LUNAR LASER RANGING

DETERMINATION OF EARTH ROTATION (UT0-UTC AND VARIATION OF LATITUDE) BY ANALYZING LUNAR LASER RANGING DATA

FSG 95 M 01

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We have analyzed Lunar Laser Ranging (LLR) data acquired between 1970 and January, 1995. The observations are taken from the usual five sites: McDonald (three locations), Grasse and Haleakala; some normal points from Wettzell are added. All in all more than 9200 LLR measurements are used.

The constants adopted for the computations are those of the IAU recommendations resp. the IERS standards (McCarthy, 1992). For the 9-year, the annual, the half-year and the half-month period we used the values of Zhu *et al.* (1990).

The station coordinates have been corrected for plate motion (NUVEL NNR-1 model); the base epoch for plate motion is December 10, 1991 (MJD 48600).

The input Earth orientation parameters are taken from a solution generated by R. Gross called COMB94; the tidally driven diurnal and semidiurnal UT1 variations have been added to the input UT1 file (Herring, 1993).

We determined the parameters of the Earth-Moon system by a least-squares fit to weighted observations. For the determination of a correction to the luni-solar precession constant and the four (two in-phase and two out-of-phase) coefficients of the 18.6 year nutation period, constraints indicated in Williams *et al.* (1991) have been used.

The post-fit residuals are analyzed by the daily-decomposition method (Dickey *et al.*, 1985) to obtain improved values for UT0-UTC and variation of latitude (VOL) for each reflector station pair on every night for which sufficient data are available. 1612 pairs were found. After having removed the bad ones the others have been smoothed using a spline filter. The series of Earth rotation parameters (UT0-UTC and VOL) have been provided to the IERS Central bureau, designated EOP(FSG) 95 M 01.

These improved values for the Earth rotation have been used in a further iteration of the global adjustment of the LLR data. The final results for the station coordinates have been provided to the IERS Central Bureau. Its designation is SSC(FSG) 95 M 01.

Besides the parameters mentioned above, relativistic quantities have been determined: two metric parameters, the Nordtvedt parameter (strong equivalence principle), the geodetic precession of the lunar orbit, the time variation of the gravitational constant, one parameter for testing Newton's inverse square law, one parameter indicating a violation of special relativity and one parameter which indicates the validity of the strong equivalence principle in the coupling of dark matter to the different compositions of Earth and Moon.

Values for all parameters are available on request.

Acknowledgements. We wish to acknowledge and thank the staffs of Cerga, Haleakala, and McDonald Observatory for providing the normal points. We wish to thank R. Gross from JPL for providing his series of Earth rotation parameters. Support from the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

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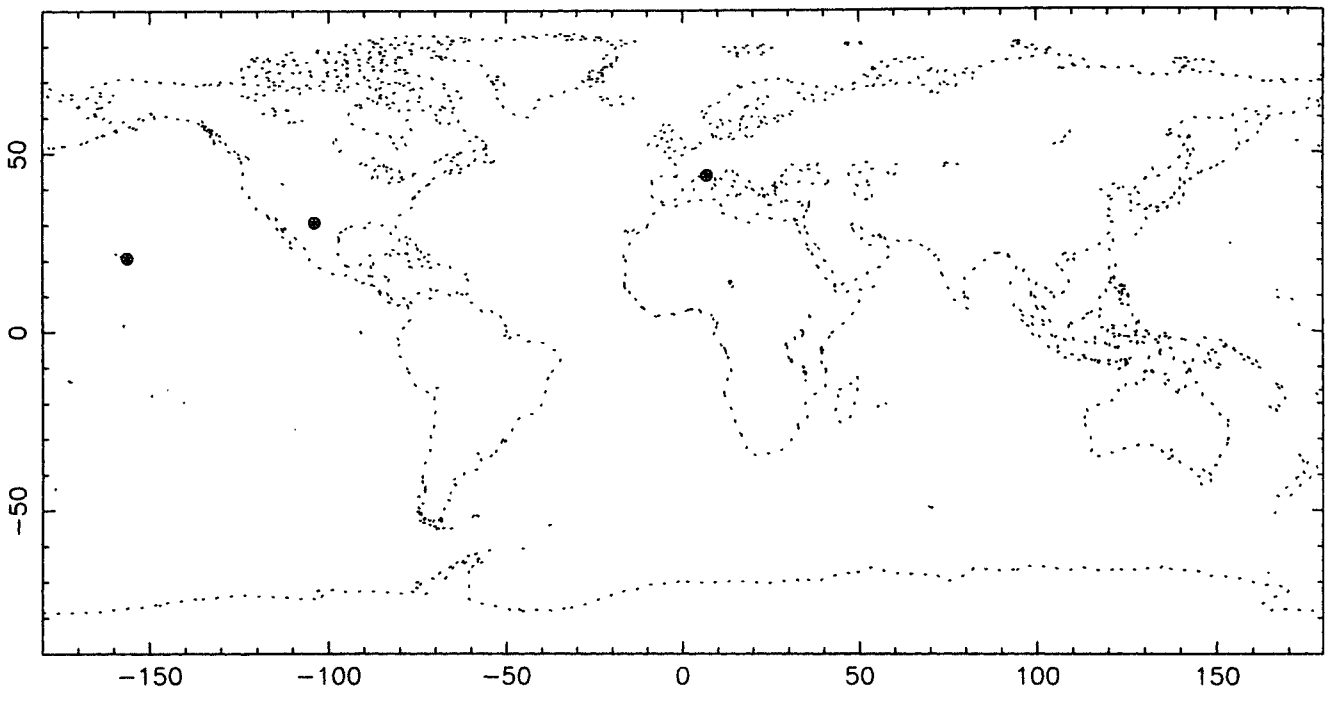
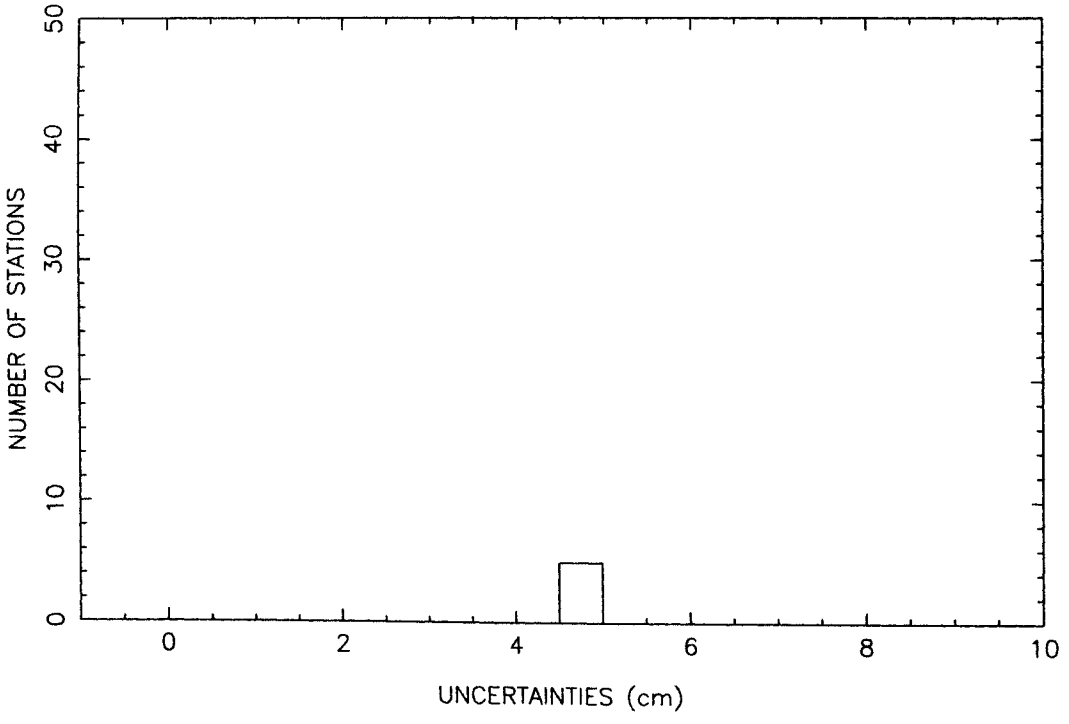
Technical description of solution FSG 95 M 01

