SATELLITE LASER RANGING

EARTH ORIENTATION AND STATION COORDINATES FROM THE CENTRAL LABORATORY FOR GEODESY ANALYSIS: 1984-1991

CLG 94 L 01, 02, 03

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Analysis of 454293 Lageos normal points, collected by the global SLR tracking network between January 1984 and December 1991 was done. It was based on fitting the orbit in 30(31) day arcs. Estimating the Earth orientation and force model parameters at different intervals (Table 1), three solutions were derived. The monthly arcs were combined to form the basis for the global parameters determination. A set of 59 station positions at epoch 1984.0 and 47 station horizontal velocities were obtained. EOP were modeled as constants over their intervals of validity. LODR series were calculated by forward differencing of the estimated UT1R values (fixing each month the first 5 day UT1 at IERS). Improved version of the least-squares orbital analysis program SLRP-3 (Satellite Laser Ranging data Processor) was used for the data processing.

Table 1. Solutions Design

Adjusted Parameters	Interval of Validity or Estimated: L 01	L 02	Yes/No L 03
Orbital State Vector	30	30	30
Solar Radiation Coefficient	30	30	15
Along Track Acceleration	30	30	15
EOP: Xp, Yp, LODR	5	5	3
Station Positions	Yes	Yes	Yes
Station Velocities	No	Yes	Yes
Love and Shida Numbers	No	Yes	Yes
Geogravitational Parameter	Yes	Yes	Yes
Selected Set of Geopotential Coefficients: C(2,0),C(3,0), C(4,0),C(2,1),S(2,1),C(3,1), S(3,1),C(4,1),S(4,1),C(2,2), S(2,2),C(3,2),S(3,2),C(4,2), S(4,2)	No	Yes	Yes

MODELS AND CONSTANTS

Reference Frame

CIS:	mean equator and equinox of J2000.0
Planetary Ephemeris:	JPL DE200/LE200
Initial Earth Orientation:	BIH Circular D, IERS Bulletin B

Precession:	IAU 1976
Nutation:	IAU 1980 + Herring 1987 corrections
Initial Station Coordinates:	ITRF91
Time Evolution:	NNR-NUVEL1
Semi Major Axis of Earth:	6378136.3 m
Flattening 1/f:	298.257

Dynamic Model

Gravity Model:	NASA/GSFC GEM-T3, truncated at 20x20, with GM=398600.436 km^3/s^2 and a=6378137 m as scale parameters with the geopotential coefficients and GM=38600.4418 km^3/s^2 with the two-body term
C(2,1), S(2,1):	applied according to IERS Standards
Third Body:	Sun, Moon, Mercury, Venus, Mars, Jupiter and Saturn
Direct Solar Radiation Pressure:	occultation by Earth and Moon and adjusted solar radiation coefficient
Air Drag:	not applied
Albedo:	not applied
Along Track Acceleration:	adjusted
Solid Tides:	Wahr model (IERS Standards)
Ocean Tides:	Schwiderski model (IERS Standards)
Pole Tide:	IERS Standards
Relativistic Motion Equation Correction:	IERS Standards

Measurement model

Tropospheric Refraction:	Marini-Murray Model
Solid Earth Tide Displacement:	IERS Standards
Ocean Loading Site Displacement:	IERS Standards
Pole Tide:	IERS Standards
Relativistic Correction for Propagation:	IERS Standards

DATA

LAGEOS normal points generated from full rate data received from GAOUA (1984-1988) and from GFZ (1989-1991) were used. All data are equally weighed.

CONSTRAINTS

The first 5 days value of UT1-UTC in each arc fixed at BIH (IERS). The latitude and longitude of 7105 and the latitude of 7210 fixed at ITRF91. The latitude and longitude rates for 12 sites fixed at NNR-NUVEL1 velocities.

The estimated EOP, station coordinates, station velocities and correlation matrices have been provided to the IERS Central Bureau.

References

McCarthy (ed.), D.D., 1992: IERS Standards (1992), *IERS Technical Note 13*, Observatoire de Paris, Paris.

Summary description of the solutions CLG 94 L 01, L 02 and L 03

1 - Technique:	SLR
2 - Analysis Center:	CLG
3 - Solution Identifier:	SSC(CLG) 94 L 01, L 02, L03
4 - Software Used:	SLRP-3
5 - Relativity Scale:	Geocentric (LE)
6 - Permanent Tidal Correction on Station:	No
7 - Tectonic Plate Motion Model:	NNR-NUVEL1
8 - Velocity of Light:	299792458 m/s
9 - Geogravitational Constant:	398600.4418 km^3/s^2
10 - Reference Epoch:	1984.0
11 - Adjusted Parameters:	Orbit: 6 cartesian elements every 30(31) days. Radiation pressure coefficient and along track acceleration every 30(31) days in L01 and L 02 or every 15 days in L 03. Stations: Epoch 1984.0 geodetic station positions for 59 sites. Latitude and longitude rates for 47 sites in L 02, L 03. EOP: Xp, Yp and LODR every 5 days in L01 and L 02 or every 3 days in L 03. Geopotential: Geogravitational constant and selected set of 15 geopotential coefficients in L 02 and L 03. Solid Earth Tides: Love and Shida numbers in L 02 and L 03.
12 - Definition of Origin:	Geocentric, C(1,0)=C(1,1)=S(1,1)=0.
13 - Definition of Orientation:	A priori EOP values from BIH Circular D or IERS Bulletin B. Fixed longitude and latitude of 7105, fixed latitude of 7210.
14 - Constraint for Time Evolution:	Latitude and longitude rates for 12 sites fixed to NNR-NUVEL1.

EOP(CLG) 94 L 01 From Jan 1984 to Dec 1991

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for DR

YEAR	X		Y		DR	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1984	72	0.50	72	0.48	52	0.16
1985	81	0.43	81	0.41	57	0.14
1986	77	0.50	77	0.43	53	0.15
1987	78	0.42	78	0.40	56	0.14
1988	77	0.39	77	0.39	53	0.13
1989	78	0.47	78	0.46	54	0.17
1990	78	0.38	78	0.42	54	0.14
1991	77	0.46	77	0.44	53	0.15

EOP(CLG) 94 L 02 From Jan 1984 to Dec 1991

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for DR

YEAR	X		Y		DR	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1984	72	0.48	72	0.45	52	0.15
1985	81	0.41	81	0.39	57	0.14
1986	77	0.48	77	0.41	53	0.14
1987	78	0.40	78	0.38	56	0.14
1988	77	0.37	77	0.37	53	0.13
1989	78	0.45	78	0.44	54	0.16
1990	78	0.37	78	0.40	54	0.14
1991	77	0.44	77	0.43	53	0.15

EOP(CLG) 94 L 03 From Jan 1984 to Dec 1991

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for DR

YEAR	X		Y		DR	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1984	107	0.59	107	0.52	87	0.28
1985	119	0.50	119	0.46	95	0.25
1986	114	0.58	114	0.48	90	0.27
1987	117	0.48	117	0.47	95	0.27
1988	118	0.47	118	0.46	94	0.24
1989	118	0.57	118	0.52	94	0.33
1990	119	0.45	119	0.50	95	0.26
1991	119	0.53	119	0.51	95	0.27

EARTH ORIENTATION AND SITE COORDINATES FROM THE CENTER FOR SPACE RESEARCH SOLUTION

CSR 94 L 01

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Earth orientation parameters were derived from a combination of Lageos full rate and quick look data. Full rate data was used from 1976 until the end of June, 1991, and quicklook data was used for July 1991 through February 1994. Mean positions for all sites were adjusted and horizontal site velocities were adjusted for 47 sites with good observing histories. For all other sites, velocities were held fixed to those predicted by the NUVEL-1 NNR model. The force and measurement models used for this solution conform generally to the IERS Standards, with the following exceptions:

1) The apriori gravity field was JGM-3, a state of the art gravity field derived as a joint effort by the Goddard Space Flight Center and the Center for Space Research.

2) The ocean tide model was an enhanced version of the Schwiderski model extrapolated to include 80 consituents complete through degree and order 20, assuming admittances which vary linearly with frequency. Some ocean tide coefficients were adjusted using Lageos-1 tracking data.

3) The solid tide model (dynamic effect) has been expanded to include third degree and fourth degree terms.

4) The geogravitational constant, GM, was 398600.4415 km^3/s^2.

5) The nominal plate motion model was NUVEL-1 NNR.

6) The free core nutation period has been changed from 460 to 430 days.

7) Diurnal and semidiurnal fluctuations in the EOP and in the motion of the geocenter for 15 tidal frequencies were simultaneously adjusted in the solution.

The data was weighted in a piecewise continuous, linearly interpolated model to reflect the improvement in laser hardware over the data span. The weights are larger than the true random component of the laser ranges in order to reflect unmodelled systematic errors, and are thus scaled so that the formal uncertainties on the Earth orientation parameters are consistent with their internal precision.

IERS(1994) Technical Note No 17.

