-4 ± 29	25	2.70
7840 - 7090	-12	-11 ± 13	10	1.75
7939 - 7090	-8	-3 ± 27	20	3.57
South American to Austro-Indian				
7907 - 7090	24	27 ± 22	17	2.03

* The standard deviations of the LAGEOS rates denote the formal uncertainties and have been scaled by the NRMS scatters (see below) of the individual baseline length residuals when the NRMS scatters were greater than unity.

** The weighted-root-mean-square (WRMS) scatter is defined as

$$\mathrm{WRMS} = [(\sum_{j=1}^{n} \delta b_j^2/\sigma_j^2)/(\sum_{j=1}^{n} 1/\sigma_j^2)]^{1/2},$$

where δb_j is the baseline length residuals from the straight-line fit by weighted least squares ("best fit"), σ_j is the standard deviation ofthe baseline length estimate, and n is the number of measurements.

*** The normalized-root-mean-square (NRMS) scatter is defined as

$$\mathrm{NRMS} = [(\sum_{j=1}^{n} \delta b_j^2/\sigma_j^2)/f]^{1/2},$$

where f is the number of degrees of freedom; f = n - 2 when a slope and intercept are estimated from the measurements.

from zero, the predicted value by the AM1-2 model. For example, the SLR-observed rates for GRF105-McDonald (7105-7086) and McDonald-Mazatlan (7086-7122) lines, both on the North American plate (NOAM), are 31 (±37) mm/yr and −43 (±23) mm/yr, respectively. Also, it is the case in most of the intra-EURA baselines. No change should occur for such baselines if the plates are really rigid. In this regard, it is of interest to note that the averages of the rates of

Table VI. SLR-Observed Rates of Change for the Intra-Plate Baselines and the Corresponding Rates Implied by the Minster-Jordan AM1-2 Model.

Baseline	AM1-2 Rate, mm/yr	LAGEOS Rate*, mm/yr	Scatters	
			WRMS*, mm	NRMS*
		Intra-North American		
7086 - 7105	0	31 ± 37	26	1.80
7086 - 7109	0	6 ± 22	15	1.21
7086 - 7122	0	-43 ± 23	16	1.25
7105 - 7109	0	26 ± 35	28	2.28
7105 - 7122	0	-20 ± 17	7	0.52
7109 - 7122	0	9 ± 18	13	1.24
		Intra-Pacific		
7110 - 7121	0	-13 ± 25	9	0.53
7110 - 7210	0	1 ± 16	5	0.46
7121 - 7210	0	7 ± 27	15	0.80
		Intra-Eurasian		
7834 - 7835	0	-15 ± 27	18	0.99
7834 - 7838	0	-8 ± 22	7	0.43
7834 - 7839	0	-38 ± 23	5	0.26
7834 - 7840	0	35 ± 35	28	1.72
7834 - 7939	0	-38 ± 18	1	0.09
7835 - 7838	0	-19 ± 25	17	1.12
7835 - 7839	0	-13 ± 27	2	0.08
7835 - 7840	0	-15 ± 34	24	1.53
7835 - 7939	0	9 ± 46	30	2.06
7838 - 7839	0	-1 ± 22	16	0.92
7838 - 7840	0	-23 ± 41	30	2.12
7838 - 7939	0	-4 ± 29	20	1.58
7839 - 7840	0	-10 ± 26	22	1.27
7839 - 7939	0	-6 ± 21	9	0.54
7840 - 7939	0	-2 ± 14	2	0.15

* See Table IV.

the intra-plate motions are not significantly different from zero as shown in Table VI. Without other geodetic evidence, it is premature to attribute the inconsistency to a problem in plate motion model, local scale deformations, or SLR data reduction errors.

The plate motions relative to SHO are of special interest to us. Fig. 11 summarizes typical results of the SLR-observed rates for the baselines between SHO and other sites. The geologic rates predicted by Minster and Jordan are shown in the parentheses. In particular, the average of our estimates of the rates of change between SHO and three sites (Haleakala, Huahine, Monument Peak) on PCFC is −73 (±25) mm/yr, while the Minster and Jordan model gives the average value of −70 mm/yr (see Table VII).

Fig. 12 presents the results for the SAFE (San

Table VII. Comparison of Plate-Averaged Rates by SLR with Geologic Rates Predicted by the Minster-Jordan AM1-2 Model.