1 - Technique:	LLR
2 - Analysis Center:	FSG/Techn. Univ. Munich
3 - Software used:	FSG LLR software
4 - Data span:	April 1970 - Jan 1995
5 - Celestial Reference Frame:	
a - Nature:	dynamical; own ephemeris program (initial values from DE200)
b - Definition of the Orientation:	referred to the equator and equinox of J2000 through the ephemeris
6 - Terrestrial Reference Frame:	SSC(FSG) 95 M 01
a - Relativity scale:	LE: relativistic geocentric frame
b - Velocity of light:	299792458 m/s
c - Geogravitational constant:	adjusted: 3.98600448 m^3/s^2 (geocentric)
d - Permanent tidal correction:	No
e - Definition of the origin:	by the geocenter through c10=0, c11=0, s11=0
f - Definition of the orientation:	EOP from 1970 to 1995 taken from a file of R. Gross (COMB94) which is aligned with the IERS system; daily corrections for UT0 and VOL are determined after the global fit
g - Reference epoch:	december 10, 1991 (MJD 48600)
h - Tectonic plate model:	NNR-NUVEL1
i - Constraint for time evolution:	fixed plate motion model (NNR-NUVEL1); estimation of UT1 and polar motion rates during the global solution
7 - Earth Orientation:	EOP(FSG) 95 M 01
a - A priori nutation model:	IAU(1980), values for the coefficients of the 9-year, annual, half-year and half-month period from Zhu et al. (1990)
b - Short-period tidal variations in x, y, UT1:	diurnal and semidiurnal tidal variations (M2, S2, N2, K1, O1, P1) in UT1 have been added (Herring, 1993), not in x and y
8 - Estimated parameters:	
a - Celestial Frame:	orbit of the Earth-Moon barycenter (X0, Y0, Z0, Xdot, Ydot, Zdot); lunar orbit (X0, Y0, Z0, Xdot, Ydot, Zdot)
b - Terrestrial Frame:	cartesian coordinates (X0, Y0, Z0); rates fixed (NNR-NUVEL1)
c - Earth Orientation:	UT0-UTC and variation of latitude VOL; luni-solar precession constant and the amplitudes of the 18.6-year nutation period (2 in-phase and 2 out-of-phase); rates for x, y, and UT1
d - Others:	lunar librations; reflector coordinates; lunar gravity; mass of the Earth-Moon system; lunar Love number and dissipation parameter; lag angle (lunar tidal acceleration); relativistic parameters



Distribution of the 3 sites of the terrestrial frame SSC(FSG) 95 M 01



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 5 stations of the terrestrial frame SSC(FSG) 95 M 01.

