LUNAR LASER RANGING

EARTH ROTATION (UT0-UTC AND VARIATION OF LATITUDE) FROM LUNAR LASER RANGING

JPL 93 M 01

X X Newhall, J.G.Williams, and J.O.Dickey
Jet Propulsion Laboratory - California Institute of Technology
Pasadena, California. 91109-8099, USA

Lunar Laser Ranging (LLR) data have been acquired and analyzed between April, 1970 and February, 1993. These data are used to estimate station locations, reflector locations, and lunar gravity and orbit parameters. Beginning in 1970, data acquisition was sufficiently dense to permit determinations of Earth rotation UT0 and variation of latitude (VOL). Values of UT0-UTC and VOL through 1991 have been submitted previously; 50 such values were derived from data acquired in 1992.

The full range data set comprises 7998 normal points taken from five sites: the McDonald Observatory 2.7-meter telescope; the McDonald Laser Ranging Station (MLRS, situated in separate locations before and after a move in early 1988); the Haleakala Observatory on Maui, Hawaii; and the CERGA system in Grasse, France. These normal points are used to estimate the set of lunar and Earth-related parameters. The post-fit residuals are analyzed by the daily-decomposition method (Dickey *et al.*, 1985) to obtain estimates of UT0-UTC and variation of latitude for each station-reflector pair on every day for which sufficient data are available. This set of values is designated EOP(JPL) 93 M 01.

The IAU expression has been used for Greenwich mean sidereal time (Aoki *et al.*, 1982). The planetary and lunar ephemeris used in the fit was DE210/LE210. The lunar librations were integrated simultaneously with the ephemeris.

Plate motion has been applied to the station coordinates using the NNR-NUVEL1 model of Argus and Gordon (1991). The base epoch for plate motion is January 1, 1991 (Julian Date 2448257.5).

The tidally driven diurnal and semidiurnal UT1 variations (M2, S2, N2, K1, O1, and P1), from the theoretical results in Wunsch and Busshoff (1992), have been added to the input UT1 file when fitting the ranges. Consequently, the output table of UT0 has these fast variations removed according to that theoretical model.

A correction to the IAU luni-solar precession constant (Lieske *et al.*, 1977; Lieske, 1979) has been taken as -3.3 mas/yr (Williams *et al.*, 1993). The correction has been made so as not to cause a rate change in UT (Williams and Melbourne, 1982; Zhu and Mueller, 1983).

To the IAU nutations (Seidelmann, 1982) we have added the ZMOA corrections (Herring *et al.*, 1991*a*; 1991*b*) for the in-phase 9 yr, 1 yr, and half-month terms and for the in-phase and out-of-phase corrections for the half-year terms. Corrections to the 18.6 yr nutation coefficients were estimated, yielding

$$\Delta\epsilon = \quad 2.2 \cos\Omega + 1.0 \sin\Omega \quad \text{mas}$$
$$\sin\epsilon\, \Delta\psi = -2.2 \sin\Omega + 0.8 \cos\Omega \quad \text{mas}$$

The constraint of the two in-phase terms (Williams *et al.*, 1991) includes a correction for the precession change and a connection between the changes of the two components. The two out-of-phase components are constrained to be in the ratio of 0.78. Subject to the constraint, the uncertainty in the nutation coefficients is about 1.3 mas, and the precession uncertainty is 0.4 mas/yr. Without the constraint these uncertainties would be larger.

With the production of the 1992 values of UT0-UTC and VOL a set of geocentric station locations has been established and provided to the IERS Central Bureau. Its designation is SSC(JPL) 93 M 01.

The separation between the Haleakala transmitter and receiver conforms to a survey. A range bias is estimated for Haleakala beginning in January, 1990. The separations between the McDonald sites were constrained to survey values.

The approximate uncertaintities in each of the cylindrical coordinates for all stations are: spin radius, 3 cm; longitude, 1.5 mas (4 cm); and z, 7 cm. Each of the three cylindrical coordinates of the five sites has significant correlation with the corresponding coordinate of the remaining four sites; these correlations are positive, implying that the coordinates shift together in the estimation process.

It should be noted that the McDonald 2.7 m telescope ceased LLR activity in June, 1985.

The station locations were derived using the formulation of the relativistic solar-system barycentric frame of reference. The transformation to the relativistic geocentric formulation requires the application of a scale factor.

