LUNAR LASER RANGING

EARTH ROTATION (UT0-UTC) FROM LUNAR LASER RANGING JPL 91 M 01

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

Lunar Laser Ranging (LLR) data have been acquired and analyzed between August, 1969 and February, 1991. 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 determination of Earth Rotation UT0. Values of UT0-UTC through 1989 have been submitted previously; 89 such values were derived from data acquired in 1990.

The full range data set comprises 7147 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. The mean uncertainty in the values of UT0-UTC for 1990 is 0.1msec. This set of values is designated EOP(JPL) 91 M 01.

The IAU expresion has been used for Greenwich mean sidereal time (Aoki *et al.*, 1982). The planetary and lunar ephemeris used in the fit was DE229/LE229; this ephemeris uses the equator and equinox of J2000. The lunar librations were integrated simultaneously with the ephemeris.

Plate motion has been applied to the station coordinates using the AM0-2 model of Minster and Jordan (1978). The base epoch of plate motion is January 1, 1988 (JD 2447161.5).

A correction to the luni-solar precession constant (Lieske *et al.*, 1977; Lieske, 1979) has been adopted from solution B of Williams *et al.* (1991), -2.7+-0.4 mas/yr. The correction has been made so as not to cause a rate change in UT (Williams and Melbourne, 1982; Zhu and Mueller, 1983).

The IAU nutation (Seidelmann, 1982) has had an annual correction of 1.8 mas (taken from Herring *et al.*, 1986) applied ($\Delta\varepsilon$ = 0".0018 cos l', and sin ε $\Delta\psi$ = 0".0018 sin l'). Corrections to the 9-year terms were applied from Kinoshita and Souchay (1990) : $\Delta\varepsilon$ = -0".0002 cos2Ω, and sin ε $\Delta\psi$ = 0".00045 sin2Ω; corrections to the 18.6 yr nutation coefficients were estimated, yielding

$$\Delta\varepsilon = 3.1 \cos\Omega + 1.4 \sin\Omega \quad \text{mas}$$

$$\sin\varepsilon\,\Delta\psi = -3.4 \sin\Omega + 1.0 \cos\Omega \quad \text{mas}$$

The two out-of-phase terms (the second terms on the right side) were constrained to the expected ratio; the constraint of the two in-phase terms also includes a correction for the precession change and the solid-body correction of Kinoshita and Souchay (1990). Subject to the two constraints, the uncertainty in the four nutation coefficients is about 1.5 mas, and the precession uncertainty is 0.4 mas/yr. Without the two constraints these uncertainties would be larger.

With the production of the 1990 values of UT0-UTC a set of station locations has been established. The IERS designation in SSC(JPL) 91 M 01; the components are given in the following table:

Cylindrical station coordinates SSC(JPL) 91 M 01

station	Spin Radius (meters)	East Longitude (arc seconds)	Z-height (meters)
McDonald 2.7 m	5492414.333	921520.7680	3235697.667
MLRS (old site)	5492037.598	921542.7991	3236146.662
MLRS (new site)	5491888.354	921545.2552	3236481.685
Haleakala Tmtr	5971474.348	733478.7006	2242188.576
CERGA	4615328.569	24917.6088	4389354.818
Haleakala Rcvr-Tmtr	-7.446	0.0000	18.151

Cartesian station coordinates (meters)

station	*X*	*Y*	*Z*
McDonald 2.7 m	-1330782.307	-5328755.357	3235697.667
MLRS (old site)	-1330121.895	-5328531.948	3236146.662
MLRS (new site)	-1330022.302	-5328402.985	3236481.685
Haleakala Tmtr	-5466007.334	-2404427.106	2242188.576
CERGA	4581692.374	556194.923	4389354.818

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

The approximative uncertaintities in each of the cylindrical coordinates for all stations are: spin radius, 4 cm; longitude, 1.5 mas (4 cm); and *z*, 9 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 above 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.

The Jet Propulsion Laboratory provides current values of UT0-UTC on the General Electric Mark 3 system for the benefit of interested users.

ACKOWLEDGMENTS

We wish to acknowledge and thank the staff 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 the 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., "The New Definition of Universal Time", *Astron. Astrophys.* **105**, 1 (1982).

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

Herring, T. A., Gwinn, C. R., and Shapiro, I. I., "Geodesy by Radio Interferometry: Studies of the Forced Nutations of the Earth. Part 1: Data Analysis", *J. Geophys. Res.* **91**, B5, 4745 (1986).

Kinoshita, H. and Souchay, J., "The Theory of the Nutation for the Rigid Earth Model at the Second Order", *Celest. Mech. and Dyn. Astr.* **4**, 187-265, (1990).