The solutions for orbit elements and Earth orientation parameters were computed using residuals from a long arc fit spanning the period from 7 May 1976 through 17 February 1994, a period of 17.8 years. The short arc adjustments were made at 3 day intervals subject to the constraint that the posteriori uncertainties were less than specified values, to allow for the change in data quantity over time. If the solution for a given 3 day interval yielded unacceptably large uncertainties on the adjusted parameters, the interval was extended by 3 days and the solution repeated. Thus, each final interval is a multiple of 3 days. For each interval, regardless of length, 6 Keplerian mean elements and xp and yp were solved. The UT1 estimates are obtained from the Lageos node residuals, with the constraint that they follow the JPL SPACE93 series at periods longer than about 60 days [Gross, 1994].

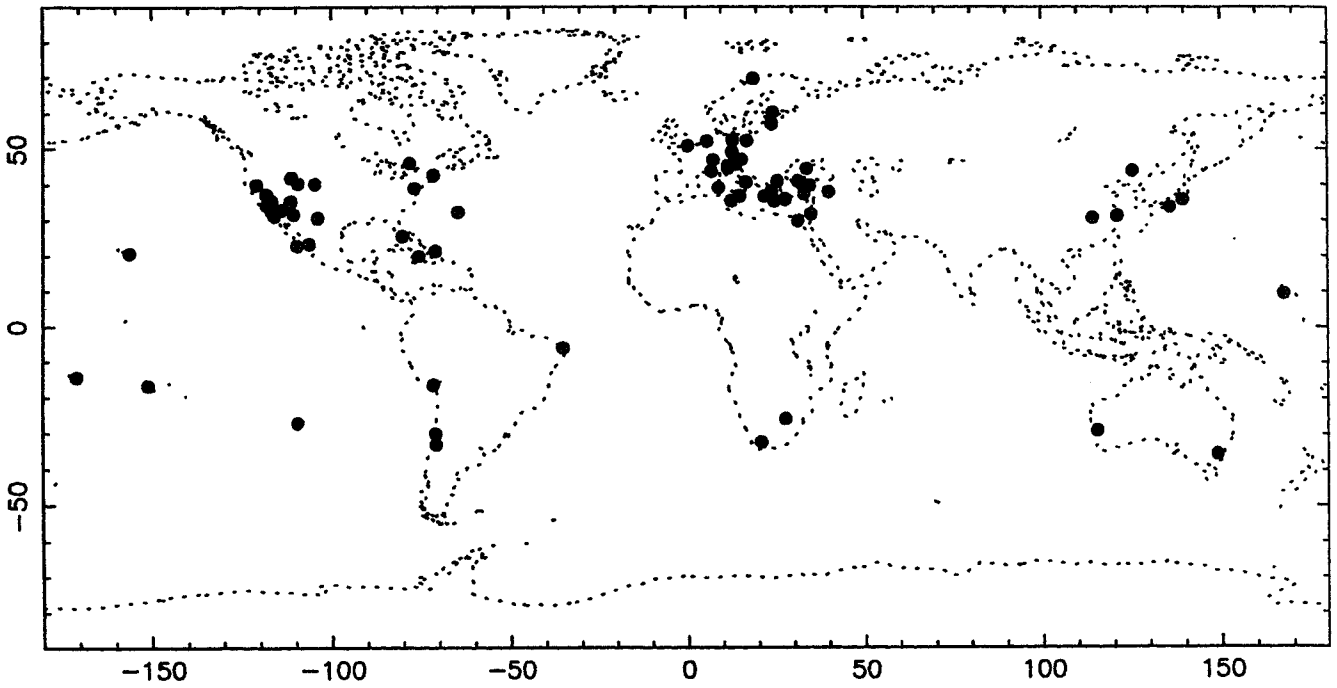
References

Gross, R.S., 1994: A Combination of Earth Orientation Data: SPACE93, *IERS Technical Note 17*, Observatoire de Paris, Paris, p. C-5.

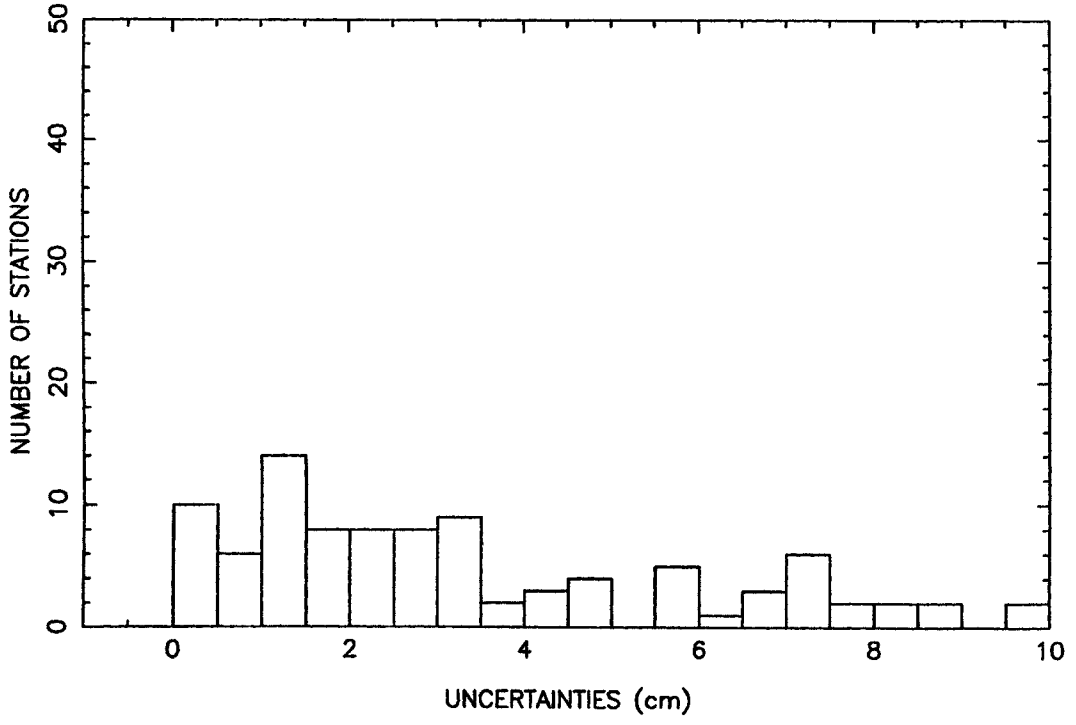
Summary description of the solution CSR 94 L 01

1 - Technique:	SLR
2 - Analysis Center:	CSR
3 - Solution Identifier:	SSC(CSR) 94 L 01
4 - Software Used:	UTOPIA
5 - Relativity Scale:	Geocentric (LE)
6 - Permanent Tidal Correction on Station:	Tidal correction has nonzero mean. Positions do not reflect true mean.
7 - Tectonic Plate model:	NUVEL-1 NNR
8 - Velocity of light (C) :	299792458 m/sec
9 - Geogravitational constant (GM) :	398600.4415 km^3/s^2
10 - Reference Epoch :	1988.0
11 - Adjusted Parameters:	
Coordinates:	Epoch 1988.0 position for all sites in cartesian coordinates solved one time for entire data span. Horizontal velocities adjusted for 47 selected sites.
Site dependent biases:	Adjusted where necessary.

Orbit:	6 Keplerian mean element corrections to long arc orbit solved every 3 days throughout span subject to constraint that posteriori uncertainties were less than specified values. If not satisfied, interval was extended in multiples of 3 days until solution was acceptable.
EOP:	x, y and UT1 (UT1 constrained by JPL SPACE93) were solved at the same intervals as the orbit.
12 - Definition of the origin:	Geocentric, C10 = C11 = S11 = 0.0
13 - Definition of the orientation:	System oriented to agree with EOP(CSR) 93 L 02 maintained through fixing the latitude and longitude of site 7210 (HOLLAS) and the latitude of site 7105 (GRF105).
14 - Constraint for time evolution:	Latitude and longitude rate of site 7210 (HOLLAS) and latitude rate of site 7105 (GRF105) fixed to NUVEL-1 NNR velocities. Horizontal site velocities adjusted with a priori sigma of 100 mm/yr for the other sites with sufficient data. Because of weak SLR data from Mojave (7288) and Owens Valley (7853) their velocity adjustment was constrained using a priori sigma of 5 mm/yr.



Distribution of the 72 sites of the terrestrial frame SSC(CSR) 94 L 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 116 stations of the terrestrial frame SSC(CSR) 94 L 01. 21 stations with uncertainties larger than 10 cm are not shown.

EOP(CSR) 94 L 01 From May 1976 to May 1994

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for UT1.