Acknowledgments. We wish to acknowledge and thank the staffs of CERGA, Haleakala, the University of Texas McDonald Observatory, and the Lunar Laser Ranging associates. Normal points were constructed from individual photon returns by R. Ricklefs, P. Shelus, A. Whipple, and J. Ries at the University of Texas for the MLRS and for Haleakala data. D. O'Gara produced Haleakala normal points independently. C. Veillet provided normal points for the CERGA data. The planetary ephemeris was produced by E. M. Standish. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

Aoki, S., Guinot, B., Kaplan, G. H., Kinoshita, H., McCarthy, D. D., and Seidelmann, P. K., 1982: The New Definition of Universal Time, *Astron. Astrophys.*, **105**, 1.

Argus, D. F., and Gordon, R. G., 1991: No-Net-Rotation Model of Current Plate Velocities Incorporating Plate Motion Model NUVEL-1, *Geophys. Res. Lett.*, **18**, 2039.

Dickey, J. O., Newhall, X X, and Williams, J. G., 1985: Earth Orientation from Lunar Laser Ranging and an Error Analysis of Polar Motion Services, *J. Geophys. Res.*, **90**, B11, 9353.

Herring, T. A., 1991a: The ZMOA-1990 Nutation Series, in *Proceedings of the 127th Colloquium of the International Astronomical Union, Reference Systems*, J. A. Hughes, C. A. Smith, and G. H. Kaplan, eds., U. S. Naval Obs., Washington, p.157.

Herring, T. A., Buffet, B. A., Mathews, P. M., and Shapiro, I. I., 1991b: Forced Motions of the Earth: Influence of Inner Core Dynamics: 3. Very Long Baseline Interferometry Data Analysis, *Geophys. Res.*, **96**, 8259.

Lieske, J. H., Lederle, T., Fricke, W., and Morando,W. 1977: Expressions for the Precession Quantities Based upon the IAU (1976) System of Astronomical Constants, *Astron. Astrophys.*, **58**, 1.

Lieske, J. H. 1979: Precession Matrix Based on IAU (1976) System of Astronomical Constants, *Astron. Astrophys.*, **73**, 282.

Seidelmann, P. K. 1982: 1980 IAU Theory of Nutation: The Final Report of the IAU Working Group on Nutation, *Celest. Mech.*, **27**, 79.

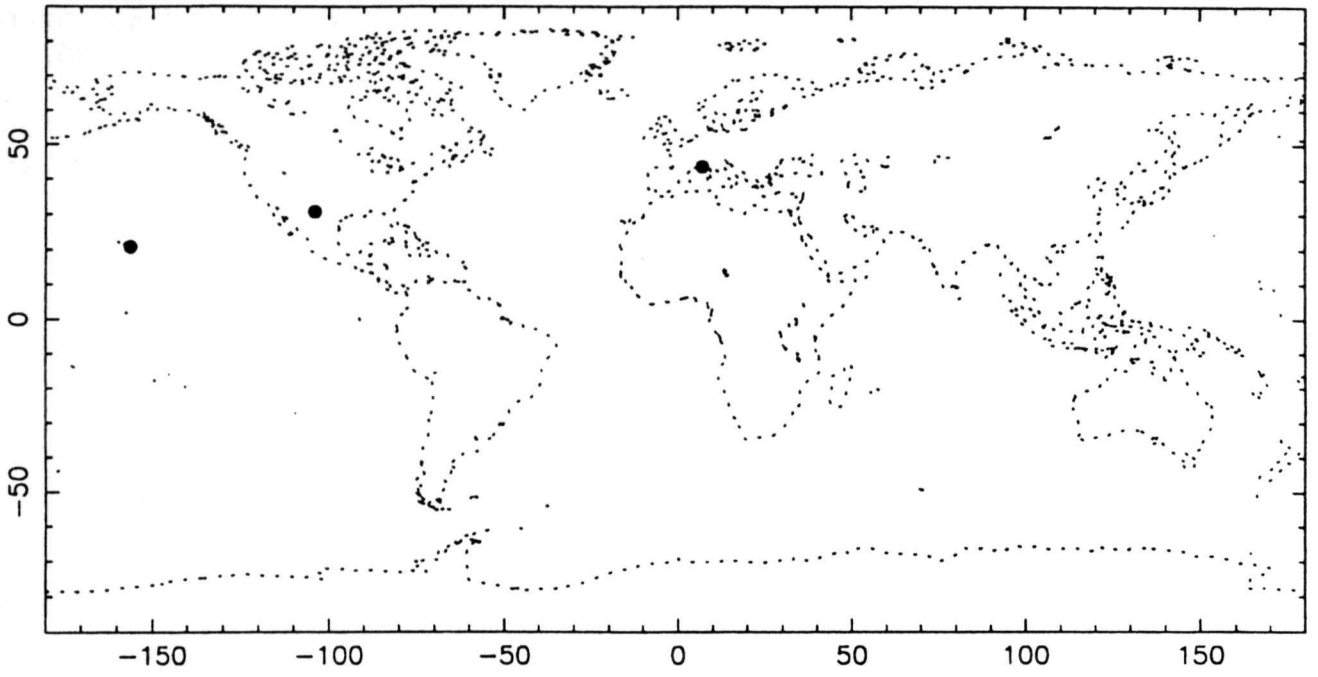
Williams, J. G. and Melbourne, W. G. 1982: Comments on the Effects of Adopting New Precession and Equinox Corrections, in *Proceedings, High-Precision Earth Rotation and Earth-Moon Dynamics: Lunar Distances and Related Observations*, O. Calame, ed., D. Reidel, Hingham, MA, p. 293.