EOP(FSG) 95 M 01 From Oct 1970 to Jan 1995

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

YEAR	φ		UT0	
	Nb	Sigma	Nb	Sigma
1970	8	15.00	8	10.00
1971	21	15.00	21	10.00
1972	62	10.31	62	3.77
1973	105	15.00	105	10.00
1974	68	15.00	68	10.00
1975	82	15.00	82	10.00
1976	77	15.00	77	6.84
1977	70	15.00	70	10.00
1978	57	15.00	57	10.00
1979	62	15.00	62	10.00
1980	68	15.00	68	10.00
1981	29	15.00	29	10.00
1982	3	7.73	3	3.43
1983	6	15.00	6	10.00
1984	77	7.91	77	4.61
1985	175	7.84	175	3.45
1986	42	4.09	42	1.65
1987	39	3.87	39	1.27
1988	49	1.27	49	0.86
1989	51	1.34	51	0.87
1990	98	1.15	98	0.67
1991	63	1.36	63	0.62
1992	81	1.69	81	1.14
1993	100	1.53	100	0.80
1994	95	1.05	95	0.69
1995	13	0.88	13	0.69

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

JPL 95 M 01, 02

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Lunar Laser Ranging (LLR) data have been acquired and analyzed between April, 1970 and February, 1995. 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 March 2, 1994 have been submitted previously; 67 such values were derived from subsequent data acquired in 1994, and 21 values were obtained from early 1995 data, giving a total of 1433 values.

The full range data set comprises 9389 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.

Two EOP solutions were performed, one with the JPL ephemeris DE247/LE247, providing the set EOP (JPL) 95 M 01; the other solution was done with the recent ephemeris DE402/LE402, providing EOP (JPL) 95 M 02. The lunar librations were integrated simultaneously with the ephemerides.

The tidally driven diurnal and semidiurnal UT1 variations (M2, S2, N2, K1, O1, and P1), from the measured results in Herring (1993), 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 model.

A correction to the IAU luni-solar precession constant has been solved for. The correction has been made so as not to cause a rate change in UT (Williams and Melbourne, 1982; Zhu and Mueller, 1983). A theoretical obliquity-rate correction of -0.24 mas/yr (Williams, 1994) has been applied.

To the IAU nutations (Seidelmann, 1982) we have added the ZMOA corrections (Herring *et al.*, 1991a; 1991b) for the in-phase 9 yr, 1 yr, and half-month term 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. The precession and nutation corrections are:

	Solution 1 (DE247)	Solution 2 (DE402)
Δp	-3.3mas/yr	3.1mas/yr
$\Delta\varepsilon$	1.7 cos Ω + 0.2 sin Ω mas	1.4 cos Ω + 0.8 sin Ω mas
$\sin\varepsilon\,\Delta\psi$	-1.6 sin Ω + 0.2 cos Ω mas	-1.1 sin Ω + 0.6 cos Ω 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 mas, and the precession uncertainty is 0.3 mas/yr. Without the constraint these uncertainties would be larger.

The station locations resulting from the two solutions are called SSC(JPL) 95 M 01, for the case with DE247, and SSC(JPL) 95 M 02, for the case with DE402. The separations between the McDonald sites were constrained to survey values. The separation between the Haleakala transmitter and receiver also conforms to a survey. A range bias is estimated for Haleakala beginning in January, 1990.

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.

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Technical description of solution JPL M 01

1 - Technique: LLR

2 - Analysis center: JPL

3 - Software used: JPL LLR software

4 - Data span: Apr 70 - Feb 95

5 - Celestial reference frame:
- a - Nature: Dynamical
- b - Definition of orientation: DE 247 orbit

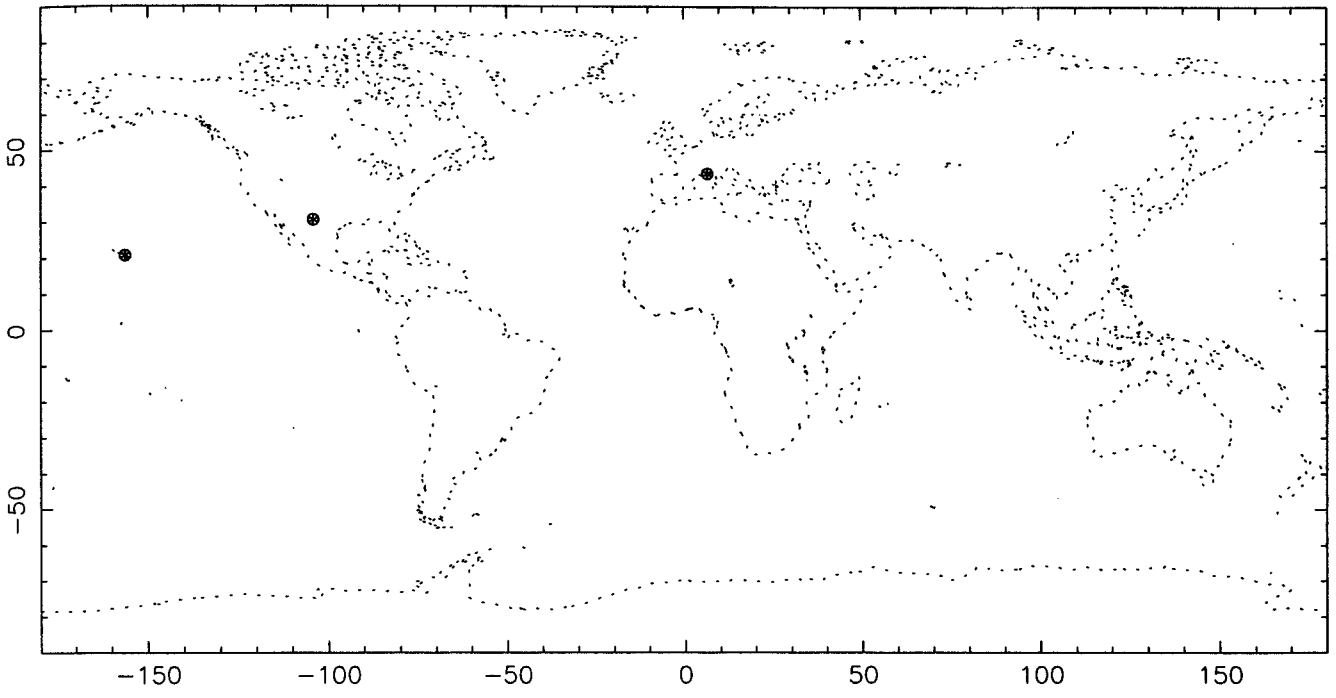
6 - Terrestrial reference frame: SSC(JPL) 95 M 01
- a - Relativity scale: SSB
- b - Velocity of light: c = 299792458 m/sec
- c - Geogravitational constant: GM0 = 3.986004427 10^{14} m^3/s^2 value is from ephemeris solution and has been converted to local earth frame. GM0 does not influence the LLR station radii.
- d - Permanent tidal correction: Yes
- e - Definition of the origin: Geocenter (center of mass)
- f - Definition of the orientation: Input Earth rotation values from 1970 to early 1995 taken from a file from R. Gross (a version of COMB-94 generated without LLR data) aligned with IERS system. Restricted by the uncertainties on the file, smoothed variation of latitude and UT0 corrections were made from LLR data during the global solution for stations, orbit, precession/ nutation, etc., but final UT0/VOL values generated after the global fit.
- g - Reference epoch: January 1, 1991 (JD 2448257.5)
- h - Tectonic plate model: NNR-NUVEL1
- i - Constraint for time evolution: Plate motion was not adjusted. Solved for overall corrections to the UT1 and polar motion rates with respect to the input UT1/polar motion file.