YEAR	X		Y		UT1	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1976	33	12.72	33	14.38	33	7.46
1977	71	12.87	71	12.06	71	6.82
1978	72	12.06	72	10.29	72	6.56
1979	76	9.38	76	9.71	76	6.01
1980	117	5.47	117	3.48	117	3.11
1981	112	5.40	112	3.20	112	2.72
1982	113	3.60	113	2.76	113	2.38
1983	118	3.08	118	2.67	118	1.86
1984	121	1.22	121	1.09	121	1.12
1985	121	1.07	121	0.90	121	0.94
1986	122	0.88	122	0.82	122	0.92
1987	122	0.60	122	0.56	122	0.77
1988	122	0.50	122	0.53	122	0.71
1989	121	0.53	121	0.51	121	0.75
1990	122	0.50	122	0.52	122	0.74
1991	122	0.62	122	0.62	122	0.75
1992	122	0.61	122	0.59	122	0.76
1993	122	0.50	122	0.40	122	0.30
1994	49	0.50	49	0.50	49	0.30

EARTH ROTATION AND STATION COORDINATES COMPUTED FROM SLR AND GPS OBSERVATIONS

EOP(DUT) 94 L 01
SSC(DUT) 94 C 01

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The solution ERP(DUT) 94 L 01 consists of a coherent set of Earth Rotation Parameters (ERPs), determined from SLR observations on LAGEOS-1 taken in the period September 1983 to December 1992 at a frequency of once per 3 days. An essential element of this computation is the development of a model for instantaneous station positions, SSC(DUT) 94 C 01, which is a combined solution based on the SLR observations already mentioned and GPS measurements taken in the periods May 16 - 28, 1989, and July 29 - August 3, 1992.

The computation of ERPs was performed in a 2-step approach: first, the model for station positions and motions was derived, and next, the polar motions parameters were computed w.r.t. this stable reference.

For the derivation of the model for station positions, the 9.3 year interval covered by the SLR observations was divided into 38 consecutive sub-intervals, with a length of 13 weeks on average. Independent network solutions were computed for each of these sub-intervals. The parameter estimation was based on a weighted least-squares fit of the satellite orbit to the observations. To limit the effect of potential dynamic model errors, the analysis programs GEODYN-2 and SOLVE-2 were executed in a so-called multi-arc mode, where each sub-interval was further divided into a series of consecutive 7-day data arcs and satellite parameters (state-vector at epoch, a constant along-track acceleration and a 1-cpr radial acceleration) were estimated for each individual data arc.

In addition to the station positions, ERP solutions were derived simultaneously. Please note that this is not ERP(DUT) 94 L 01. To prevent numerical singularities, the parameters were constrained in a Bayesian way. The a priori standard deviation of the pole position and UT1 were assigned values of 100 marcsec and 10 ms, respectively, with a priori values taken from the IERS (EOP) 90 C 04 solution. The initial station coordinates, computed during a preliminary data screening run, were given an a priori uncertainty of 1 m. The ascending nodes of the satellite state-vectors were kept fixed at the values determined in the same data screening. The interval June - December 1985 was not analyzed because measurements in a form suitable for the analysis were not available. The SLR computation model is summarized in Table 1a.

Table 1a: Models and constants (SLR component).

DYNAMIC MODEL:	
Gravity field	NASA/CSR JGM-1 model, truncated at 20x20
GM	398600.4415 km^3/s^2
c	299792.458 km/s
ae	6378.1363 km
1/f	298.2564
Solid earth tides	Wahr model
Ocean tides	NASA/CSR JGM-1 model
Solar radiation	CR fixed at 1.13; occultation by Earth and Moon; umbra and penumbra
Along-track acceleration	constant value; adjusted
Radial acceleration	sine and cosine 1cpr term; adjusted
Third body attraction	Sun, Moon, Venus, Mars, Jupiter, Saturn; positions from JPL DE200/LE200 ephemeris
Pole tide (dynamic part)	applied
REFERENCE FRAME:	
Station coordinates	adjusted (step 1); SSC(DUT) 94 C 01 (step 2)
Earth rotation	adjusted at 3-day intervals; a priori values from IERS (EOP) 90 C 04
CIS	mean equator and equinox of J2000.0
Precession	IAU 1976 (Lieske model)
Nutation	IAU 1980 (Wahr model)
Plate motion	not applied (step 1); close to NUVEL-1 NNR (step 2)
Tidal uplift	h2 = 0.609, l2 = 0.0852
Pole tide (geometric part)	applied
Ocean loading	not applied
Atmospheric pressure loading	not applied
MEASUREMENT MODEL:	
Observations	Release B normal points, computed at NASA (September 1983 - May 1985), DGFI (January - October 1986, 1987), DUT (November, December 1986) and ATSC/BFEC (1988 - 1992)
Data weighting	determined from overall model accuracy and system characteristics
Tropospheric refraction	Marini-Murray model

The information on the terrestrial network was further augmented by the addition of two solutions based on GPS observations. These contributions were computed from data taken during the EUREF-89 and IGS EPOCH92 campaigns. The results from these analyses proved valuable for the European part of the station network, particularly for the Italian, Greek and Turkish stations. The computation model used for the reduction of the GPS observations is summarized in Table 1b.

Table 1b: Models and constants (GPS component).

DYNAMIC MODEL:	
Gravity field	NASA/GSFC GEM-T3 model, truncated at 8x8
Solar radiation	Rock-4 for Block I and Rock-42 for Block II satellites
Third body attraction	Sun and Moon; positions from JPL DE200/LE200 ephemeris
REFERENCE FRAME:	
Station coordinates	a priori values from ETRF 89 (EUREF 89) and ITRF 92 (EPOCH92)
CIS	mean equator and equinox of J2000.0
Tidal uplift	h2 = 0.609, l2 = 0.0852
Ocean loading	not applied
Receiver clocks	Kootwijk reference
MEASUREMENT MODEL:	
Observations	Data sampled at 1 point / 6 minutes; ionosphere-free linear combinations of the pseudorange and carrier phase observations (i.e. P3 and L3)
Data weighting	1.0 m for pseudoranges; 1.0 cm for carrier phases
Tropospheric refraction	nominal zenith delay (dry component); nominal zenith delay (10 cm), adjusted using random-walk model (wet component); Lanyi model for elevation mapping

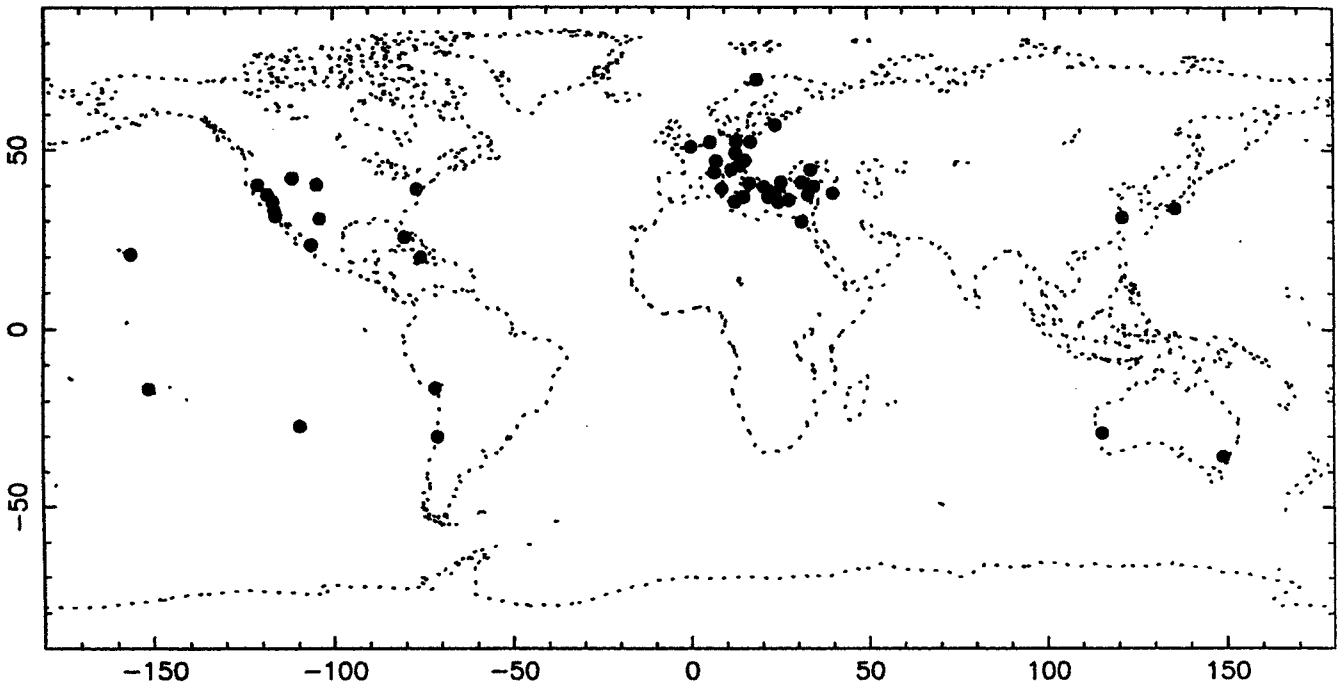
The final element of the first step was the conversion of the series of network solutions (40 in total) into a coherent model for the description of the station positions as a function of time. This model consists of initial coordinates for the geodetic monument at epoch (January 1, 1988) plus time-derivatives of these. In the computations, Helmert parameters, absorbing systematic differences in scale (GPS only), orientation and origin, were estimated for all individual network solutions but one. To avoid numerical instabilities, the motion of 12 stations was constrained with a standard deviation of 1 mm/yr to the a priori value which was taken from the NUVEL-1 No Net Rotation model. The remainder of the parameters were adjusted freely.