Plates	AM1-2 Average, mm/yr	LAGEOS Observation Average, mm/yr	LAGEOS Observation Sigma, mm/yr	LAGEOS Observation Number of Lines
SHO to				
EURA*	0	-11	10	5
NOAM	-6	-12	12	4
SOAM	-7	-7	16	1
INDI	-65	-65	15	1
PCFC	-70	-73	25	3
NOAM to				
EURA*	16	25	25	20
SOAM	-8	-13	11	4
INDI	-15	-26	15	4
PCFC	13	8	30	12
PCFC to				
EURA*	-5	-2	18	15
SOAM	47	37	10	3
INDI	-47	-60	17	3
SOAM to				
INDI	24	27	22	1
EURA*	14	10	18	5
INDI to				
EURA*	-10	-9	15	5
Intra-NOAM	0	2	28	6
Intra-PCFC	0	-2	10	3
Intra-EURA*	0	-9	21	10

*Only 5 European stations are considered.

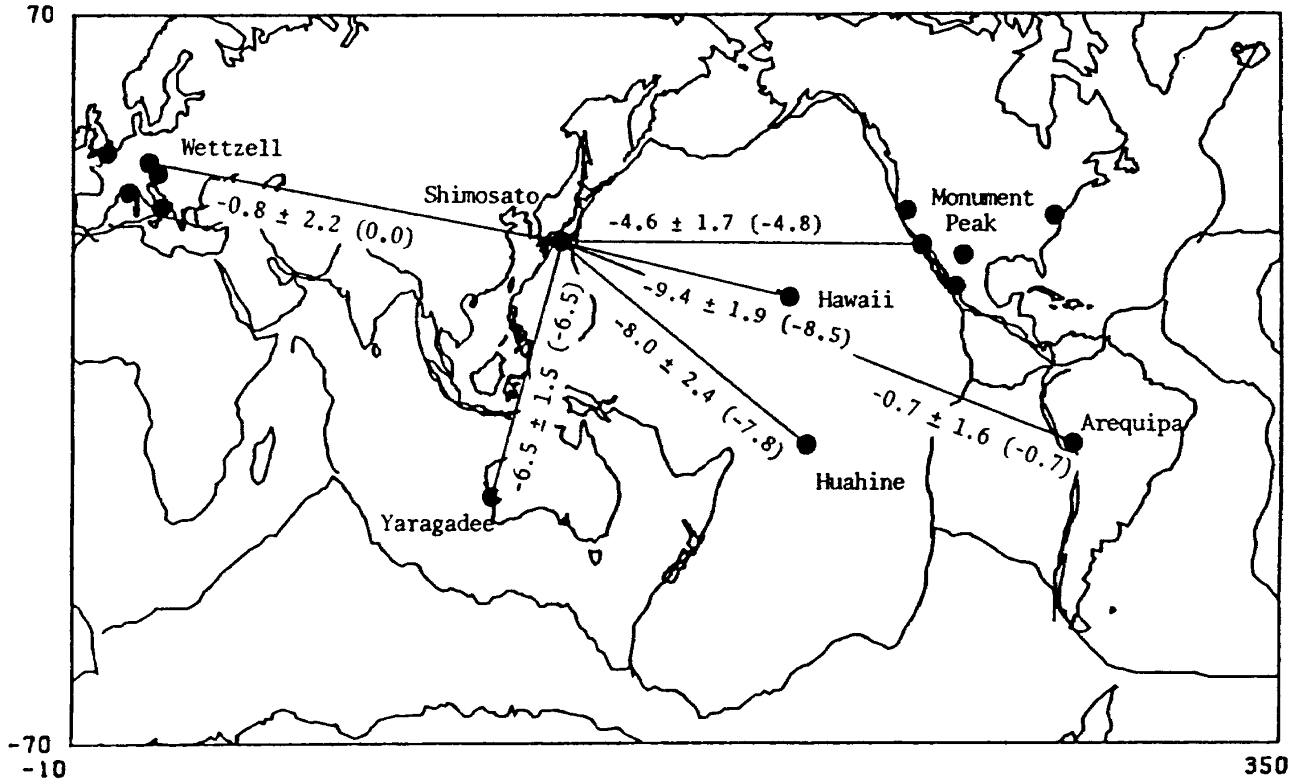
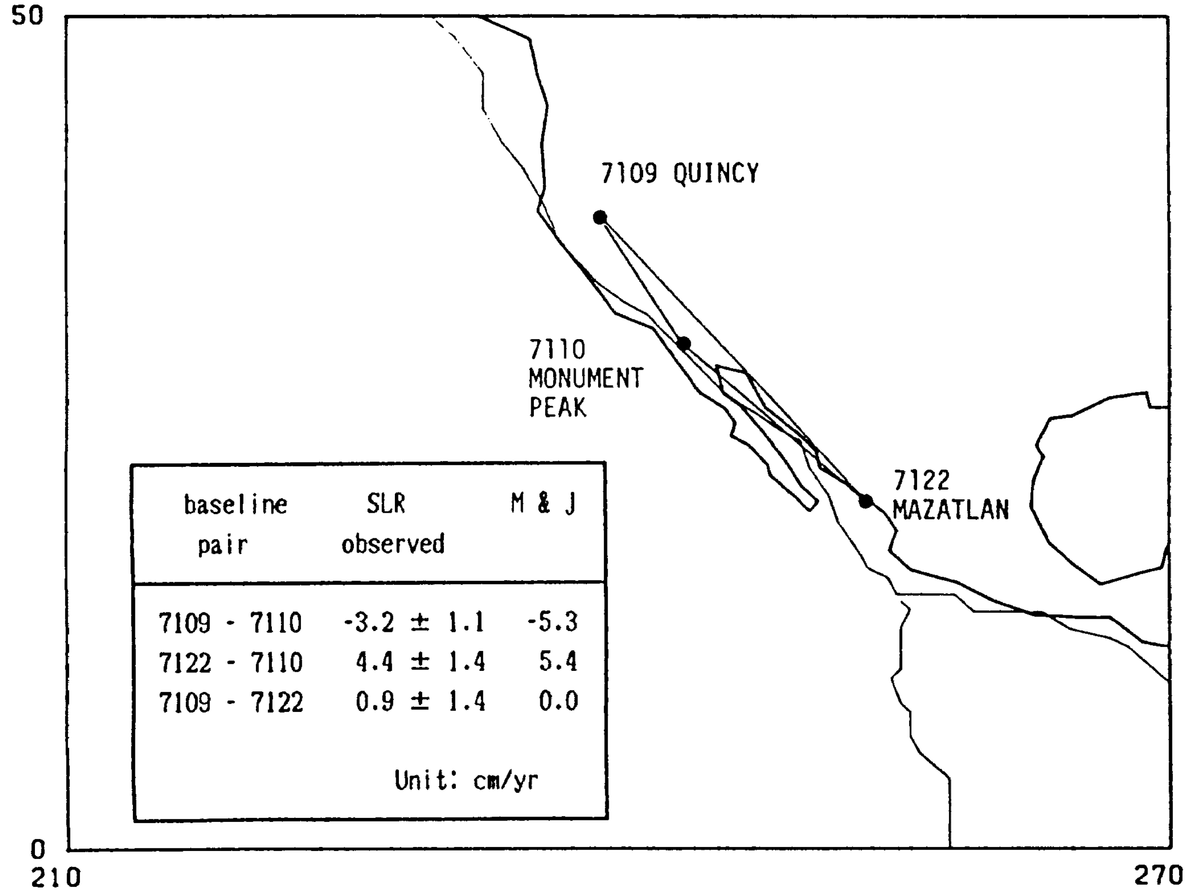