Williams, J. G., Newhall, X X, and Dickey, J. O. 1991: Luni-solar Precession: Determination from Lunar Laser Ranges, *Astron. Astrophys.*, **241**, L9.

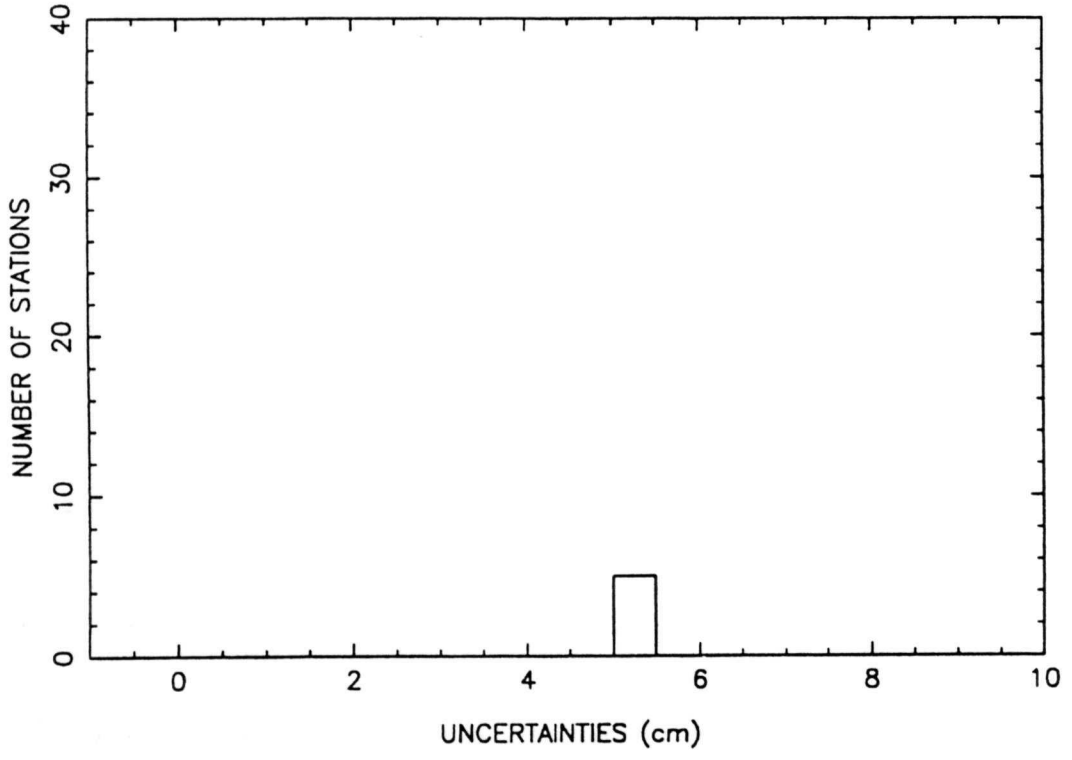
Williams, J. G., Newhall, X X, and Dickey, J. O. 1993: Lunar Laser Ranging: Geophysical Results and Reference Frames, in *Space Geodesy and Geodynamics*, American Geophysical Union Monograph, D. Turcott, ed., (in press).