In the second step, the resulting model for instantaneous station positions was back-substituted into the previous step: the GEODYN/SOLVE computations were repeated, but now with these station positions held fixed and the pole position and UT1 parameters estimated freely. Because of the limited time-span covered by the GPS observations (19 days in total, divided over two campaigns), this second step was executed for the SLR component only. The computation model used here is listed in Table 1, and is identical to the one used for the SLR component of step 1. It closely follows the IERS Standards, with few exceptions: (i) the JGM-1 solution, both for the gravity field and for the ocean tides, was used instead of the advised GEM-T1 and Schwiderski models; (ii) the effect of ocean loading and atmospheric pressure loading on station positions was not applied; (iii) no plate motion was applied during each sub-interval; and (iv) new values for GM, ae and the flattening of the Earth were used. Details of the terrestrial system are given in the summary description below.

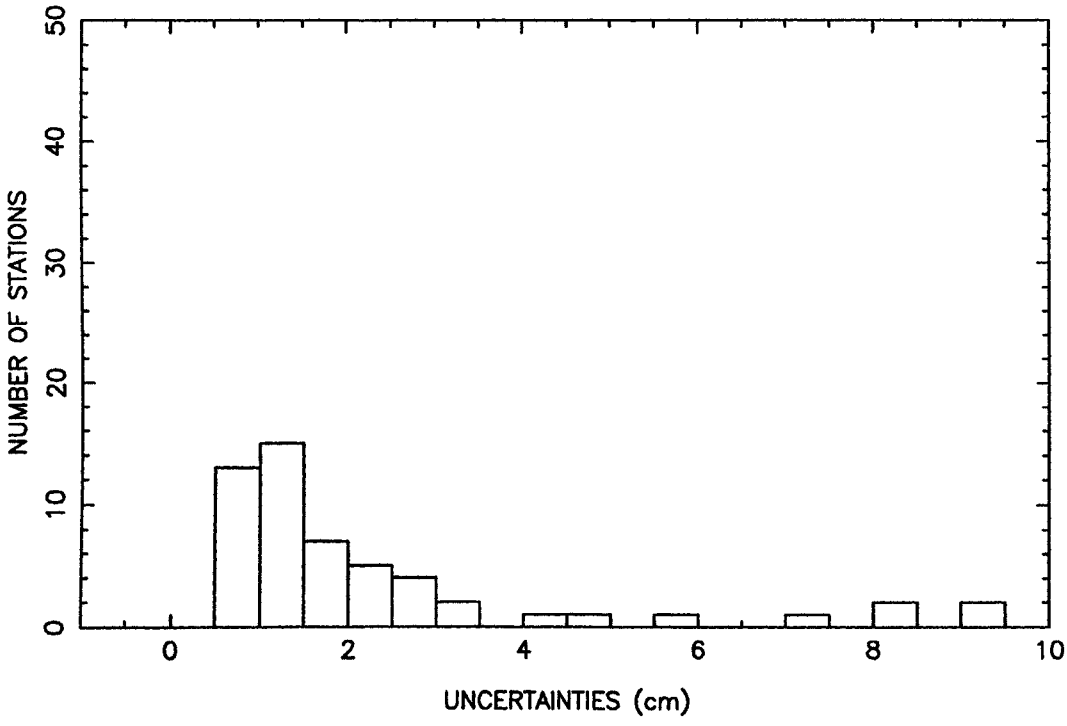
The solution for each station consists of the cartesian monument coordinates at epoch, the corresponding standard deviations (both in m), the apparent motions and the standard deviations of the latter (in m/yr). The reference epoch of the solution is January 1, 1988.

Summary description of the terrestrial system attached to the set of station coordinates SSC(DUT) 94 C 01

1 - Technique	combined SLR and GPS
2 - Analysis center	DUT
3 - Solution identifier	SSC(DUT) 94 C 01
4 - Software used	GEODYN-2/SOLVE-2/GIPSY
5 - Relativity scale	local Earth
6 - Tidal uplift	yes
7 - Tectonic plate model	NUVEL-1 NNR for selected sites (Yarragadee, Easter Island, Greenbelt, Platteville, Huahine, Mazatlan, Maui, Wettzell, Graz, RGO, Orroral Valley, Kootwijk); DUT solutions derived for the remainder of the stations, determined w.r.t. a reference frame moving according to NUVEL-1 NNR
8 - Velocity of light	299792.458 km/s
9 - Gravitational constant	398600.4415 km^3/s^2
10 - Reference epoch	January 1, 1988
11 - Adjusted parameters	X0, Y0, Z0 (for selected stations); X0, Y0, Z0, Xdot, Ydot, Zdot (remainder)
12 - Origin definition	C(1,0) = C(1,1) = S(1,1) = 0
13 - Orientation definition	initial coordinates at reference epoch
14 - Evolution constraint	NUVEL-1 NNR (for selected stations); DUT apparent motions (remainder)



Distribution of the 49 sites of the terrestrial frame SSC(DUT) 94 C 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 59 stations of the terrestrial frame SSC(DUT) 94 C 01. 5 stations with uncertainties larger than 10 cm are not shown.

EOP(DUT) 94 L 01 From Sep 1983 to Dec 1992

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for UT1.

YEAR	X		Y		UT1	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1983	39	0.44	39	0.43	39	0.33
1984	120	0.35	120	0.30	120	0.28
1985	48	0.48	48	0.34	48	0.33
1986	117	0.29	117	0.26	117	0.23
1987	119	0.26	119	0.23	119	0.21
1988	122	0.27	122	0.26	122	0.22
1989	119	0.24	119	0.22	119	0.20
1990	122	0.22	122	0.21	122	0.17
1991	120	0.25	120	0.24	120	0.20
1992	120	0.23	120	0.23	120	0.19

EARTH ROTATION AND TERRESTRIAL REFERENCE FRAME FROM LAGEOS I AND II OBSERVATIONS

EOP(GAOUA) 94 L 01
SSC(GAOUA) 94 L 02

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Solution GAOUA 94 L 01 consists of a set of 89 station coordinates, velocities of 45 sites, having good observing history, as well as a corresponding set of Earth rotation parameters. Analysis is based on Lageos I normal points spanning the period from September 1983 through October 1993 (48007 passes) and Lageos II normal points from November 1992 through October 1993 (4666 passes) using software package Kiev-Geodynamics-5.

The models and constants used for analysis follows the IERS recommendations with the following exceptions:

- gravity field and ocean tides are modelled according to GSFC/CSR UT JGM-2 model truncated at 20x20;
- nutation corrections are according to McCarthy *et al.* (1991)

For the analysis the whole interval of data was divided into 15 day arcs and on the first step only the orbits of LAGEOS I & II were adjusted on each of these arcs. On the second step the combination of 15-day arcs yielded the final solution, consisting of the parameters listed in the summary sheet below.

Earth rotation parameters (x, y and UT1) were adjusted at daily intervals. In the case of poor data distribution or lack of observing stations, ERPs were held fixed to EOP(IERS) C 04 (about 15% of data). Despite this procedure there are still some spurious data caused probably by the bad geometry of the observing network. It should be noted that adding LAGEOS II data resulted in an improvement of the formal error of the ERPs by a factor of 1.5 even though the orbit of this satellite is modelled a bit worse than that of LAGEOS I.