Fig. 11 SLR-Observed Rates of Change of Baselines between Shimosato and Other Sites (Unit: cm/year)



baseline pair	SLR observed	M & J
7109 - 7110	-3.2 ± 1.1	-5.3
7122 - 7110	4.4 ± 1.4	5.4
7109 - 7122	0.9 ± 1.4	0.0

Unit: cm/yr

Fig. 12 SLR-Observed Rates of Change of Baselines among Sites in the SAFE SLR Network

Andreas Fault Experiment) SLR network consisting of Monument Peak (7110) on PCFC and Quincy (7109) and Mazatlan (7122) both on NOAM. The SAFE lines have been paid a special attention in the NASA's CDP and extensively monitored by geodetic space techniques as well as conventional surveying methods. In particular, SLR has acquired data records for more than a decade. For the Quincy-to-Monument Peak line, the value of −64 mm/yr [7] [8] was determined on the basis of the observations for periods prior to 1983. The rate predicted by the Minster-Jordan model is −53 mm/yr. On the contrary, the NAL results yield a baseline changing rate of −32 (±11) mm/yr, which compares reasonably well with the latest NASA SL7 estimate [28] of −23 mm/yr. For other two baselines, the SLR-observed rates were 44 (±14) mm/yr for Monument Peak to Mazatlan, and the intra-plate rate of 9 (±11) mm/yr between Quincy and Mazatlan. The early result by Christodoulidis et al. [7] of the average of the baseline changing rates between PCFC and Arequipa (7907) on the South American plate (SOAM) was −5 (±12) mm/yr, while the Minster-Jordan rate is 47 mm/yr. This large discrepancy has been eliminated in our solution. The average of our estimates of the rates for the PCFC-to-Arequipa line is 37 (±10) mm/yr.

The results shown above indicate the general agreement between the SLR-observed rates compared to the rates observed in a geological time scale, that is, about 10^6 years. When all of 15 selected stations are considered, a correlation of 0.79 is obtained between the SLR-observed and geologically predicted values for all 105 individual rates. If only 10 sites in the Circum-Pacific area are taken, excluding 5 European sites, a cross correlation substantially increased to 0.90 for 45 observed rates as shown in Fig. 13.

As already shown, we can determine the 3-dimensional geocentric coordinates of each laser

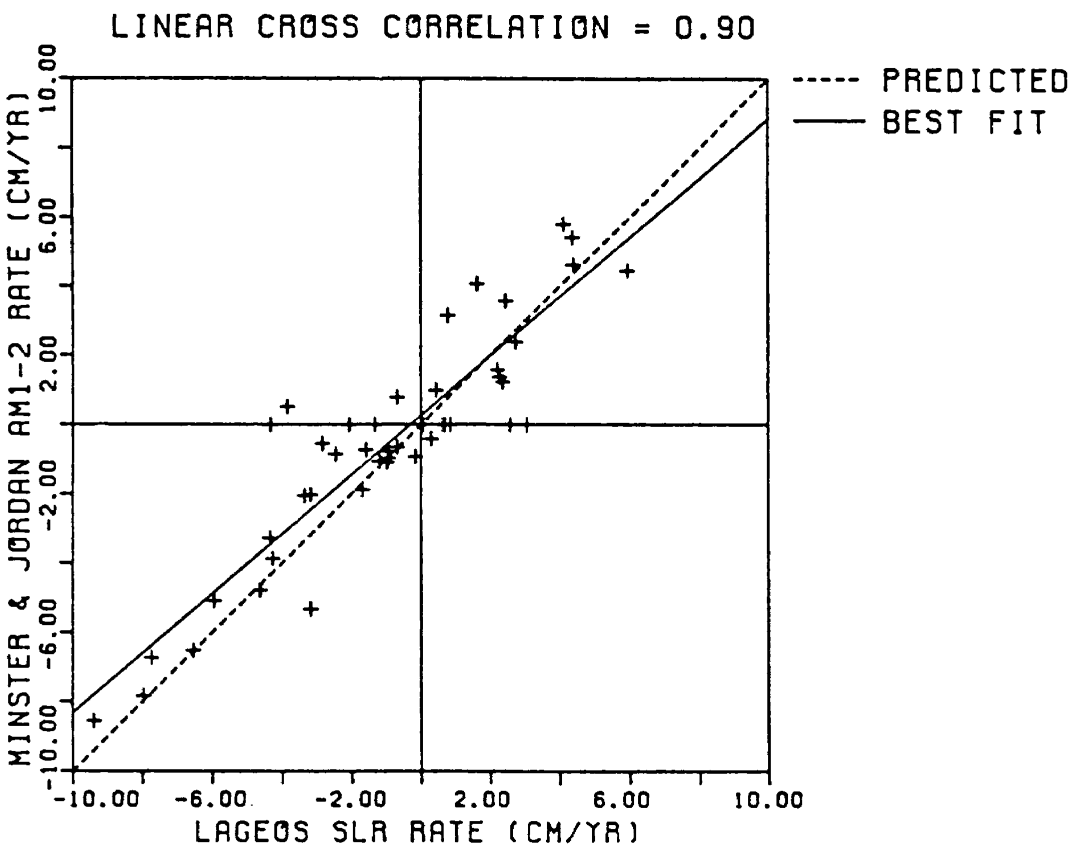


Fig. 13 Comparison of SLR-Observed Rates with Geologic rates of Minster and Jordan