7 - Earth orientation: EOP(JPL) 95 M 01
- a - A priori nutation model: IAU (1980) plus corrections from ZMOA for in-phase 9.3 yr, annual, and semi-monthly coefficients plus semiannual in- and out-of phase corrections.
- b - Short-period tidal variations in x, y, UT1: Daily and subdaily variations in UT1 for M2, S2, N2, K1, O1, and P1 tides from Herring (1993). These fast variations are not in EOP file.

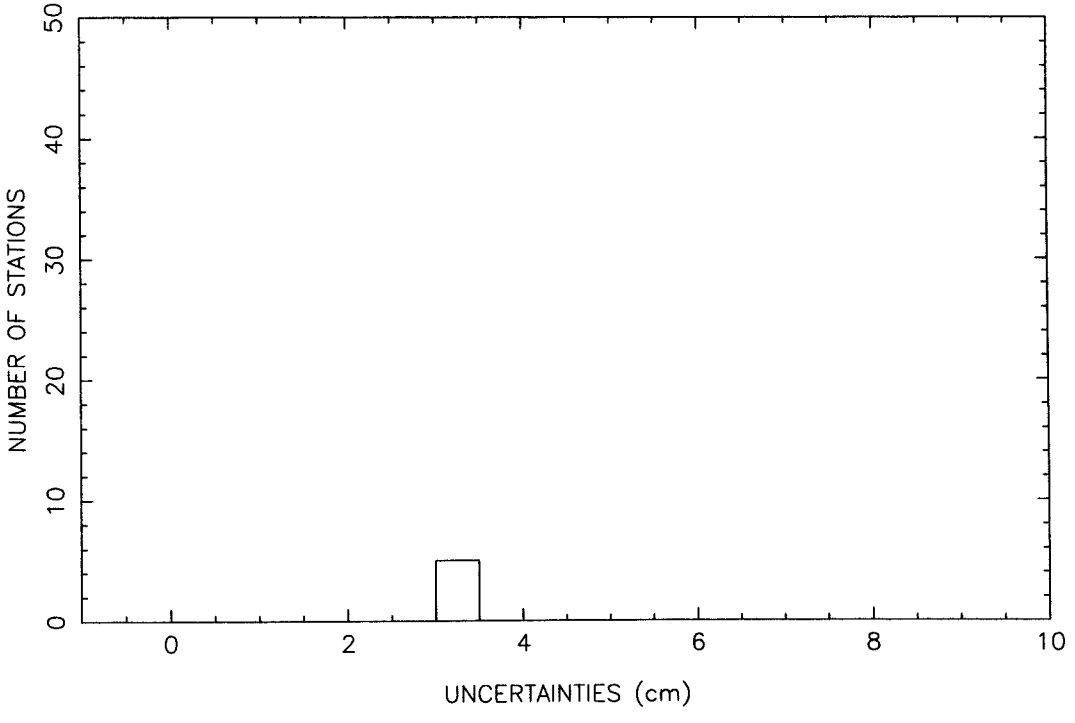
8 - Estimated parameters
- a - Celestial frame: Orbit parameters.
- b - Terrestrial frame: Spherical station coordinates (rates fixed) from full data span. Differences between three McDonald sites are constrained to surveys.
- c - Earth orientation: Precession rate and 18.6 yr nutation coefficients estimated. Daily UT0 and VOL values are generated after global solution.
- d - Others: Lunar orientation, tidal acceleration, obliquity.

