LUNAR LASER RANGING
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 expression 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 \( \Delta \varepsilon = 0''\cdot0018 \cos \lambda \), and \( \sin \varepsilon \Delta \psi = 0''\cdot0018 \sin \lambda \). Corrections to the 9-year terms were applied from Kinoshita and Souchay (1990) : \( \Delta \varepsilon = -0''\cdot0002 \cos 2\Omega \), and \( \sin \varepsilon \Delta \psi = 0''\cdot00045 \sin 2\Omega \); corrections to the 18.6 yr nutation coefficients were estimated, yielding

\[
\begin{align*}
\Delta \varepsilon &= 3.1 \cos \Omega + 1.4 \sin \Omega \quad \text{mas} \\
\sin \varepsilon \Delta \psi &= -3.4 \sin \Omega + 1.0 \cos \Omega \quad \text{mas}
\end{align*}
\]

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 UTO-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

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

### Cartesian station coordinates (meters)

<table>
<thead>
<tr>
<th>station</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>McDonald 2.7 m</td>
<td>-1330782.307</td>
<td>-328755.357</td>
<td>3235697.667</td>
</tr>
<tr>
<td>MLRS (old site)</td>
<td>-1330121.895</td>
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<td>3236146.662</td>
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<td>MLRS (new site)</td>
<td>-1330022.302</td>
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<tr>
<td>Haleakala Tmtr</td>
<td>-5466007.334</td>
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<td>2242188.576</td>
</tr>
<tr>
<td>CERGA</td>
<td>4581692.374</td>
<td>556194.923</td>
<td>4389354.818</td>
</tr>
</tbody>
</table>

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 uncertainties 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 UTO-UTC on the General Electric Mark 3 system for the benefit of interested users.

ACKNOWLEDGMENTS

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


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: AMO-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 UTO

<table>
<thead>
<tr>
<th>YEAR</th>
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<th>φ</th>
<th>Sigma</th>
<th>Nb</th>
<th>UTO</th>
<th>Sigma</th>
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<td>36.49</td>
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<td>37.44</td>
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<td>1987</td>
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<td>1988</td>
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<td>71</td>
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<td>42</td>
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<td>1.11</td>
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</tr>
<tr>
<td>1990</td>
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<td>2.55</td>
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<td>1.09</td>
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</tr>
<tr>
<td>1991</td>
<td></td>
<td>20</td>
<td>2.82</td>
<td>20</td>
<td>0.97</td>
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</tr>
</tbody>
</table>
DETERMINATION OF UNIVERSAL TIME BY LUNAR LASER RANGING

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

<table>
<thead>
<tr>
<th>Spherical station coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station Code</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>1910</td>
</tr>
<tr>
<td>56610</td>
</tr>
<tr>
<td>71111</td>
</tr>
<tr>
<td>71112</td>
</tr>
</tbody>
</table>

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


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

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

<table>
<thead>
<tr>
<th>YEAR</th>
<th>Nb</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>39</td>
<td>3.77</td>
</tr>
<tr>
<td>1988</td>
<td>66</td>
<td>2.23</td>
</tr>
<tr>
<td>1989</td>
<td>61</td>
<td>3.37</td>
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<tr>
<td>1990</td>
<td>94</td>
<td>2.78</td>
</tr>
</tbody>
</table>
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/retroreflector 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 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.

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.

<table>
<thead>
<tr>
<th>IGNF SITE NUMBER</th>
<th>DOMES SITE NUMBER</th>
<th>X m</th>
<th>Y m</th>
<th>Z m</th>
<th>PLATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>25001 FORT DAVIS</td>
<td>40442S002</td>
<td>-1330780.490</td>
<td>-5328755.546</td>
<td>3235697.863</td>
<td>NOAM</td>
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<tr>
<td>25002 FORT DAVIS</td>
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<td>-1330120.237</td>
<td>-5328532.139</td>
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</tr>
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<td>-5328403.204</td>
<td>3236481.860</td>
<td>NOAM</td>
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<td>4581692.210</td>
<td>556196.338</td>
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</table>

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 UTC0 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 UTC0-UTC and variation of latitude. A minimum of three normal points for each station/reflectors pair and at least a 1.5 hour span of coverage were the criteria we adopted for the nightly UTC0 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 UTC0 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 UTC0 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 UTC0 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.

<table>
<thead>
<tr>
<th>Station</th>
<th>Bias (mas)</th>
<th>Slope (mas/yr)</th>
<th>WRMS (mas)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERGA</td>
<td>-1.57 +/- 0.18</td>
<td>-1.00 +/- 0.14</td>
<td>2.10</td>
<td>171</td>
</tr>
<tr>
<td>DPhi</td>
<td>-6.91 +/- 0.20</td>
<td>0.65 +/- 0.15</td>
<td>1.91</td>
<td></td>
</tr>
<tr>
<td>MLRS (Saddle)</td>
<td>9.05 +/- 3.37</td>
<td>1.69 +/- 2.07</td>
<td>1.76</td>
<td>7</td>
</tr>
<tr>
<td>DPhi</td>
<td>13.99 +/- 6.61</td>
<td>7.48 +/- 4.26</td>
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</tr>
<tr>
<td>MLRS (Mt. Fowlkes)</td>
<td>2.94 +/- 0.88</td>
<td>-1.08 +/- 0.62</td>
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<tr>
<td>DPhi</td>
<td>1.45 +/- 0.98</td>
<td>1.02 +/- 0.71</td>
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<tr>
<td>Maui</td>
<td>1.24 +/- 0.27</td>
<td>-0.73 +/- 0.20</td>
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<tr>
<td>DPhi</td>
<td>5.30 +/- 0.37</td>
<td>0.29 +/- 0.30</td>
<td>6.01</td>
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</tbody>
</table>

REFERENCES


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.

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