New improvements in the reduction of LLR observations. News of the LLR at Grasse with one particular night of Full Moon.

Jean Chapront[1], Michelle Chapront-Touzé[1], Gerard Francou[1], Patrick Bidard[1]
Jean-François Mangin[2], Dominique Feraudy[2], Maurice Furia[2], Alain Journet[2],
Jean-Marie Torre[2], Gérard Vigouroux[2].
[1] Observatoire de Paris, DANOF UMR8630, 61 Avenue de l'Observatoire, 75014 Paris, France
[2] Observatoire de la Côte d'Azur, Avenue N.Copernic, 06130 Grasse, France
Presentation given by Jean-François Mangin

Abstract

Since 1988, a new analysis of Lunar Laser Ranging (LLR) observations has been performed from January 1972 till May 2000. Taking advantage of several recent improvements in the reduction of LLR observations (numerical precision in ephemerides computation, distribution of the normal points weights, improved libration solution, new model of nutation, enlargement of the time span), new values of the lunar and solar parameters have been determined, as well as the orientation of the celestial axes, the correction to the IAU 1976 value of the precession constant in longitude and the determination of the Earth rotation parameter UT0-UTC. In order to illustrate the increase of precision, the rms of LLR residuals in distance is of 2.5 centimeters during 6 months of observations made at CERGA in 2000. The LLR determinations of the offsets of Celestial Ephemeris Pole and the correction to the precession constant converge to the best VLBI estimates.
Improvements in the quality and the quantity of results on the Moon are incontestable since 1996. The reasons of these improvements are discussed. Attempts to get returns during the different phases of the Moon have been tried and in particular results for the night of the eclipse of January 21, 2000 are shown.

New improvements in the reduction of LLR observations

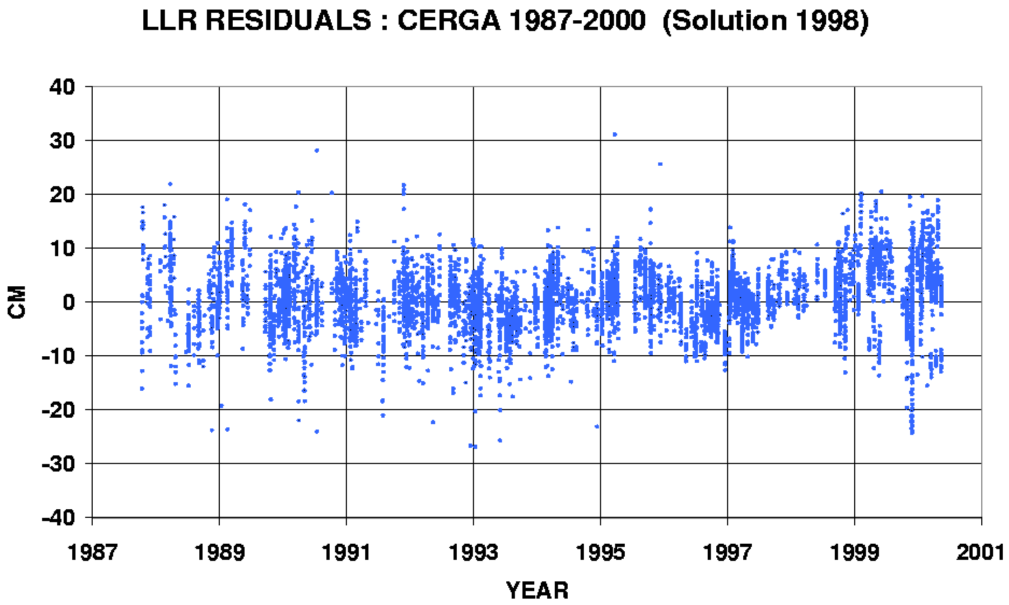
The main improvements in the analysis of LLR observations using the new solution S2000 instead of S1998 are :