Technical description of solution JPL 95 M 02

1 - Technique:	LLR
2 - Analysis center:	JPL
3 - Software used:	JPL LLR software
4 - Data span:	Apr 70 - Feb 95
5 - Celestial reference frame:	
a - Nature:	Dynamical, but oriented to IERS celestial frame.
b - Definition of orientation:	DE 402 orbit is oriented to IERS frame.
6 - Terrestrial reference frame:	SSC(JPL) 95 M 02
a - Relativity scale:	SSB
b - Velocity of light:	c = 299792458 m/sec
c - Geogravitational constant:	GM0 = 3.986004425 10^{14} m^3s^2 value is from ephemeris solution and has been converted to local earth frame. GM0 does not influence the LLR station radii.
d - Permanent tidal correction:	Yes
e - Definition of the origin:	Geocenter (center of mass)
f - Definition of the orientation:	Input Earth rotation values from 1970 to early 1995 taken from a file from R. Gross (a version of COMB-94 generated without LLR data) aligned with IERS system. Restricted by the uncertainties on the file, smoothed variation of latitude and UT0 corrections were made from LLR data during the global solution for stations, orbit, precession/ nutation, etc, but final UT0/VOL values generated after the global fit.
g - Reference epoch:	January 1, 1991 (JD 2448257.5)
h - Tectonic plate model:	NNR-NUVEL1
i - Constraint for time evolution:	Plate motion was not adjusted. Solved for overall corrections to the UT1 and polar motion rates with respect to the input UT1/polar motion file.
7 - Earth orientation:	EOP(JPL) 95 M 02
a - A priori nutation model:	IAU(1980) plus corrections from ZMOA for in-phase 9.3 yr, annual, and semi-monthly coefficients plus semiannual in- and out-of phase corrections.
b - Short-period tidal variations in x, y, UT1:	Daily and subdaily variations in UT1 for M2, S2, N2, K1, O1, and P1 tides from Herring (1993). These fast variations are not in EOP file.
8 - Estimated parameters	
a - Celestial frame:	Orbit parameters.
b - Terrestrial frame:	Spherical station coordinates (rates fixed) from full data span. Differences between three McDonald sites are constrained to surveys.
c - Earth orientation:	Precession rate and 18.6 yr nutation coefficients estimated. Daily UT0 and VOL values are generated after global solution.
d - Others:	Lunar orientation, tidal acceleration, obliquity.



Distribution of the 3 sites of the terrestrial frame SSC(JPL) 95 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) 95 M 01.

EOP(JPL) 95 M 01

From Apr 1970 to Feb 1995

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

YEAR	φ		UT0	
	Nb	Sigma	Nb	Sigma
1970	15	13.91	15	9.81
1971	34	12.55	34	7.38
1972	72	8.24	72	5.06
1973	102	13.95	102	7.51
1974	69	11.21	69	6.40
1975	87	10.31	87	6.87
1976	64	8.44	64	5.10
1977	68	6.61	68	4.02
1978	49	8.20	49	5.75
1979	65	6.67	65	4.73
1980	68	5.90	68	4.09
1981	45	8.24	45	4.26
1982	6	8.30	6	4.97
1983	0		0	
1984	26	4.29	26	2.26
1985	111	5.72	111	2.49
1986	28	3.40	28	1.60
1987	19	2.78	19	1.06
1988	71	1.97	71	1.01
1989	42	1.50	42	0.92
1990	89	1.42	89	0.90
1991	56	1.31	56	0.73
1992	53	1.23	53	0.82
1993	82	1.42	82	1.15
1994	87	0.91	87	0.80
1995	21	1.01	21	0.80

EOP(JPL) 95 M 02

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

YEAR	φ		UT0	
	Nb	Sigma	Nb	Sigma
1970	15	13.93	15	9.82
1971	34	12.56	34	7.39
1972	72	8.25	72	5.06
1973	102	13.96	102	7.52
1974	69	11.22	69	6.41
1975	87	10.32	87	6.87
1976	64	8.45	64	5.11
1977	68	6.62	68	4.03
1978	49	8.21	49	5.76
1979	65	6.68	65	4.74
1980	68	5.91	68	4.09
1981	45	8.25	45	4.27
1982	6	8.30	6	4.98
1983	0		0	
1984	26	4.29	26	2.26
1985	111	5.72	111	2.49
1986	28	3.40	28	1.60
1987	19	2.78	19	1.06
1988	71	1.98	71	1.01
1989	42	1.50	42	0.92
1990	89	1.42	89	0.90
1991	56	1.31	56	0.73
1992	53	1.23	53	0.82
1993	82	1.42	82	1.15
1994	87	0.91	87	0.80
1995	21	1.01	21	0.80

DETERMINATION OF UNIVERSAL TIME BY LUNAR LASER RANGING

SHA 95 M 01

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Lunar Laser Ranging (LLR) data have been analyzed during JD 2447187.0 - JD 2449709.0. These data set of McDonald (71111, 71112), Grasse (1910) and Haleakala (56610) contain 4111 normal points reflected from four reflectors.

Theoretical models and astronomical constants (solid earth tide and ocean tide, etc) were adopted from IERS standards (1992). The influence of plate motion is taken into account with NUVEL model. The base epoch for plate motion is January 1,1993. The relativistic effects (propagation correction, scale factor and Lorentz effect) are considered. The planetary ephemeris DE245/LE245 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, third degree and order lunar potential, and orbit parameters of the Earth-Moon system were estimated.

The post-fit residuals are analysed to obtain 449 values of UT0-UTC during this period. Due to the need of solving the normal equation, the span 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 produced are designated SSC(SHA) 95 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 as the weight of observational equation.

Acknowledgments

We wish to thank Dr. Myles Standish and Dr. Veillet who supplied the planetary ephemeris DE245/LE245 and the global data of lunar laser ranging.