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

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

Minster, J. B., and Jordan, T. H., "Present-Day Plate Motions", *J. Geophys. Res.* **83**, B11 (1978).

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

Williams, J. G., and Melbourne, W. G., "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., 293-304, D. Reidel, Hingham, MA (1982).

Williams, J. G., Newhall, X X, and Dickey, J. O.: "Luni-solar Precession: Determination from Lunar Laser Ranges", *Astron. Astrophys.* **241**, L9-L12, (1991).

Zhu, S.-Y. and Mueller, I. I., "Effects of Adopting New Precession, Nutation, and Equinox Corrections on the Terrestrial Reference Frame", *Bull. Geod.*, **57**, 29-42 (1983).

SUMMARY SHEET FOR THE DESCRIPTION OF THE TERRESTRIAL SYSTEM ATTACHED TO A SET OF STATIONS COORDINATES

1.	Technique:	LLR
2.	Analysis center:	JPL
3	Solution identifier:	SSC(JPL) 91 M 01
4	Software used:	JPL LLR software
5	Relativity scale for station coordinates:	SSB
6	Permanent tidal correction on stations:	No (periodic included)
7	Tectonic plate model:	AM0-2
8	Velocity of light :	299792458 m/sec

9	Geogravitational constant (GM):	From the solution 398600443E14 (geocentric) GM does not influence the LLR station radii.
10	Reference epoch:	January 1, 1988 (JD 2447161.5)
11	Adjusted parameters:	Cylindrical station coordinates (rates fixed). The three McDonald sites are independently adjusted.
12	Definition of the origin:	Geocenter (center of mass)
13	Definition of the orientation:	Earth rotation values from 1976 to 1991 taken from a file (not aligned with IERS system) provided by R. Gross. Pre 1976 Earth rotation was adjusted from LLR data.
14	Constraint for time evolution:	The above earth rotation file was based on AM0-2 plate motions.

EOP(JPL) 91 M 01 Available from 1970 to 1991

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

YEAR	φ		UT0	
	Nb	Sigma	Nb	Sigma
1970	15	36.49	15	14.11
1971	35	34.12	35	12.48
1972	72	30.12	72	6.72
1973	106	37.44	106	9.76
1974	69	32.47	69	8.11
1975	87	23.86	87	9.51
1976	64	18.78	64	6.50
1977	68	14.08	68	5.18
1978	49	14.16	49	6.16
1979	66	13.76	66	5.35
1980	68	13.24	68	4.82
1981	45	16.36	45	4.81
1982	6	22.61	6	5.47
1983	0	0.00	0	0.00
1984	26	6.86	26	2.81
1985	111	8.99	111	2.93
1986	28	6.16	28	2.36
1987	19	5.02	19	1.53
1988	71	3.44	71	1.31
1989	42	3.19	42	1.11
1990	89	2.55	89	1.09
1991	20	2.82	20	0.97

DETERMINATION OF UNIVERSAL TIME BY LUNAR LASER RANGING SHA 90 M 01

Jin Wenjing , Xu Hua Guan - Shanghai Observatory , Academia Sinica , Shanghai , China

Universal time has been determined from global data of Lunar Laser Ranging during October 1987-December 1990. The data set obtained from the McDonald Laser Ranging Station (71111, 71112) , Grasse (1910) and Haleakala (56610) contains 2042 normal points reflected from four reflectors and were usable for determination of universal time. Due to the need of solving the normal equation the observing interval between first and last normal points should be greater than 0.8 hour and more than two points per day are need. The theoretical distances from the stations to the retro-reflectors of the Moon are calculated using the IERS standards. The influence of plate motion is not taken into account.

The planetary and lunar ephemeris DE 303/LE 303 are used for calculating the positions of the Earth and the Moon. The lunar librations integrated simultaneously with the ephemeris is adopted for calculating the lunar physical libration.

The reflector coordinates are adopted from IERS standards.

The mathematical model is described in reference 2 (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.

The station coordinates are adopted as follows

Spherical station coordinates

Station Code	Radius (km)	East Longitude (°)	Latitude (°)
1910	6369.277323	6.92156500	43.56245573
56610	6378.550976	203.74409422	20.58040141
71111	6374.568224	255.98412053	30.50843366
71112	6374.609734	255.98480229	30.51170897

Acknowledgments

The planetary ephemeris DE303/LE303 is supplied by Jet Propulsion Laboratory , California Institute of Technology. The global data of Lunar Laser Ranging are obtained from Dr. Veillet , CERGA.

References

1. D.D. McCarthy *et al.* 1989 : IERS Standards (1989)-IERS Technical Note 3.

2. 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. 287-295.