The terrestrial reference system is attached to ITRF91 by fixing the latitude of station 7105 and the longitude and latitude of station 7210. Time evolution of the system is modelled by NUVEL-1 NNR for sites with either poor data distribution or short-term activity periods. The velocities of 45 sites (59 collocated stations) have been estimated and linked to NUVEL-1 NNR through fixing the latitude change rate of station 7210 and the longitude and latitude change rates of station 7105. The reference epoch for the site positions is 1988.0 (MJD 47161). Separate estimation of station positions using LAGEOS I and LAGEOS II data shows up to 5 cm difference in

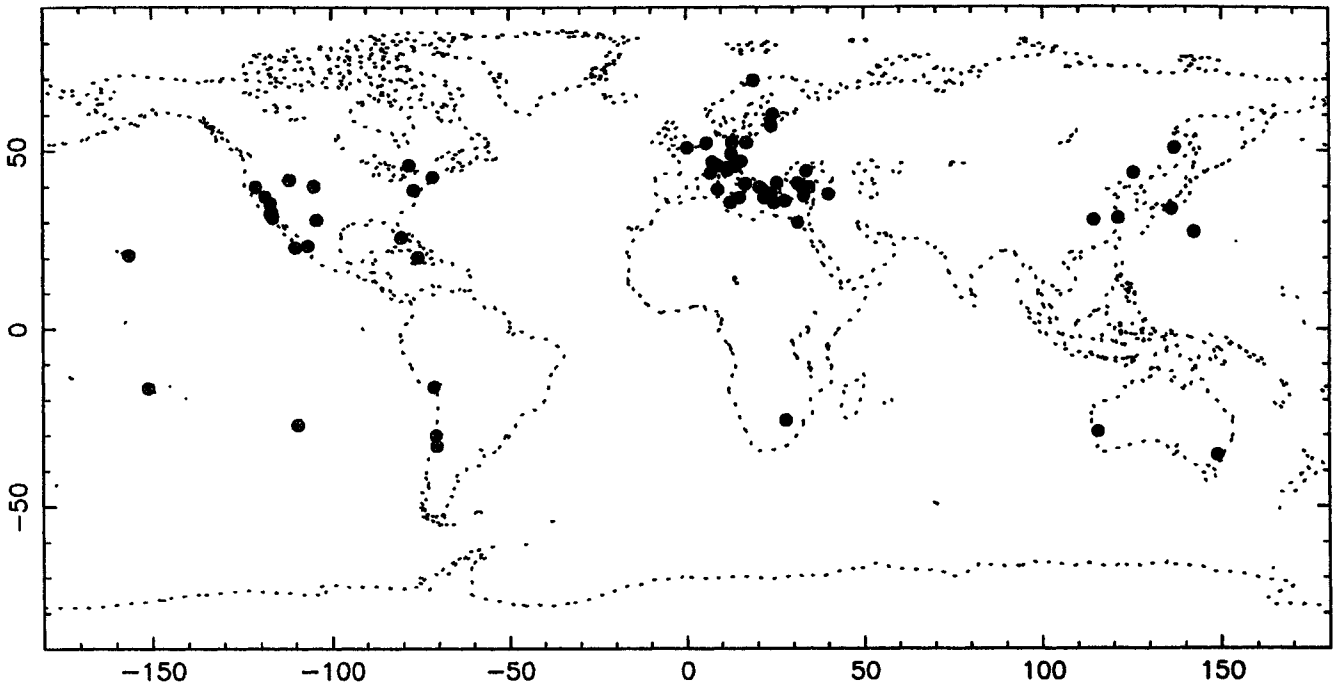
translational components of transformation between reference frames and up to 0".0009 in rotational components. The scale difference is about 4 ppb.

References

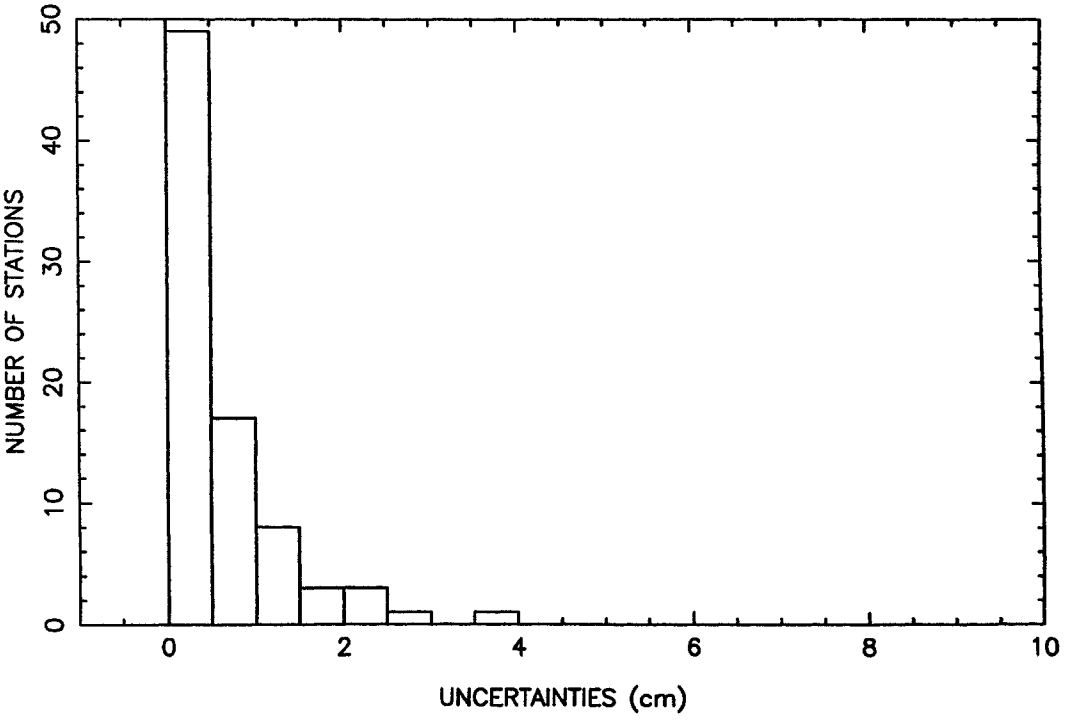
McCarthy, D.D., and Luzum, B.J., 1991: Observations of Luni-solar and Free Core Nutation, *Astron. J.*, **102**, 1889-1895.

Summary sheet for the description of the solutions GAOUA L 01 and L 02

1 - Technique :	SLR to LAGEOS I & II
2 - Analysis Center :	GAOUA
3 - Solution identifier :	SSC(GAOUA) 94 L 01
4 - Software used :	KIEV-GEODYNAMICS - 5
5 - Relativity scale :	LE
6 - Permanent tidal correction on station :	YES
7 - Tectonic plate model :	NUVEL-1 NNR
8 - Velocity of light (C) :	299 792 458
9 - Geogravitational constant (GM) :	$3.9860\ 04415\ 10^{14}$
10 - Reference epoch :	MJD 47161 (1988.0)
11 - Adjusted parameters :	
Coordinates:	X,Y,Z for 89 stations Xdot, Ydot, Zdot for 45 sites
Orbit :	5 keplerian mean elements estimated every 3 days, Ct and Cr every 15 days
EOP :	Xp, Yp, UT1-UTC every 1 day
12 - Definition of the origin :	C10=C11=S11=0
13 - Definition of the orientation :	ERP values from EOP(IERS) 90 C 04 Longitude and latitude of station 7105 and latitude of station 7210 fixed.
14 - Constraint for time evolution :	Fixed plate motion model for stations with unsufficient data or short observing history. Latitude and longitude rate of station 7105 and latitude rate of station 7210 fixed to NUVEL-1 NNR velocities.



Distribution of the 63 sites of the terrestrial frame SSC(GAOUA) 94 L 02.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 84 stations of the terrestrial frame SSC(GAOUA) 94 L 02. 2 stations with uncertainties larger than 10 cm are not shown.

EOP(GAOUA) 94 L 01 From Sep 1983 to Oct 1993

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for UT1.

YEAR	X		Y		UT1	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1983	78	0.90	78	0.90	78	0.68
1984	272	0.70	272	0.60	272	0.57
1985	280	0.70	281	0.60	281	0.54
1986	297	0.60	296	0.60	297	0.51
1987	314	0.60	314	0.50	314	0.48
1988	314	0.50	314	0.50	314	0.47
1989	295	0.60	295	0.60	295	0.50
1990	309	0.50	309	0.50	309	0.47
1991	293	0.60	293	0.60	293	0.49
1992	323	0.60	323	0.60	323	0.50
1993	294	0.50	294	0.40	294	0.37

STATION COORDINATES AND EARTH ROTATION PARAMETERS BASED ON LAGEOS LASER RANGING

EOP(GFZ) 94 L 01, 02, 03, 04
SSC(GFZ) 94 L 01

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Summary

On the basis of Satellite Laser Ranging (SLR) data till Mid-August, 1993, an improved Set of Station Coordinates SSC (GFZ) 94 L 01, including site motions was determined, and four series of Earth Rotation Parameters (ERP) with time resolutions of 5 days (ERP (GFZ) 94 L 01, main solution), 3 days (L02), 2 days (L03) and 1 day (L04) have been produced.

Model parameters and data

In continuation of the former years solutions (Montag *et al.*, 1993) an improved Set of Station Coordinates (SSC) and four sets of Earth Rotation Parameters (ERP) with different time resolution were determined. The constants and model parameters implemented in the GFZ software package EPOS.P.V1 used for the multistage-multiarc parameter estimation procedure conform to the IERS Standards (McCarthy (Ed.), 1992) with the following exceptions:

- tidal variations in UT1 caused by zonal tides with periods larger than 35 days not considered,
- nutation corrections derived by VLBI included,
- GEM-T1 instead of T3 applied.

The normal points for both LAGEOS 1 and LAGEOS 2 were used until August 10, 1993 (MJD 49209). For the new time interval from Sept. 92 to Aug. 93 altogether 8780 passes (4960 of LAGEOS 1 and 3820 of LAGEOS 2) with 12800 normal points (62300 of LAGEOS 1 and 58500 of LAGEOS 2) from 36 stations were included in the analysis.