Wunsch, J., and Busshoff, J. 1992: Improved Observations of Periodic UT1 Variations Caused by Ocean Tides, *Astron. Astrophys.*, **266**, 588-591.

Zhu, S.-Y. and Mueller, I. I. 1983: Effects of Adopting New Precession, Nutation, and Equinox Corrections on the Terrestrial Reference Frame, *Bull. Geod.*, **57**, 29.



Distribution of the 3 sites of the terrestrial frame SSC(JPL) 93 M 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 5 stations of the terrestrial frame SSC(JPL) 93 M 01.

EOP(JPL) 93 M 01 From Apr 1970 to Feb 1993

Number of measurements per year and median uncertainties
Units : 0.001" for φ; 0.0001s for UT0

YEAR	φ		UTO	
	Nb	Sigma	Nb	Sigma
1970	15	19.86	15	10.64
1971	35	18.16	35	8.43
1972	72	11.70	72	5.47
1973	106	22.70	106	8.15
1974	69	15.99	69	6.94
1975	87	14.71	87	7.44
1976	64	12.01	64	5.53
1977	68	9.35	68	4.33
1978	49	10.33	49	5.49
1979	66	8.48	66	4.55
1980	68	7.40	68	3.89
1981	45	10.30	45	4.07
1982	6	10.40	6	4.75
1983	0		0	
1984	26	5.20	26	2.73
1985	111	6.96	111	2.88
1986	28	5.48	28	2.05
1987	19	4.68	19	1.34
1988	71	2.50	71	1.16
1989	42	2.44	42	1.08
1990	89	1.76	89	1.01
1991	56	1.44	56	0.81
1992	50	1.24	50	0.73
1993	23	1.56	23	1.15

DETERMINATION OF UNIVERSAL TIME BY LUNAR LASER RANGING

SHA 93 M 01

Jin Wenjing, Xu Huaguan, Huang Chengli, Shanghai Observatory, China

Lunar Laser Ranging (LLR) data have been analyzed during JD 2447187.5 - JD 2448989.5. These data set of McDonald (71111, 71112), Grasse (1910) and Haleakala (56610) contain 2726 normal points reflected from four reflectors.

Theoretical models and astronomical constants solid Earth tide and ocean tide, etc were adopted from IERS Standards (McCarthy, 1992). The influence of plate motion is taken into account with NUVEL model. The base epoch for plate motion is January 1, 1988.

The relativistic effects (propagation correction, scale factor and Lorentz effect) are considered. The planetary ephemeris DE303/LE303 and the lunar librations integrated simultaneously with the ephemeris were used for calculating the theoretical distances from the observing stations to the reflectors on the Moon. In this global solution, more than 50 parameters like station and retro-reflector coordinates, lunar potential, and orbit parameters of the Earth-Moon system were estimated.

The post-fit residuals are analyzed to obtain 313 values of UT0-UTC during this period. Due to the need of solving, the normal time between the first and last normal points should be greater than 1.5 hour and more than two points per day are needed. The cylindrical station coordinates are designated SSC(SHA) 93 M 01.

The mathematical model is described in Jin *et al.* (1985). UT0 is calculated in one day interval. The precision of the normal point is taken for the weight of observational equation.

Acknowledgments. The planetary ephemeris DE303/LE303 is supplied by Jet Propulsion Laboratory, California Institute of Techology. The global data of lunar laser ranging are obtained from Dr.Veillet, CERGA.