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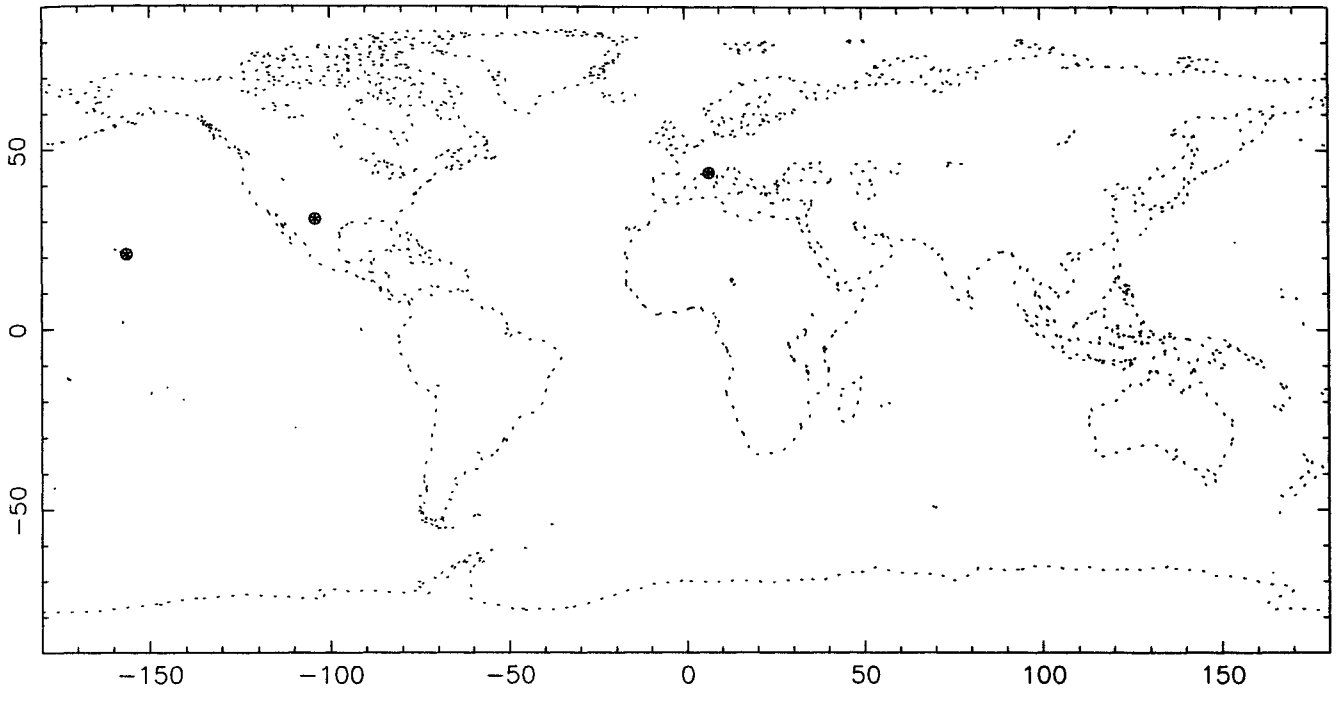
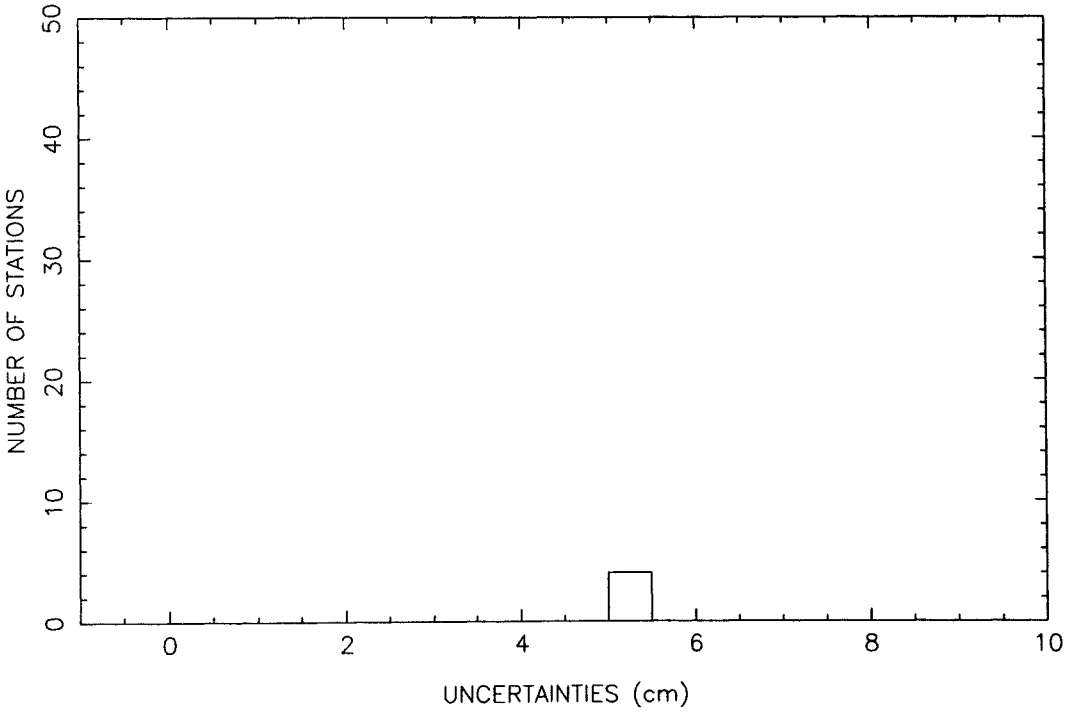
Technical description of solution SHA 95 M 01

1 - Technique:	LLR
2 - Analysis Center:	SHA
3 - Software used:	SHA LLR software
4 - Data span:	
5 - Celestial Reference Frame:	
a - Nature:	Dynamical
b - Definition of the orientation:	
6 - Terrestrial Reference Frame:	SSC(SHA) 95 M 01
a - Relativity scale:	SSB
b - Velocity of light:	299792458
c - Geogravitational constant:	$3.986004418\ 10^{14}$
d - Permanent tidal correction:	No
e - Definition of the origin:	Geocenter (center of mass)
f - Definition of the orientation:	EOP from 1988 to 1994 taken from IERS Circular B
g - Reference epoch:	1993.0
h - Tectonic plate model:	NUVEL
i - Constraint for time evolution:	Constrained to NUVEL
7 - Earth Orientation:	EOP(SHA) 95 M 01
a - A priori nutation model:	
b - Short-period tidal variations in x, y:	
8 - Estimated parameters:	
a - Celestial Frame:	
b - Terrestrial Frame:	Cylindrical coordinates of stations (rates fixed)
c - Earth Orientation:	
d - Others:	



Distribution of the 3 sites of the terrestrial frame SSC(SHA) 95 M 01



Distribution of the uncertainties (quadratic mean of σ_X, σ_Y, σ_Z) for the 4 stations of the terrestrial frame SSC(JPL) 95 M 01.