Set of station coordinates and velocities

The Set of Station Coordinates SSC (GFZ) 94 L 01 was determined from LAGEOS 1 data over the whole 13 years time interval. It contains 103 marker positions at 71 stations. For 46 stations (69 markers; colocated markers at one station were constrained (with weight of 105) to have the same velocities) the data distribution was good enough to adjust the site motions simultaneously. For the other stations the velocities were held fixed to those of the NUVEL-1 no net rotation model (de Mets *et*

al., 1990). In the summary description below some details on the adopted model for the terrestrial system are given. The site positions were refered to epoch 1988.0. The origin of the reference system was defined by C10= C11 = S11 = 0. The orientation was constrained by fixing the latitude and longitude for station 7840 and the latitude for the station 7105. Additionally, no common net rotation was permitted in relation to the reference coordinate set SSC (GFZ) 93 L 01 (also ITRF 89). Corrections due to the permanent tidal deformation of the Earth were applied. The given mean errors for SSC (GFZ) 94 L 01 have been scaled by a factor of 5, because the obtained formal errors seem to be too optimistic. The errors for the velocities were defined to be zero for all stations which were fixed to the NUVEL-1 velocity model.

Earth rotation parameters

Based on the set of station coordinates SSC (GFZ) 94 L 01 with adjusted site velocities four sets of ERP (pole coordinates and length of day - LOD) with different time resolutions were determined. The main solution ERP (GFZ) 94 L 01 has a time resolution of 5 days. Additionally two series with a time resolution of 3 days (ERP (GFZ) 94 L 02) and 2 days (ERP (GFZ) 94 L 03) were derived. These series beginning in 1980 and the 1-day resolution series (ERP (GFZ) 94 L 04) beginning in 1983 are now all updated till August, 1993. Because, contrary to the L01 solution, the LOD results for the L02, L03 and L04 solutions were not estimated directly but via UT1, the time epochs have to be transferred for the LOD values by - 1.5 d, - 1.0 d and - 0.5 d, respectively. Generally, the SLR data were weighted according to their estimated accuracy. In addition, several non-permanent stations were included with smaller weights in order to reduce the influence of a changing station distribution. No post-adjustment smoothing or filtering procedure was applied. The formal errors (standard deviation) of the pole coordinates and the LOD are rather optimistic, generally. Compared to the solutions of the past years the inclusion of LAGEOS 2 data did not essentially increase the precision. They are ± 0.1 mas for the pole coordinates with a time resolution of 5d and 3d, ± 0.15 mas for a time resolution of 2 days and ± 0.2 mas for pole coordinates with a 1-day time resolution. The precision estimates of LOD are ± 0.006 ms, ± 0.01 ms and ± 0.02 ms, respectively. The formal error of LOD with a time resolution of 5 days (± 0.006 ms) was scaled by a factor of 4 in order to make it comparable with the other ones determined via UT1.

The accuracy is mostly influenced by the data density and distribution. Therefore it could be improved by including LAGEOS 2 data. In cases of poor data density and distribution the errors can increase several times. If the data density is poor, problems can especially arise for high resolution results. Then also the correlations between the estimated ERP become very high. This fact was used as an automatical elimination criterion (if higher 0.9). As an average about 3 per cent of the results with a time resolution of 2d and 15 per cent of 1-day resolution results were eliminated. With the additional LAGEOS 2 data the accuracy could be improved by a factor of about 1.5. The errors are now smaller than ± 1 mas for the pole coordinates with a time resolution of 5d and about ± 1.5 mas for 1-day resolution results. In the case of LOD it ranges between ± 0.07 ms (5d resolution) and ± 0.15 ms (1d). With the improved accuracy due to the inclusion of LAGEOS 2 data an essential decrease of the scattering of the ERP differences between different solutions is associated. Displaying e.g. the differences between our 5-day solution and the IERS combined solution the

smaller scattering after the addition of LAGEOS 2 data is evident. Additionally, the differences between our solution ERP (GFZ) 94 L 01 on one hand and our solutions L02, L03 and L04 on the other hand (Table 1) show a decrease of the scattering (r.m.s deviation from the mean) by 30 to 60 per cent.

Table 1. Scattering of the differences between different GFZ solutions before and after including LAGEOS 2 data

	ERP (GFZ) 94 Solutions								
	L01-L02			L01-L03			L01-L04		
	x_p mas	y_p mas	LOD µs	x_p mas	y_p mas	LOD µs	x_p mas	y_p mas	LOD µs
LAGEOS1	±0.77	±0.86	±70	±1.09	±0.95	±78	±1.35	±1.57	±143
LAGEOS1+2	.51	.37	44	.68	.51	59	.85	.66	103

Conclusion

As a contribution to the realization and monitoring of the terrestrial reference frame an improved set of station coordinates including site motions and several sets of earth rotation parameters were derived. The series of ERP show a good agreement with the previously reported series and with IERS results in the overlapping zones. Comparing with the solutions from last year, the addition of LAGEOS 2 data brought a significant improvement in the accuracy for the ERP series. With the prolongation of the LAGEOS 2 data series in the next years essential improvements can also be expected for the determination of site motions as part of the set of station coordinates.

References

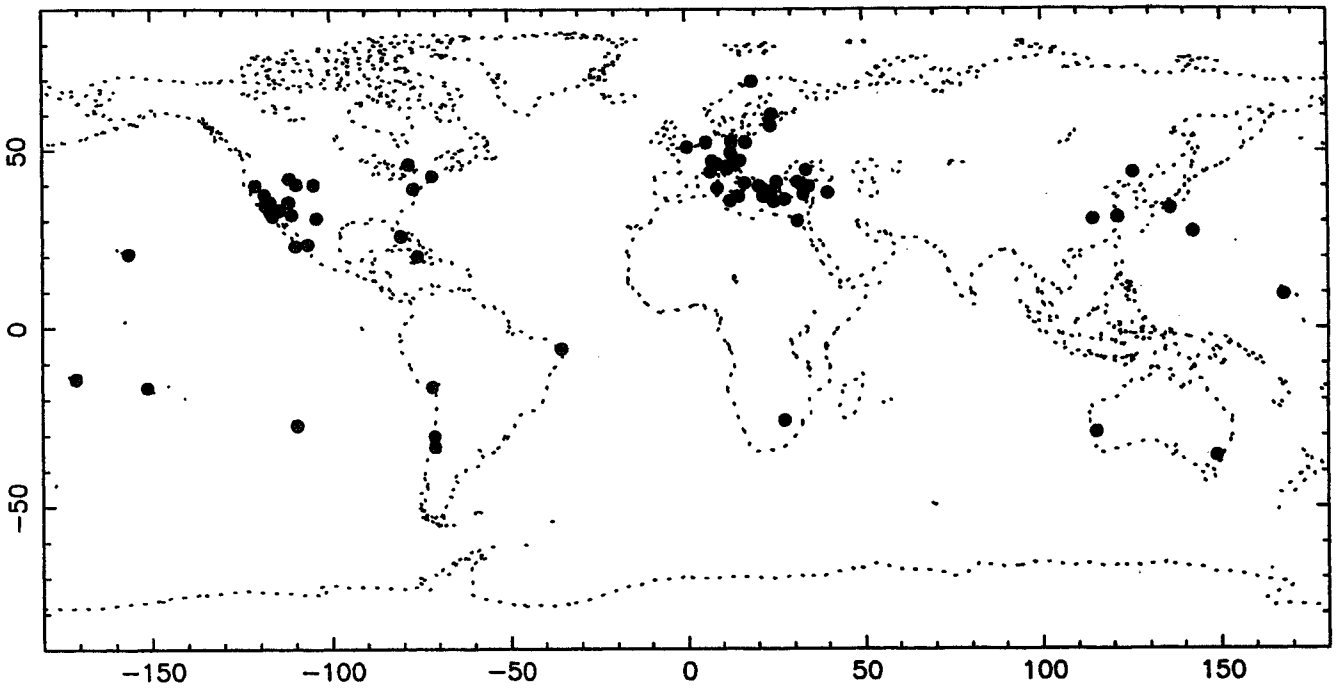
DeMets, C., Gordon, R.G., Argus D.F., and Stein, S., 1990: Current plate motions, *Geophys. J. Int.*, **101**, 425-478.

McCarthy, D.D. (ed.), 1992: International Earth Rotation Services Standards (1992), *IERS Technical Note No. 13*, Observatoire de Paris, Paris.