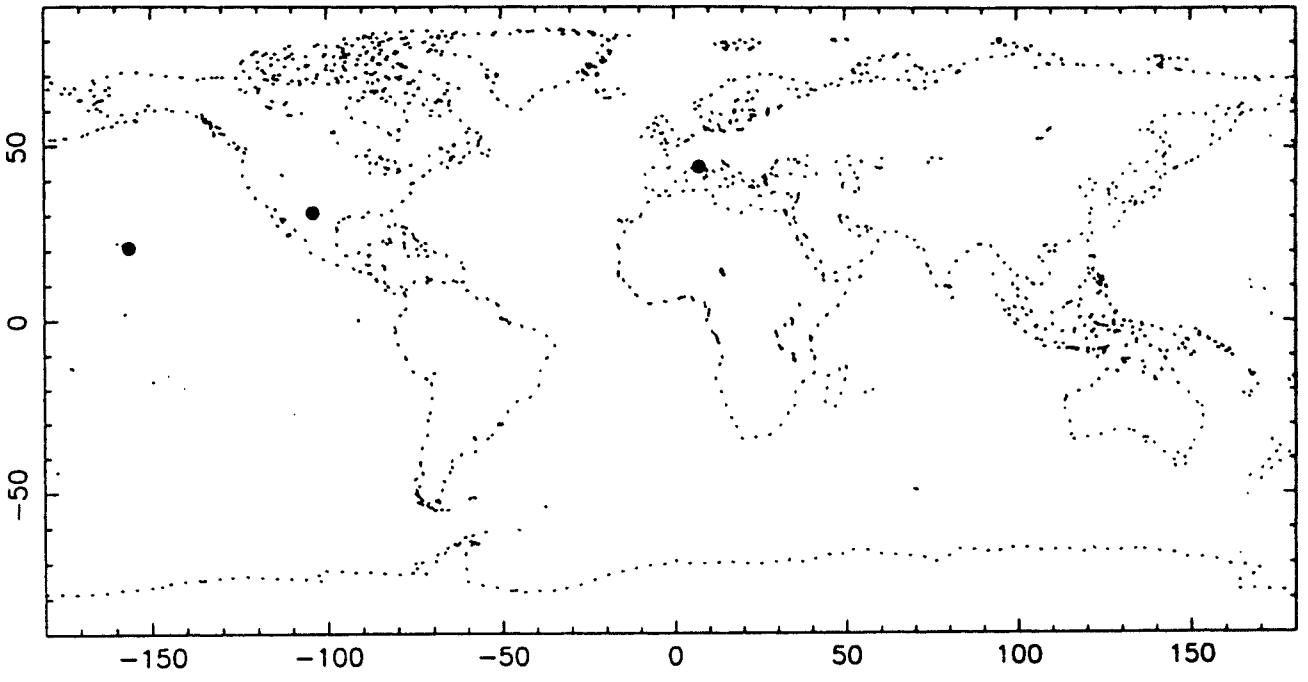
References

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

Jin Wenjing, Wang Qiangguo, 1985: Determination of ERP with lunar laser ranging and discussion of the influence of the adopted parameters, *Proceedings of the international conference on earth rotation and the terrestrial reference frame* p. 287-285.

Summary description of the terrestrial system attached to the set of station coordinates SSC(SHA) 93 M 01

1 - Technique	LLR
2 - Analysis Center	SHA
3 - Solution identifier	EOP(SHA) 93 M 01
4 - Software used	SHA LLR software
5 - Relativity scale	SSB
6 - Permanent tidal correction on station	No
7 - Tectonic plate model	NUVEL
8 - Velocity of light	299792458
9 - Geogravitational constant(GM)	$3.986004418\ 10^{14}$
10 - Reference epoch	1988.0
11 - Adjusted parameters	Cylindrical coordinate of stations (rates fixed)
12 - Definition of the origin	Geocenter (center of mass)
13 - Definition of orientation	EOP from 1988 to 1992 taken from IERS circular B
14 - Contraint for time evolution	Contrained to NUVEL



Distribution of the 3 sites of the terrestrial frame SSC(SHA) 93 M 01.

EOP(SHA) 93 M 01 From Jan 1988 to Dec 1992

Number of measurements per year and median uncertainties
Units : 0.0001s for UT0

YEAR	UTO	
	Nb	Sigma
1988	62	1.40
1989	54	1.40
1990	88	1.50
1991	56	1.60
1992	46	1.45

UT0 AND VARIATION OF LATITUDE DETERMINATION FROM LUNAR LASER RANGING OBSERVATIONS FOR 1969-1992 UTXMO 93 M 01

A. L. Whipple, J. Gyorgyey Ries, R. L. Ricklefs, P. J. Shelus, J. R. Wiant
McDonald Observatory / Department of Astronomy
The University of Texas at Austin - Austin, Texas 78712 (USA)