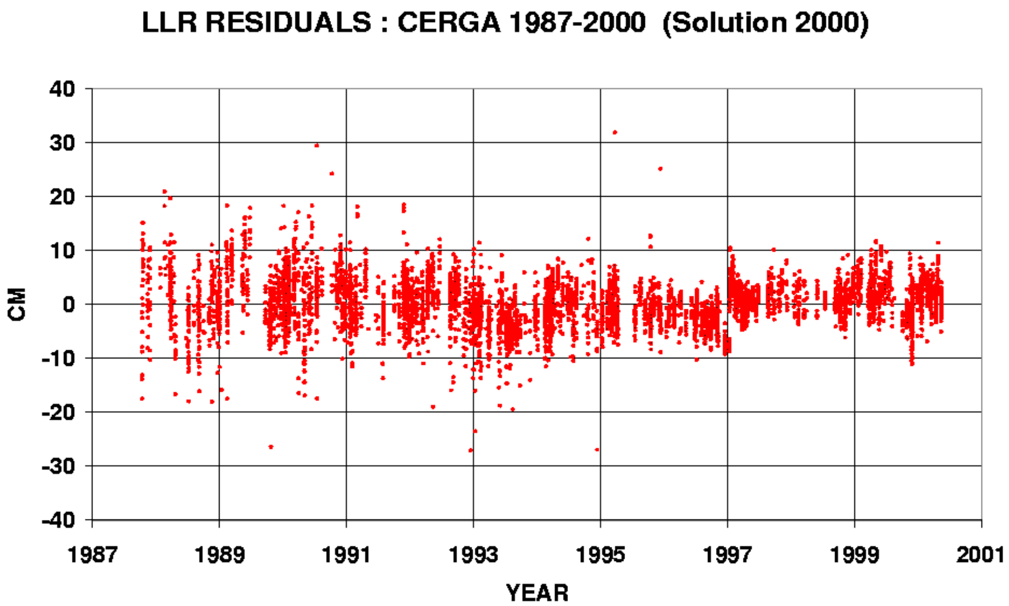
- a better numerical precision in computation of lunar ephemerides,
- new complements in the libration solution (Moons' model),
- a more appropriate distribution of the weights of LLR observations,
- the adoption of the nutation model of the IERS Conventions 1996,
- an enlargement of the time span.

In order to appreciate the global gain of precision of the new solution S2000 compared to S1998, we show on figures 1a-b the residuals in distance O – C for the observations made at CERGA between 1987 and 2000, for the two solutions. We note for S2000 a dispersion less important on the whole interval and a better fit for the two last years (in case of S1998 the solution is extrapolated). A comparable statement can be done with the observations made at McDonald on figures 2a-b.

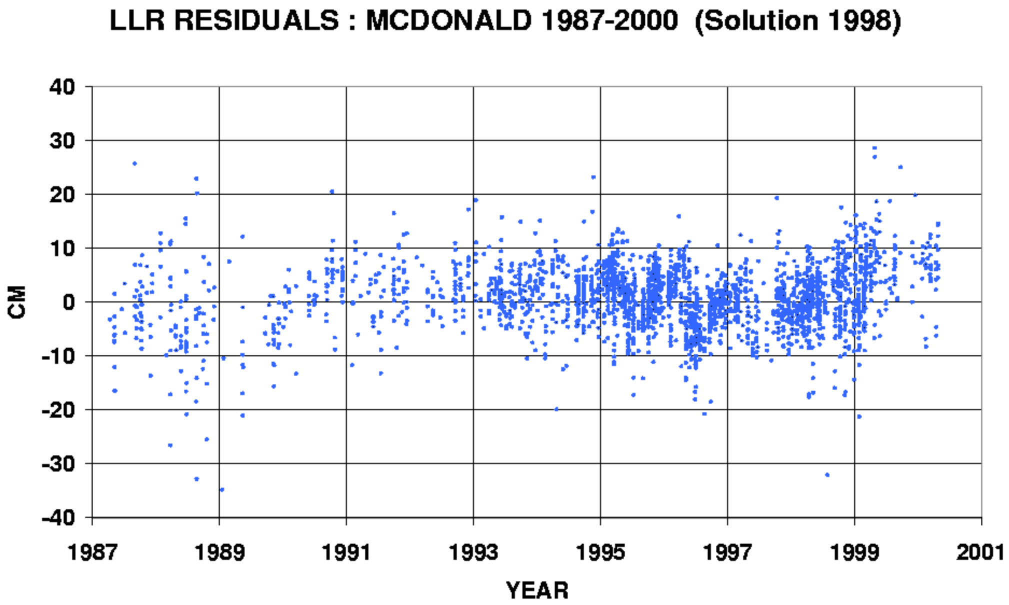
In Table 1 we put in evidence quantitatively the increase of precision on the residuals (rms on the distances Station-Reflector). Clearly, in each group, the recent observations have a greater weight than the oldest one. Hence the unknowns are noticeably determined with a better accuracy.