EOP(SHA) 95 M 01 From Jan 1988 to Dec 1994

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

YEAR	UT0	
	Nb	Sigma
1988	58	1.40
1989	55	1.40
1990	87	1.40
1991	56	1.25
1992	45	1.00
1993	75	1.40
1994	73	1.20

UT0 AND VARIATION OF LATITUDE DETERMINATION FROM LUNAR LASER RANGING OBSERVATIONS FOR 1969-1994

UTXMO 95 M 01

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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, 1995. A total of 9751 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), the CERGA station in Grasse, France, and the Wettzell Laser Ranging Station in Germany 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 976 station/reflector pair estimations of UT0-UTC including 81 UT0 estimates, on 69 nights, in 1994. This is about the same as for 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. We estimated a piecewise linear spline for the polar motion components and UT1 to model long period deficiencies in the series. 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 EOP corrections contained in the splines, and the a priori EOP 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 post-fit range residuals, for the entire span of data, was 4.6 cm. The weighted rms of the post-fit residuals for the 822 normal points obtained by the three active stations during 1994 was 2.8 cm.

We have compared our UT0 and variation of latitude series with the 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 NAVNET UT1 and polar motion values. Interpolation of the NAVNET 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 1995.2).

Table 1.Comparison between University of Texas McDonald Observatory LLR UT0R and variation of latitude (DPhi) and NAVNET VLBI values. The period of comparison is 1986.5 to 1995.2. The epoch of the linear fit is 1990.8.

Station		Bias (mas)	Slope (mas/yr)	WRMS (mas)	N
CERGA	DUT0R:	1.26 +/- 0.10	0.77 +/- 0.05	3.04	362
	DPHI:	-1.54 +/- 0.10	2.31 +/- 0.04	3.36	
MLRS	DUT0R:	0.52 +/- 0.41	-1.53 +/- 0.14	3.36	83
	DPHI:	0.46 +/- 0.46	0.04 +/- 0.15	2.83	
Maui	DUT0R:	3.31 +/- 0.73	0.79 +/- 0.26	3.10	43
	DPHI:	2.78 +/- 0.98	0.62 +/- 0.36	3.50	