We have analyzed the total set of lunar laser ranging data available to us to determine UT0-UTC. These data were acquired between September, 1969 and March, 1993. A total of 8252 normal points, from the McDonald Observatory 2.7m telescope (which ceased operation in 1985), the McDonald Laser Ranging Station (saddle site and Mt. Fowlkes site) near Fort Davis, Texas, the Haleakala Observatory on Maui, Hawaii (which ceased operation in 1990) and the CERGA station in Grasse, France were used in this solution. The data were edited and weighted using an automated and objective scheme which identifies suspected outliers and adjusts station assigned weights to yield consistent distributions of the weighted residuals for all stations. There were sufficient data for 877 station/reflector pair estimations of UT0-UTC including 78 UT0 estimates, on 63 nights, in 1992. This is an increase of approximately 35% over last year.

Our method of analysis was similar to that described by Langley *et al.* (1981). We first used the MIT Planetary Ephemeris Program (PEP) to estimate corrections to the global parameters. The IERS standards were used with corrections made to the mass of the Earth-Moon system, the constant of precession, obliquity of the ecliptic, and the 18.6 year, annual, semi-annual, and fortnightly nutation terms. Adjustments to the MIT ITR-78 solution were made for the Earth-Moon barycenter orbit, lunar orbit, and lunar libration. The node of the Earth-Moon barycenter orbit was fixed to tie the longitude of the celestial reference frame. The AM0-2 plate motion model was used without adjustment. Our a priori Earth orientation series was the MIT UT1COM42/WOBCOM29 until 2 April 1988 (MJD 47253.0) followed by the University of Texas Center for Space Research (CSR) LGN7692. We have biased the UT1COM42/WOBCOM29 series to the LGN7692 series to reduce the arbitrary bias between our UT0 series and the IRIS VLBI 5-day and CSR SLR 3-day series. We estimated a piecewise linear spline for the polar motion components and UT1 to model long period deficiencies in the series. The orientation of the terrestrial reference frame was tied by fixing the zero point of the a priori ERP adjustments at 11 January 1985 (MJD 46076.0). A full correlation matrix for these station coordinates has been provided to the IERS Terrestrial Frame Section. We also estimated a third degree and order lunar potential, lunar love number, and lunar dissipation parameter along with the selenocentric retroreflector coordinates. Lastly, we estimated time delay biases, relative to MLRS, for the McDonald 2.7m, Maui and CERGA data.

Following the global solution, we analyzed the post-fit residuals in the usual fashion (e.g., Stolz *et al.*, 1976) to determine nightly corrections to UT0 and variation of latitude. The nightly corrections were then added to the ERP corrections contained in the splines, and the a priori ERP series to obtain the final values of UT0-UTC and variation of latitude. A minimum of three normal points for each station/reflector pair and at least a 1.5 hour span of coverage were the criteria we adopted for the nightly UT0 estimations. The weighted root mean square of the final postfit range residuals, for the entire span of data, was 5.1 cm. The weighted rms of the postfit residuals for the 508 normal points obtained by the two active stations during 1992 was 3.6 cm.

We have compared our UT0 and variation of latitude series with the IRIS/NAVNET VLBI series. We calculated the bias, slope and weighted rms about the linear fit of the differences between our UT0R and variation of latitude estimates and those implied by the IRIS/NAVNET UT1 and polar motion values. Interpolation of the IRIS series was performed using a four point Newton interpolation scheme. Table 1 gives the results of this comparison for the period where all stations operated with short pulse lasers (1986.5 to 1993.2).

Table 1. Comparison between University of Texas McDonald Observatory LLR UT0R and variation of latitude (DPhi) and IRIS VLBI 5-day values. The period of comparison is 1986.5 to 1993.2. The epoch of the linear fit is 1989.85.