Figures 1a and 1b





Figures 2a and 2b



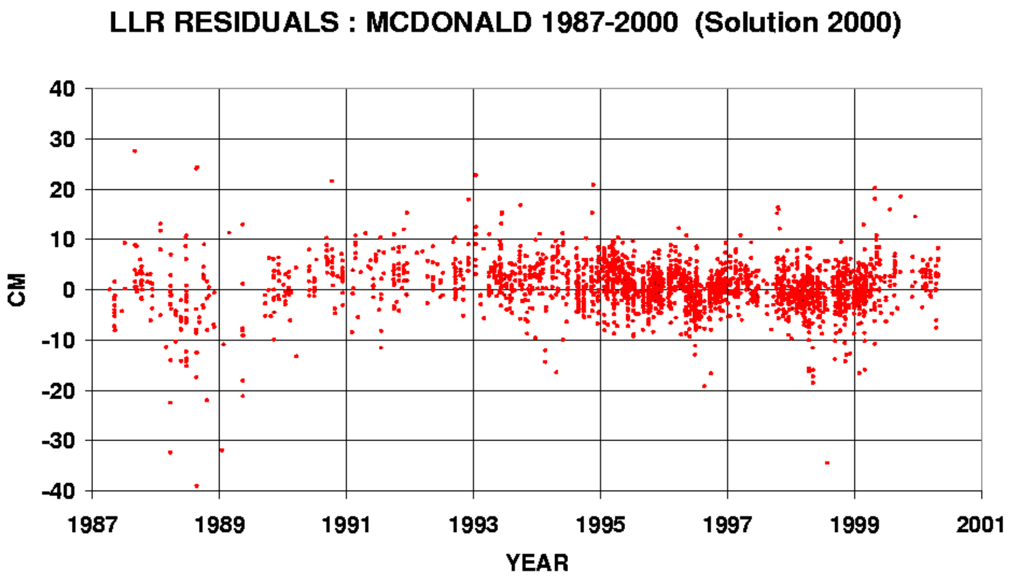


Table 1. Distribution of LLR residuals
(rms in centimeter)

Observatory and instrument	Sub-group	rms (1)	rms (2)	Sub-group	rms (3)	N
McDonald,				1972-1975	43.0	1487
Tel 2.70 m	1972-1986	34.7	34.5	1976-1979	27.3	1029
& MLRS1				1980-1986	29.5	992
CERGA, Rubis	1984-1986	18.2	18.8	1984-1986	19.6	1166
Haleakala	1987-1990	11.1	8.0	1987-1990	7.9	455
McDonald,				1987-1991	5.6	230
MLRS2	1987-1998	5.0	3.8	1991-1995	4.3	581
				1995-2000	3.4	1621
CERGA,				1987-1991	5.1	1570
Yag	1987-1998	4.8	3.8	1991-1995	3.8	2040
				1995-2000	3.1	2754

N : Number of normal points in each sub-group

(1) S1998 : 1 sub-group per observatory
(2) S2000 : 1 sub-group per observatory (improvement : numerical precision + libration)
(3) S2000 : same as (2) with sub-groups (improvement : nutation model + time interval)

Correction to the precession constant

With the recent improvements in the reduction of LLR observations (solution S2000), new values of the lunar and solar parameters have been determined, as well as the orientation of the celestial axes.

We have also determined a new correction Δp to the value IAU 1976 of the precession constant in longitude.

Method	Source	Δp ("/cy)
LLR	S1998	-0.3437 ± 0.0040
LLR	S2000	-0.3164 ± 0.0027
VLBI	Fukushima	-0.2968 ± 0.0043

The values for Δp in the new solution S2000 and in the previous solution S1998 are significantly different. Now the values for Δp obtained by LLR and VLBI have a separation smaller than 0.2 mas/y.

Values of UT0-UTC obtained by Lunar Laser Ranging analysis.