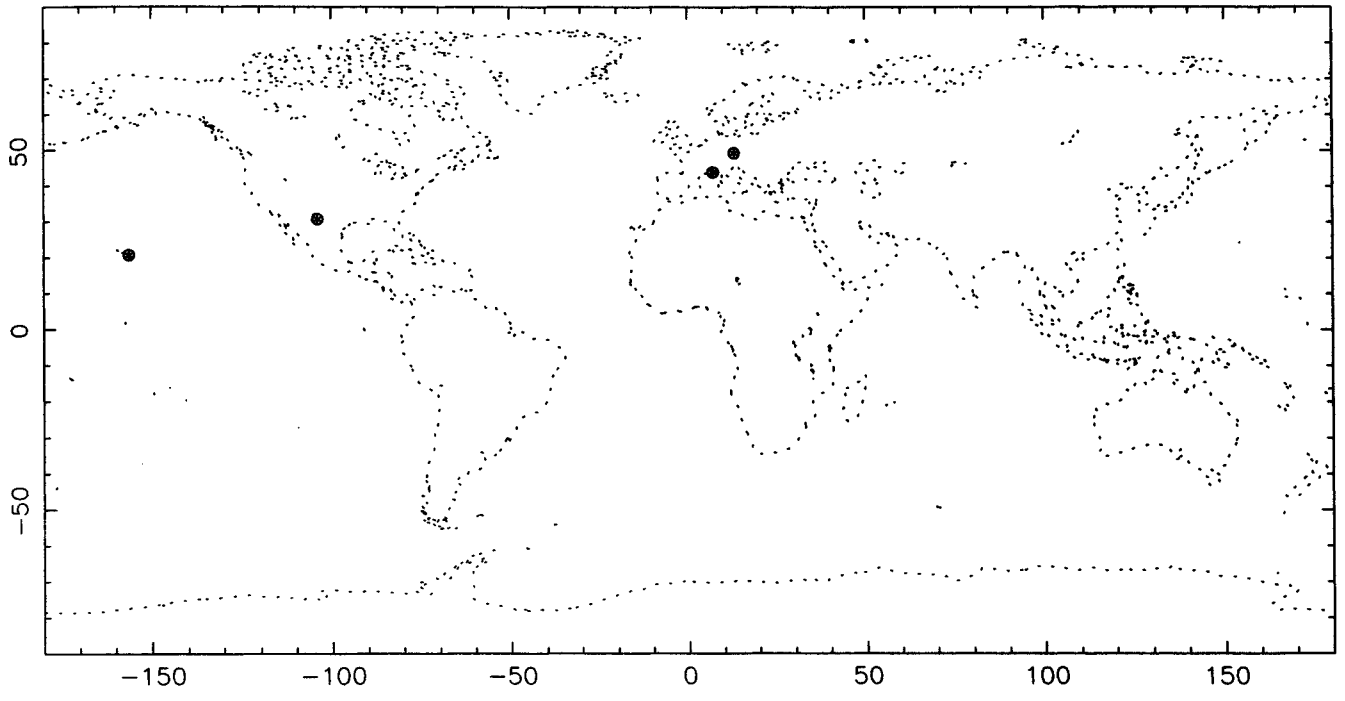
References

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

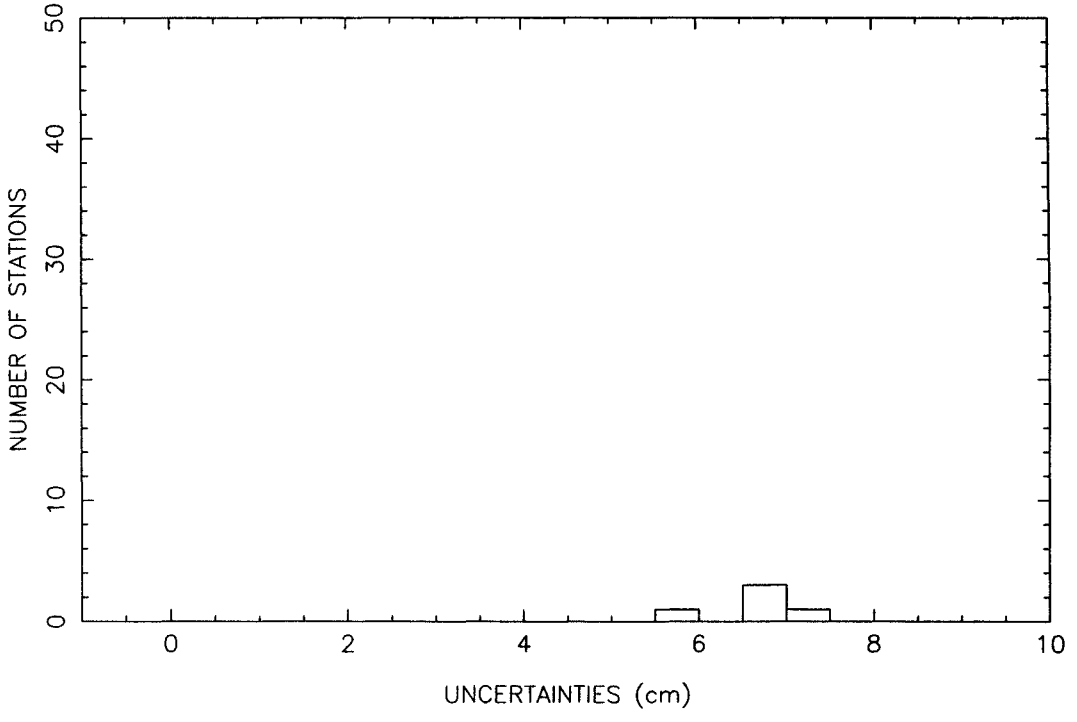
Stolz, A., Bender, P. L., Faller, J. E., Silverberg, E. C., Mulholland, J. D., Shelus, P. J., Williams, J.G., Carter, W. E., Gurnie, D. G., Kaula, W. M., 1976: Earth Rotation Measured by Lunar Laser Ranging, *Science,* **193**, 997-999.

Technical description of solution UTXMO 95 M 01

1 - Technique:	LLR
2 - Analysis Center:	UTXMO
3 - Software used:	PEP
4 - Data span:	Sep 69 - Mar 95
5 - Celestial Reference Frame:	
a - Nature:	Dynamical. The EMbary and lunar ephemerides were estimated.
b - Definition of the orientation:	The node of the EMbary orbit was fixed to the MIT ITR-78 ephemeris to tie the longitude of the celestial reference frame.
6 - Terrestrial Reference Frame:	SSC(UTXMO) 95 M 01
a - Relativity scale:	SSB
b - Velocity of light:	299792458
c - Geogravitational constant:	3.986004415 (geocentric)
d - Permanent tidal correction:	No
e - Definition of origin:	Geocenter
f - Definition of orientation:	Fixed to CSR EOP(CSR) 94 L 01 series at 11 Jan 1985
g - Reference epoch:	1984.0
h - Tectonic plate model:	AM0-2
i - Constraint for time evolution:	Constrained to AM0-2
7 - Earth orientation:	EOP(UTXMO) 95 M 01
a - A priori nutation model:	IAU(1980)
b - Short-period tidal variations in x, y, UT1:	No
8 - Estimated Parameters:	
a - Celestial Frame:	EMbary orbit (node fixed), lunar orbit, GM, lunar librations, third order gravitational potential of the moon, retro-reflector coordinates
b - Terrestrial Frame:	Cylindrical station coordinates
c - Earth Orientation:	Precession constant, 14d, 183d, 365d, and 18.6 yr nutation amplitudes, UT0, $d\varphi$
d - Others:	Range biases for McDonald 2.7m, CERGA, Maui, and Wettzell stations



Distribution of the 4 sites of the terrestrial frame SSC(UTXMO) 95 M 01



Distribution of the uncertainties (quadratic mean of σ_X, σ_Y, σ_Z) for the 6 stations of the terrestrial frame SSC(UTXMO) 95 M 01. 1 station with uncertainty larger than 10 cm is not shown.

EOP(UTXMO) 95 M 01 From Oct 1970 to Jul 1995

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

YEAR	φ		UT0	
	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	23	6.90	23	4.54
1980	6	6.25	6	3.75
1981	4	18.25	4	4.02
1982	0		0	
1983	6	5.10	6	4.20
1984	35	4.80	35	4.07
1985	103	7.50	103	3.97
1986	24	6.50	24	3.22
1987	21	8.70	21	2.91
1988	56	4.80	56	2.67
1989	43	4.10	43	2.84
1990	77	4.10	77	2.79
1991	57	3.60	57	2.37
1992	51	4.00	51	2.60
1993	87	3.90	87	3.37
1994	81	2.50	81	2.81
1995			64	2.60