EOP(SHA) 91 M 01 Available from 1987 to 1990

Number of measurements and RMS uncertainty per year
Units : 0.0001s for UT0.

YEAR	UT0	
	Nb	Sigma
1987	39	3.77
1988	66	2.23
1989	61	3.37
1990	94	2.78

UT0 AND VARIATION OF LATITUDE DETERMINATION FROM LUNAR LASER RANGING OBSERVATIONS FOR 1969-1990

UTXMO 91 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, 1991. A total of 7287 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 and the CERGA station in Grasse, were used in this solution. The data were edited and reweighted 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 834 station/reflector pair estimations of UT0-UTC including 94 UT0 estimates, on 67 nights, in 1990. This is up 74% from the number of estimates we were able to make in 1989 is up 68% on the number of nights covered.

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 UT1 COM42/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). The station coordinates which resulted from the fit are given in Table 1. 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 2.7m, Maui and CERGA data.

Table 1. Station coordinates for the five past and present LLR sites. The three Fort Davis sites are the McDonald Observatory 2.7m telescope, the MLRS saddle site, and the MLRS Mt. Fowlkes site, respectively.

SSC(UTXMO) 91 M 01

IGNF NUMBER	SITE	DOMES NUMBER	X m	Y m	Z m	PLATE
2S001	FORT DAVIS	40442S002	-1330780.490	-5328755.546	3235697.863	NOAM
2S002	FORT DAVIS	40442S007	-1330120.237	-5328532.139	3236146.910	NOAM
2S003	FORT DAVIS	40442S014	-1330020.636	-5328403.204	3236481.860	NOAM
8S002	MAUI	40445S005	-5466006.482	-2404428.892	2242188.515	PCFC
10S001	GRASSE	10002S002	4581692.210	556196.338	4389354.808	EURA

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 4.9 cm. The weighted rms of the postfit residuals for the 715 normal points obtained by the three active stations during 1990 was 3.0 cm. This number of normal points is up 58% from last year while therms has remained exactly the same.

We have compared our UT0 and variation of latitude series with the IRIS VLBI 5-day series posted to the G.E. MarkIII system. 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 UT1 and polar motion values. Interpolation of the IRIS series was performed using a four point Newton interpolation scheme. Table 2 gives the results of this comparison for the period where all stations operated with short pulse lasers (1986.5 to 1991.2).

Table 2. 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 1991.2. The epoch of the linear fit is 1988.85.

Station		Bias (mas)	Slope (mas/yr)	WRMS (mas)	N
CERGA	DUT0R:	-1.57 +/- 0.18	-1.00 +/- 0.14	2.10	171
	DPhi:	-6.91 +/- 0.20	0.65 +/- 0.15	1.91	
MLRS	DUT0R:	9.05 +/- 3.37	1.69 +/- 2.07	1.76	7
(Saddle)	DPhi:	13.99 +/- 6.61	7.48 +/- 4.26	4.74	
MLRS	DUT0R:	2.94 +/- 0.88	-1.08 +/- 0.62	1.38	13
(Mt. Fowlkes)	DPhi:	1.45 +/- 0.98	1.02 +/- 0.71	2.92	
Maui	DUT0R:	1.24 +/- 0.27	-0.73 +/- 0.20	3.09	81
	DPhi:	5.30 +/- 0.37	0.29 +/- 0.30	6.01	

REFERENCES

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

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

SUMMARY SHEET

1 - Technique:	LLR
2 - Analysis Center:	UT/McD
3 - Solution identifier:	UTXMO 91 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) =	3.986004440E14
10 - Reference epoch =	1984.0
11 - Adjusted parameters:	lambda, phi, 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

EOP(UTXM0) 91 M 01 Available from 1970 to 1991

Number of measurements and RMS uncertainty per year
Units : 0.001" for PHI; 0.0001s for UT0.

YEAR	PHI		UT0	
	Nb	Sigma	Nb	Sigma
1970	5	49.70	5	6.17
1971	12	26.55	12	5.77
1972	49	20.01	49	5.58
1973	56	22.37	56	5.72
1974	28	15.87	28	4.58
1975	41	12.66	41	5.77
1976	41	12.55	41	5.39
1977	30	11.18	30	4.46
1978	22	11.81	22	4.86
1979	27	11.00	27	4.61
1980	36	11.33	36	4.28
1981	3	13.50	3	4.29
1982	1	29.70	1	4.15
1983	6	5.92	6	4.67
1984	53	25.88	53	6.75
1985	129	22.60	129	5.66
1986	32	34.52	32	6.42
1987	37	58.84	37	13.05
1988	60	9.87	60	3.30
1989	54	36.22	54	9.08
1990	94	11.68	94	2.76
1991	0	0.00	20	2.78