Station		Bias (mas)	Slope (mas/yr)	WRMS (mas)	N
CERGA	DUT0R:	2.29 ± 0.13	-1.46 ± 0.08	2.18	249
	DPhi:	-11.05 ± 0.13	0.69 ± 0.08	2.71	
MLRS	DUT0R:	4.93 ± 0.74	-0.97 ± 0.41	2.18	15
	DPhi:	2.80 ± 0.70	2.03 ± 0.38	2.98	
Maui	DUT0R:	4.85 ± 0.82	1.84 ± 0.42	2.33	20
	DPhi:	9.96 ± 0.80	0.58 ± 0.43	3.52	

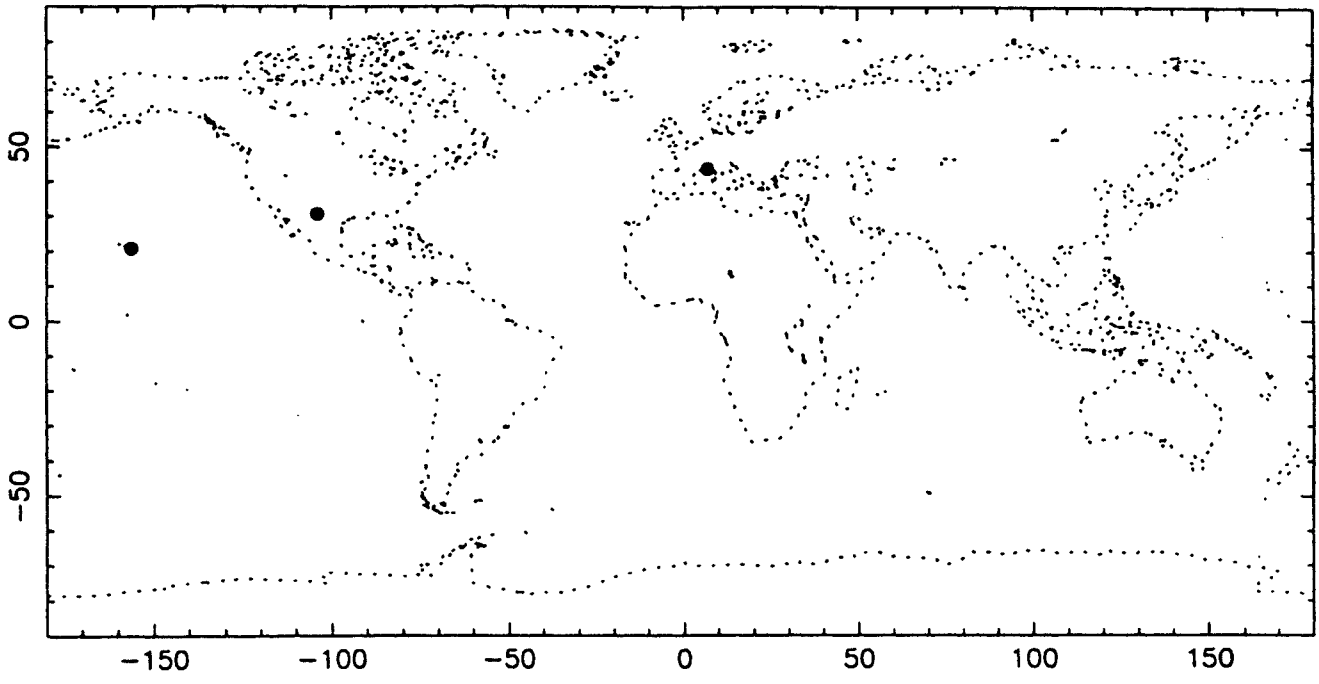
References

Langley, R. B., King, R.W., Shapiro, I.I., 1981: Earth Rotation from Lunar Laser Ranging, *J. Geophys. Res.*, **86**, 11913-11918.