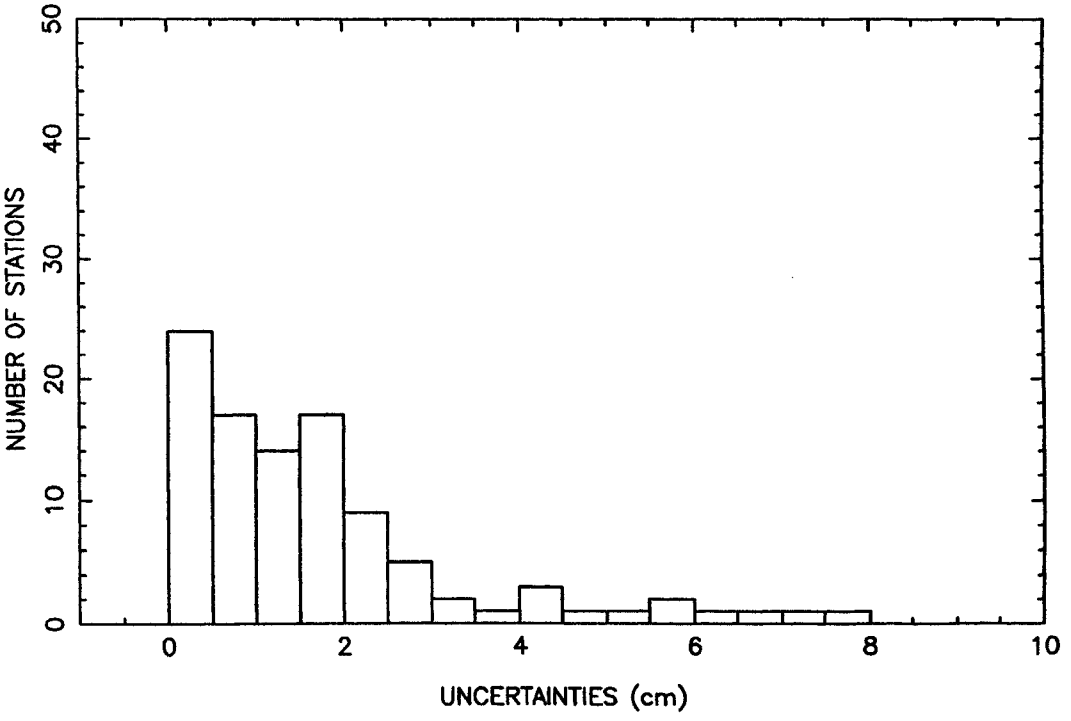
Montag, H., Gendt, G., Dick, G., Reigber, Ch., Nischan, Th., Sommerfeld, W., 1993: Earth Rotation Parameters and Station Coordinates by LAGEOS Laser Ranging Data Updated till Mid September, 1992, *IERS Technical Note No. 14*, Observatoire de Paris, Paris,L23-L30.

Summary description of the solutions GFZ 94 L 01, 02, 03 and 04

1 - Technique:	SLR
2 - Analysis Center:	GFZ
3 - Solution Identier:	SSC (GFZ) 94 L 01
4 - Software Used:	EPOS.P.V1
5 - Relativity Scale:	Geocentric (LE)
6 - Permanent Tidal Correction on station:	Yes
7 - Tectonic Plate model:	adjusted, partly NUVEL-1
8 - Velocity of light (C):	299792458 m/sec
9 - Geogravitational constant (GM):	adjusted to 398600.451km^3/s^2
10 - Reference Epoch:	1988.0 (MJD 47160.)
11 - Adjusted Parameters:	
Coordinates:	radius, longitude and latitude for all sites plus velocities in each of the coordinates, all solved one time for the whole data span
Orbit:	6 Keplerian mean elements for intervals of 5 days
EOP:	x, y and LOD, solved at 5-day intervals (the same as orbit) x, y and UT1, solved at 1-, 2- and 3-day intervals (the orbit is solved for 6 days)
12 - Definition of the origin:	Geocentric, C10 = C11 = S11 =0
13 - Definition of the orientation:	System oriented by fixing: - the latitude of 7105, 7840 - the longitude of 7840
14 - Constraint for time evolution :	no net rotation by fixing NUVEL-1 velocities for: - the latitude of 7105, 7840 - the longitude of 7840



Distribution of the 70 sites of the terrestrial frame SSC(GFZ) 94 L 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 102 stations of the terrestrial frame SSC(GFZ) 94 L 01. 2 stations with uncertainties larger than 10 cm are not shown.

EOP(GFZ) 94 L 01 From Jun 1991 to Aug 1993

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for DR

YEAR	X		Y		DR	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1991	39	0.09	39	0.09	39	0.04
1992	73	0.10	73	0.09	73	0.04
1993	44	0.10	44	0.08	44	0.04

EOP(GFZ) 94 L 02 From Jun 1991 to Aug 1993

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for DR

YEAR	X		Y		DR	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1991	65	0.12	65	0.13	65	0.05
1992	122	0.14	122	0.13	122	0.05
1993	74	0.14	74	0.12	74	0.05

EOP(GFZ) 94 L 03 From Jun 1991 to Aug 1993

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for DR

YEAR	X		Y		DR	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1991	92	0.15	92	0.15	92	0.08
1992	180	0.17	180	0.15	180	0.09
1993	108	0.17	108	0.14	108	0.08

EOP(GFZ) 94 L 04 From Jun 1991 to Aug 1993

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for DR

YEAR	X		Y		DR	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1991	161	0.18	161	0.17	161	0.18
1992	336	0.22	336	0.18	336	0.21
1993	217	0.20	217	0.18	217	0.20

EARTH ORIENTATION FROM GSFC SOLUTION SL8.5

GSFC 94 L 01

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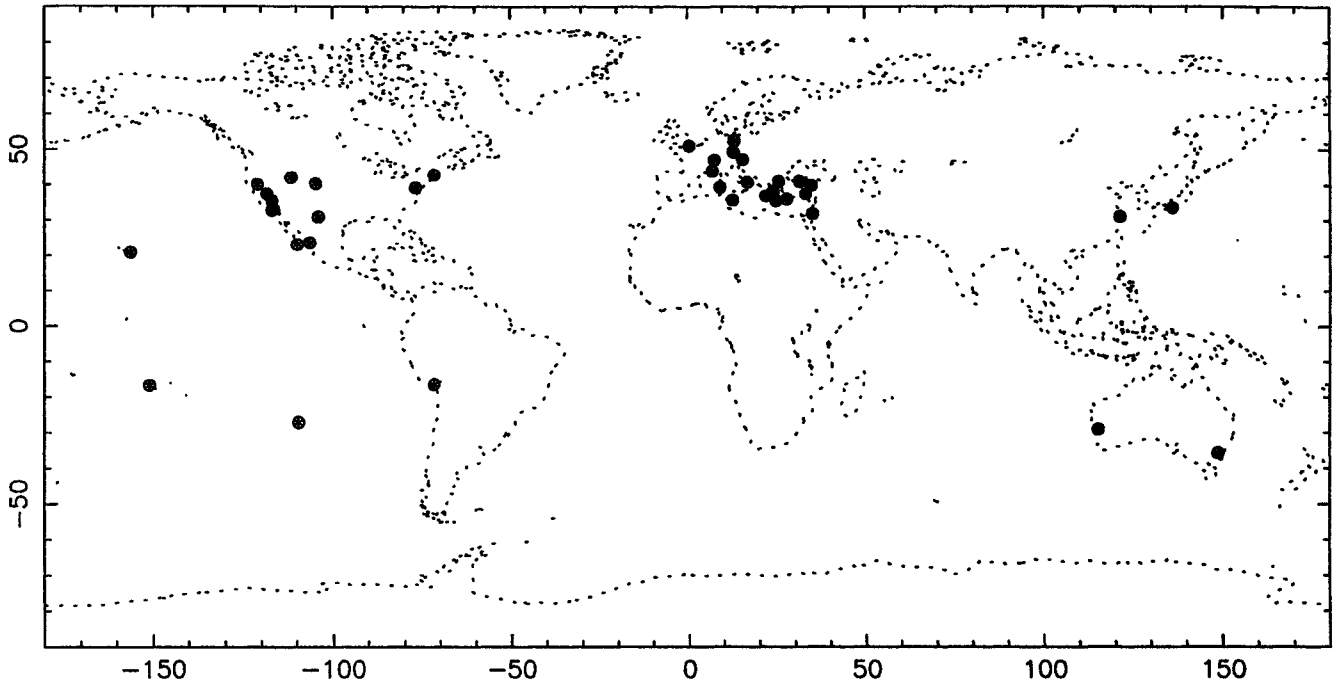
The SL8.5 solution was obtained by fitting data from LAGEOS II between November 1992 and December 1993, and LAGEOS I between January 1980 and December 1993 in 30 day (and occasionally 35 day) arcs using normal points from the global SLR tracking network. The monthly arcs were combined to derive a set of station positions at epoch 880101, and station velocities. Earth Orientation Parameters were estimated as independent values of time and polar motion at 5 day intervals from January 1980 through December 1982, and daily intervals since January 1983. Orbit and force model parameters were adjusted at the intervals indicated below. The IERS standards were followed except that the JGM3 gravity field with expanded ocean tidal terms, and a value of GM of 398600.4415 km^3/s^2 were adopted.