station. This capability of positioning is one of the essential advantages of SLR technique over VLBI in which only relative interstation vectors can be measured. Furthermore, the estimates of laser station positions are obtained such that the horizontal components and height above the assumed reference ellipsoid are separated accurately. Thus global vertical geodetic control could be established. In this analysis we could determine height components with a formal precision of 2 to 3 cm for the selected stations, as shown in Tables II and IV. Table VIII presents the results of vertical positioning from annual laser solutions for sites used in the baseline solution. The weighted mean of annual height estimates and an rms scatter about the mean computed using values in Table IV are shown in this table. The results indicate that height variations from the average were within about 2 to 3 cm during this 3-year interval.

SUMMARY AND CONCLUSIONS

The results of analyses of SLR data taken on LAGEOS for the period of September 1983 to December 1986 have been described. From this analysis, a new global solution (NAL 8701) for laser station coordinates of 39 tracking sites was established, and a new series of the 5-day average earth rotation parameters, which are consistent with this terrestrial reference frame, was derived for this 3.3-year interval.

For the 1984-1986 period, baseline length estimates from successive annual solutions are used to infer baseline change rates. The laser observed rate of −9.4 cm/yr for the SHO-Haleakala line is consistent with velocity of −8.5 cm/yr predicted by the Minster-Jordan AM1-2 model, and also with the latest VLBI rate

Table VIII. Statistics of Height Estimates.

ID	Station	Plate	Mean of Annual Heights, m	RMS about Mean, m
7105	GRF105	NOAM	22.511	0.009
7086	MCDON	NOAM	1963.623	0.008
7109	QUINC2	NOAM	1109.643	0.010
7122	MAZTLN	NOAM	34.155	0.028
7210	HOLLAS	PCFC	3068.476	0.006
7121	HUAHIN	PCFC	47.333	0.040
7110	MNPEAK	PCFC	1842.348	0.016
7090	YARAGADEE	INDI	244.611	0.024
7907	ARELAS	SOAM	2492.358	0.011
7838	SHO	EURA	101.658	0.026
7834	WETTZELL	EURA	661.346	0.028
7835	GRASSE	EURA	1323.028	0.004
7839	GRAZ	EURA	539.457	0.024
7840	RGO	EURA	75.552	0.021
7939	MATERA	EURA	535.984	0.020

of −8.0 cm/yr obtained at Kashima Space Center [29]. In general, many, but not all, agree very well with those predicted by a geological model of Minster and Jordan, which are the averages over a few millions of years. The NAL results are very preliminary, but provide interesting observations for the contemporary plate motions. Further analyses over more extended periods could yield more reliable estimate for plate motions and deformations.

Finally, variations in vertical directions can be measured with a precision of better than 2 to 3 cm, suggesting that SLR technique can be promising for monitoring vertical control to subduction and uplift preceding the large earthquakes.

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REFERENCES

[1] Feissel, M. and P. Wilson: MERIT Campaign: Connection of Reference Frames: Implementation Plan, Bureau International de l'Heure, (1983).

[2] Mueller, I.I. (edited): Proceedings of the International Conference on Earth Rotation and the Terrestrial Reference Frame, (1986).

[3] Murata, M.: Earth Rotation, Station Coordinates and Orbit Determination from Satellite Laser Ranging, Proc. of 14th ISTS, Tokyo, (1986), 557-565.

[4] Murata, M. and H. Shingu: Determination of Polar Motion and Earth Rotation from Laser Tracking of LAGEOS, Proc. of the International Conference on Earth Rotation and the Terrestrial Reference Frame (edited by Mueller, I.I.), (1986), 236-245.

[5] Murata, M.: Earth Rotation from Laser Ranging to LAGEOS−ERP (NAL) 85 L 01/02/03, Reports on the MERIT-COTES Campaign on Earth Rotation and Reference Systems (Part III), (1986), B93-B102.

[6] NASA Geodynamics Program: Annual Report for 1979, NASA TM (1980).

[7] Christodoulidis, D.C., D.E. Smith, R. Kolenkiewicz, S.M. Klosko, M.H. Torrence and P.J. Dunn: Observing Tectonic Plate Motions and Deformations from Satellite Laser Ranging, J. Geophys. Res. 90, (1985), 9249-9263.