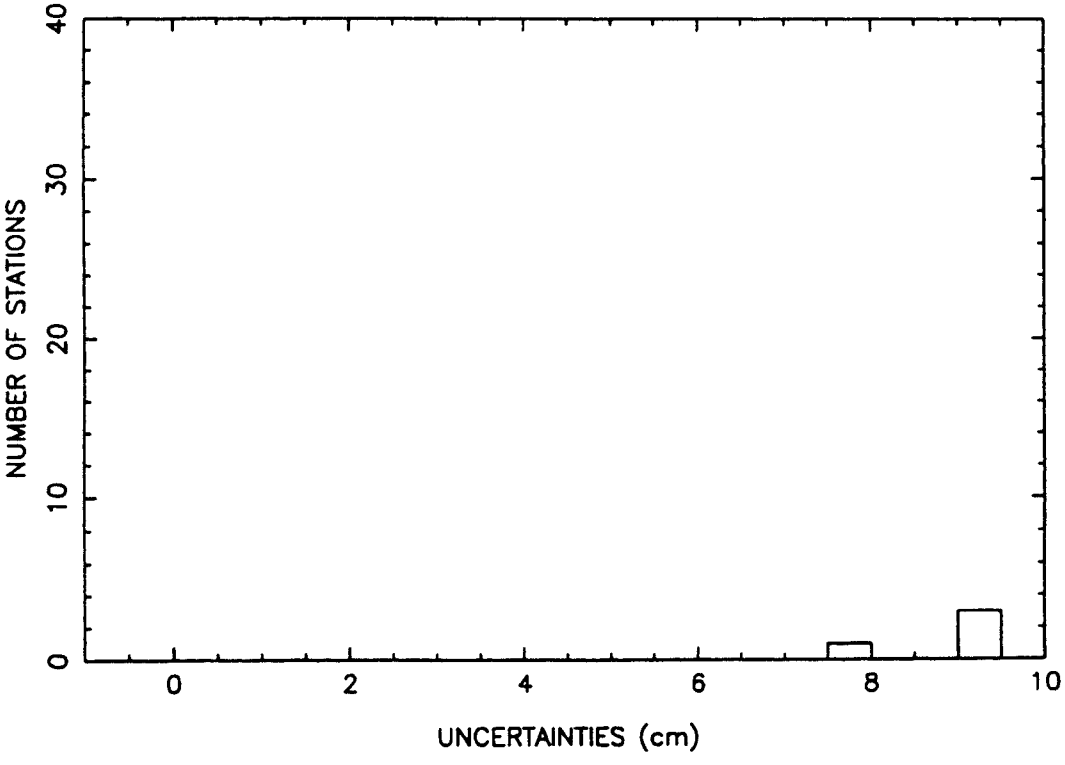
Stolz, A., Bender, P. L., Faller, J. E., Silverberg, E. C., Mulholland, J. D., Shelus, P.J., Williams, J. G., Carter, W. E., Gurnie, D. G., Kaula, W. M., 1976: Earth Rotation Measured by Lunar Laser Ranging, *Science*, **193**, 997-999.

Summary description of the terrestrial system attached to the set of station coordinates SSC(UTXMO) 93 M 01

1 - Technique:	LLR
2 - Analysis Center:	UT/McD
3 - Solution identifier:	UTXMO 93 M 01
4 - Software used:	PEP
5 - Relativity scale:	SSB
6 - Permanent tidal correction on station:	No
7 - Tectonic plate model:	AM0-2
8 - Velocity of light (C):	299792458
9 - Geogravitational constant (GM):	$3.98600444\ 10^{14}$ (geocentric)
10 - Reference epoch:	1984.0
11 - Adjusted parameters:	λ, φ, h
12 - Definition of the origin:	Geocenter
13 - Definition of the orientation:	Fixed to CSR LGN7692 series at 11 Jan 1985
14 - Constraint for time evolution:	Constrained to AM0-2



Distribution of the 3 sites of the terrestrial frame SSC(UTXMO) 93 M 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 5 stations of the terrestrial frame SSC(UTXMO) 93 M 01. 1 station with uncertainty larger than 10 cm is not shown.

EOP(UTXMO) 93 M 01 From Oct 1970 to Dec 1992

Number of measurements per year and median uncertainties
Units : 0.001" for φ; 0.0001s for UT0

YEAR	φ		UTO	
	Nb	Sigma	Nb	Sigma
1970	5	46.90	5	6.61
1971	11	15.30	11	5.39
1972	48	8.50	48	5.61
1973	56	16.20	56	5.53
1974	28	7.60	28	4.59
1975	41	8.10	41	5.54
1976	41	7.60	41	5.20
1977	29	7.10	29	4.42
1978	22	8.30	22	4.70
1979	27	7.20	27	4.43
1980	33	6.50	33	3.90
1981	3	5.00	3	4.21
1982	0		0	
1983	6	5.60	6	3.89
1984	45	5.90	45	4.09
1985	104	8.25	104	4.06
1986	24	6.50	24	3.22
1987	26	10.05	26	3.10
1988	57	5.00	57	2.70
1989	46	4.10	46	2.91
1990	89	4.10	89	2.60
1991	58	3.65	58	2.31
1992	52	3.90	52	2.57