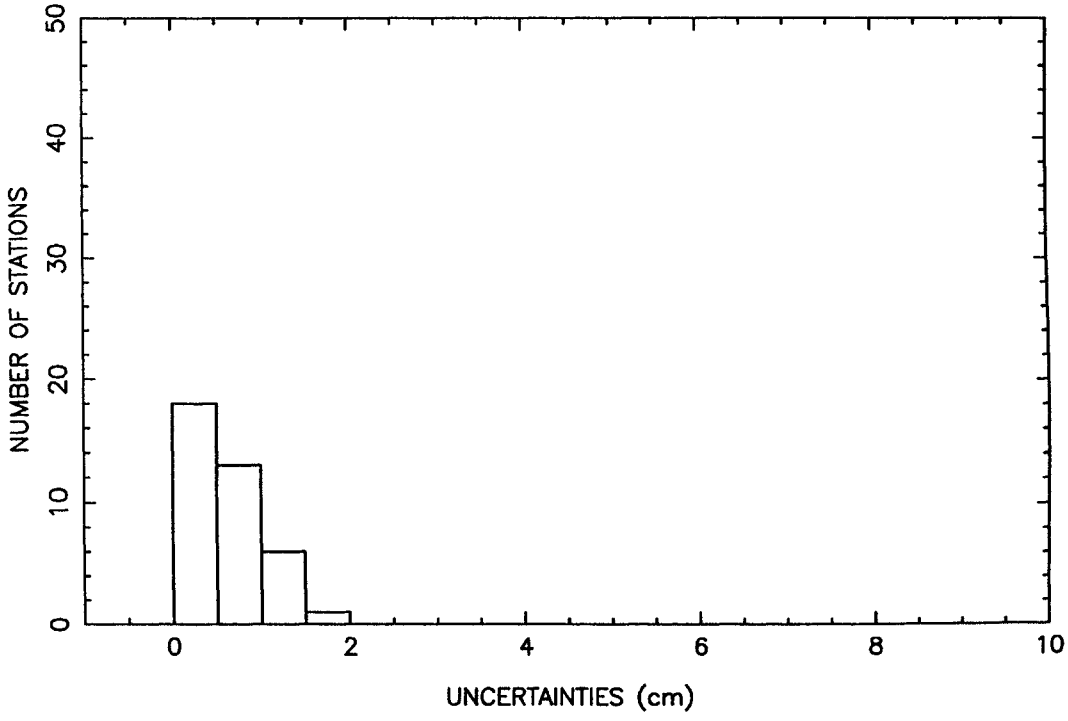
The EOP series from this solution was edited by means of a "Vondrak"-smoothing procedure using an epsilon value of 100. The resulting series are identical to the "raw" series except for the few cases where some spurious values were substituted with values interpolated from adjacent data points. This only happens when there is a lack of observations during the estimation interval; less than 4% of the data have been edited in this fashion. The LODR series were obtained from differences of the UT1R series with IERS-nodes at arc-length intervals. The forward difference was performed on the weakly smoothed UT1R series to minimize noise amplification. Examination of the RMS differences between the raw and the weakly smoothed series indicated that the smoothing did not compromise its signal content given the accuracy of the series.

Summary description of the solution GSFC 94 L 01

1 - Technique:	SLR data to LAGEOS I and LAGEOS II
2 - Analysis Center:	NASA/GSFC
3 - Solution Identifier:	GSFC SL8.5
4 - Software Used:	GEODYN II and SOLVE II
5 - Relativity Scale:	Local Earth
6 - Station Tidal Correction:	Earth tides and Ocean loading (Scherneck)
7 - Tectonic plate model:	GSFC SL8.5
8 - Velocity of light:	299792458 m/s
9 - GM:	398600.4415 km^3/s^2
10 - Reference epoch:	880101
11 - Adjusted Parameters:	
Orbit:	6 elements every 30(35) days, along track acceleration twice per arc, once per revolution acceleration twice per arc.
Stations:	position and velocity estimated except lat, lon of Washington and lat of Maui and lat rate, lon rate of Washington and lat rate of Maui
EOP:	Xp, Yp, UT1 every 5 days from 800101 to 821228, every day from 821229 to 931231, one UT1 value fixed at IERS each month
12 - Definition of Origin:	Geocentric
13 - Definition of Orientation:	a priori ERP from IERS 90 C 04 and fixed station components
14 - Constraint for time evolution:	lat, lon rate of Washington and lat rate of Maui



Distribution of the 38 sites of the terrestrial frame SSC(GSFC) 94 L 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 38 stations of the terrestrial frame SSC(GSFC) 94 L 01.

EOP(GSFC) 94 L 01 From Jan 1980 to Dec 1993

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for UT1.

YEAR	X		Y		UT1	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1980	74	1.21	74	0.46	74	0.90
1981	73	0.55	73	0.32	73	0.40
1982	75	0.66	75	0.57	75	0.90
1983	365	0.82	365	0.81	365	0.70
1984	366	0.50	366	0.44	366	0.50
1985	365	0.47	365	0.41	365	0.40
1986	365	0.47	365	0.39	365	0.40
1987	365	0.38	365	0.35	365	0.40
1988	366	0.39	366	0.38	366	0.40
1989	364	0.40	364	0.38	365	0.40
1990	365	0.35	365	0.37	365	0.40
1991	365	0.48	365	0.45	365	0.50
1992	366	0.40	366	0.39	366	0.40
1993	364	0.30	364	0.27	364	0.30

EARTH ORIENTATION AND STATION COORDINATES FROM LAGEOS LASER RANGING

SHA 94 L 01

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The solutions EOP(SHA) 94 L 01 and SSC(SHA) 94 L 01 were derived from Lageos normal point data. The Lageos normal point data from Dec.27,1992 to Jun.24, 1993 came from the GSFC. The 180-day Lageos NP data was divided into two 90-day interval parts. A multistage multiarc method was used to estimate simultaneously satellite states, EOPs and some station coordinates. The station coordinates, as the global parameters, are adjusted in the whole long arc (90-day interval). The satellite states (position vector and velocity vector), as the first-stage local parameters, are independently adjusted in the different subarc (10-day interval). The EOPs, as the second-stage local parameters are independently adjusted in a sub-subarc (5-day interval).

The convergent criterion of the solutions in the whole long arc was that the change of satellite position in a subarc is not larger than 0.05 m and the relative error of residual mean error in a subarc is not larger than 0.005. There are mean positions for stations at epoch 1988.0 in SSC(SHA) 94 L 01. The positions of all stations refer to the optical axis of the laser ranging system.

Each set of EOP solution includes three earth orientation parameters Xp, Yp, and DR. In our solution the overall RMS fit of the laser observations to the orbits is less than 10 cm. Most of the station coordinates of SSC(SHA) 94 L 01 were adjusted except the latitude and longitude of station 7840 (RGO) and the latitude of station 7105 (GRF105).

The force and measurement models used for this solution adhere closely to the IERS standards (McCarthy, 1992).

Reference frame

- Mean equinox and equator of J 2000.0
- Station coordinates SSC(SHA) 91 L 01
- IAU 1976 precession
- IAU 1980 nutation
- DE200/LE200 planetary ephemerides
- TAI as the coordinate time scale of the earth-centered frame

Force model

- GEM-T1 earth gravity field with C(2,1) and S(2,1) of IERS standards, GM=398600.436 km^3/sec^2
- Luni-Solar and planetary gravity perturbation
- Wahr solid earth tides
- Schwiderski ocean tides
- Solar radiation pressure (Cr adjusted)
- Drag-like perturbation (Cd adjusted)
- Atmospheric tide
- Earth's radiation pressure
- General relativistic perturbation (geocentric frame)

Measurement model

- Marini Murray refraction model
- Solid earth tides displacement
- Ocean loading site displacement
- Relativistic correction

References

McCarthy, D.D. (ed.), 1992: IERS Standards (1992), *IERS Tech. Note 13*, Observatoire de Paris, Paris.

Summary description of the solution SHA 94 L 01

1 - Technique:	SLR
2 - Analysis Center:	SHA
3 - Solution Identifier:	SSC(SHA) 94 L 01
4 - Software Used:	SHORDE-1
5 - Relativity Scale:	Geocentric (LE)
6 - Permanent Tidal Correction on Station:	No
7 - Tectonic Plate model:	NNR-NUVEL1
8 - Velovity of light(C):	299 792 458 m/sec
9 - Geogravitational constant (GM):	398600.436 km^3/s^2
10 - Reference Epoch:	1988.0
11 - Adjusted Parameters:	
Coordinates:	X,Y,Z for 21 stations
Orbit:	6 Keplerian mean elements, and Ct and Cr estimated every 10 days
EOP:	Xp,Yp, and Dr every 5 days
12 - Definition of the origin:	Geocentric, C10 = C11 = S11 = 0
13 - Definition of the orientation:	System oriented by fixing: - the latitude of 7105,7840 - the longitude of 7840
14 - Constraint for time evolution:	Latitude and longitude rate of station 7840 and latitude rate of station 7105 fixed to NNR- NUVEL1 velocities

EOP(SHA) 94 L 01 From Dec 1992 to Jun 1993

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for DR

YEAR	X		Y		DR	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1992	1	60.83	1	86.14	1	0.34
1993	35	46.39	35	42.90	35	0.18