[8] Tapley, B.D., B.E. Schutz and R.J. Eanes: Station Coordinates, Baselines and Earth Rotation from LAGEOS Laser Ranging: 1976-1984, J. Geophys. Res. 90, (1985), 9235-9248.

[9] Jordan, T. H., J. B. Minster, D. C. Christodoulidis and D. E. Smith: Constraints on Western U.S. Deformation from Satellite Laser Ranging, (1984), (Draft Copy).

[10] Wakker, K.F., R. Noomen and B.A.C. Ambrosius: Analysis of 1986 WEGENER-MEDLAS Full-Rate Data, Presented at NASA Crustal Dynamics Working Group Meeting, Goddard Space Flight Center, (1987), October 21-23.

[11] Sasaki, M.: Satellite Laser Ranging at the Shimosato Hydrographic Observatory and its Preliminary Results, J. Geod. Soc. Japan, 30, (1984), 29-40.

[12] Kolenkiewicz, R., P.J. Dunn, R.J. Eanes and R. Johnson: Comparison of LAGEOS Satellite Laser Ranging Normal Points, 6th International Workshop on Laser Ranging Instrumentation, 1, (1986), 11-19.

[13] Murata, M. and K. Kobayashi: Compressing Space Data and its Application, 4th Guidance and Control Symposium, SICE, (1987), 57-66 (in Japanese).

[14] Murata, M.: Large-Scale Parameter Estima-

tion Problem in Satellite Geodesy, 2nd Guidance and Control Symposium, SICE, (1985), 113-128 (in Japanese).

[15] Melbourne, W., R. Anderle, M. Feissel, R. King, D. McCarthy, D. Smith, B.D. Tapley and R. Vicente: MERIT Standards, (1983).

[16] Lerch, F.J., S.M. Klosko, G.B. Patel and C.A. Wagner: A Gravity Model for Crustal Dynamics (GEM-L2), J. Geophys. Res., 90, (1985), 9301-9311.

[17] Standish, E.M. Jr.: JPL Export Ephemeris DE-200 Users Guide, JPL, Pasadena, (1982).

[18] Wahr, J.M.: Body Tides on an Elliptical, Rotating, Elastic and Oceanless Earth, Geophys. J.R. astr. Soc., 64, (1981), 677-703.

[19] Gilbert, F. and A.M. Dziewonski: An Application of Normal Mode Theory to the Retrieval of Structural Parameters and Source Mechanism from Seismic Spectra, Phil. Trans. R. Soc. London, Ser. A, 278, (1975), 187-269.

[20] Schwiderski, E.W.: On Charting Global Ocean Tides, Reviews of Geophysics and Space Physics, 18, (1980), 243-268.

[21] Lieske, J.H., T. Lederle, W. Fricke and B. Morando: Expressions for the Precession Quantities Based upon the IAU (1976) System of Astronomical Constants, Asron. Astrophys., 58, (1977), 1-16.

[22] Wahr, J.M.: The Forced Nutations of an Elliptical, Rotating, Elastic and Oceanless Earth, Geophys. J.R. astr. Soc., 64, (1981), 705-727.

[23] Aoki, S., B. Guinot, G.H. Kaplan, H. Kinoshita, D.D. McCarthy and P.K. Seidelmann: The New Definition of Universal Time, Astron. Astrophys., 105, (1982), 359-361.

[24] Yoder, C.F., J.G. Williams and M.E. Parke: Tidal Variations of Earth Rotation, J. Geophys. Res., 86, (1981), 881-891.

[25] Marini, J.W. and C.W. Murray, Jr.: Correction of Laser Range Tracing Data for Atmospheric Refraction at Elevations above 10 Degrees, NASA X-591-73-351, GSFC, Maryland, (1973).

[26] Minster, J.B. and T.H. Jordan: Present-Day Plate Motions, J. Geophys Res., 83, (1978), 5331-5354.

[27] Noomen, R., B.A.C. Ambrosius, K.F. Wakker and H.J.D. Piersma: European Laser Station Positioning from LAGEOS Laser Ranging, Proc. 2nd International Symposium on Spacecraft Flight Dynamics, Darmstadt, FR Germany, (1986), 215-222.

[28] NASA Goddard Space Flight Center, SL7 Yearly Global Station Coordinate Solutions, Retrieved from the Crustal Dynamics Data Information Systems (CDDIS), (1987).

[29] Heki, K.: Private Communication, (1987).

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