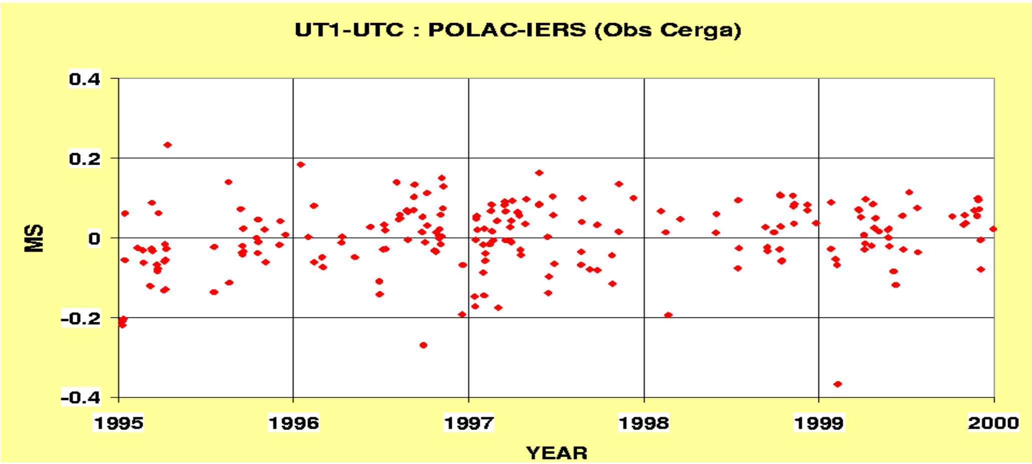
The method has been applied to observations from January 1995 till December 1999, that is 2793 normal points produced by Grasse (CERGA) and 1747 from McDonald (MLRS2). The values are determined by station and for the mean dates of observations. We have disregarded the nights/reflector with less than 4 observations and the nights/reflector with 4 observations over a span shorter than 1.5 hour. For the nights with several reflectors involved, we have retained only one reflector, mainly Apollo 15. Finally, 386 values of UT0-UTC have been produced, 214 from CERGA observations and 172 from MLRS2 observations.

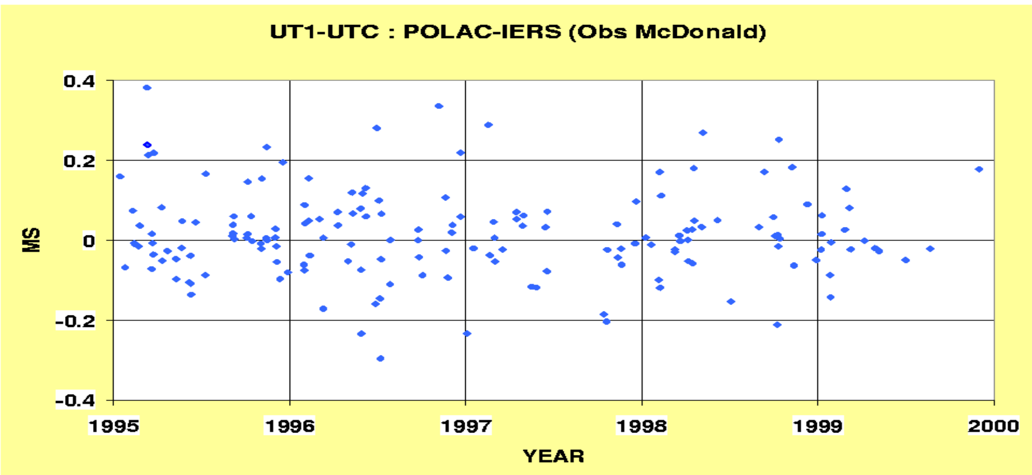
The figures 3a-b allow to compare the values of UT1-UTC deduced from our determination of UT0-UTC (POLAC) with those recommended by IERS (C04 series). Over the time span [January 1995 – December 1999], the average μ and rms σ of the differences POLAC - IERS are respectively ,

CERGA :	$\mu = 0.005$ ms	$\sigma = 0.100$ ms
McDonald :	$\mu = 0.018$ ms	$\sigma = 0.112$ ms

These results agree with those of UTMX0 (Texas) and FSG (Munich).

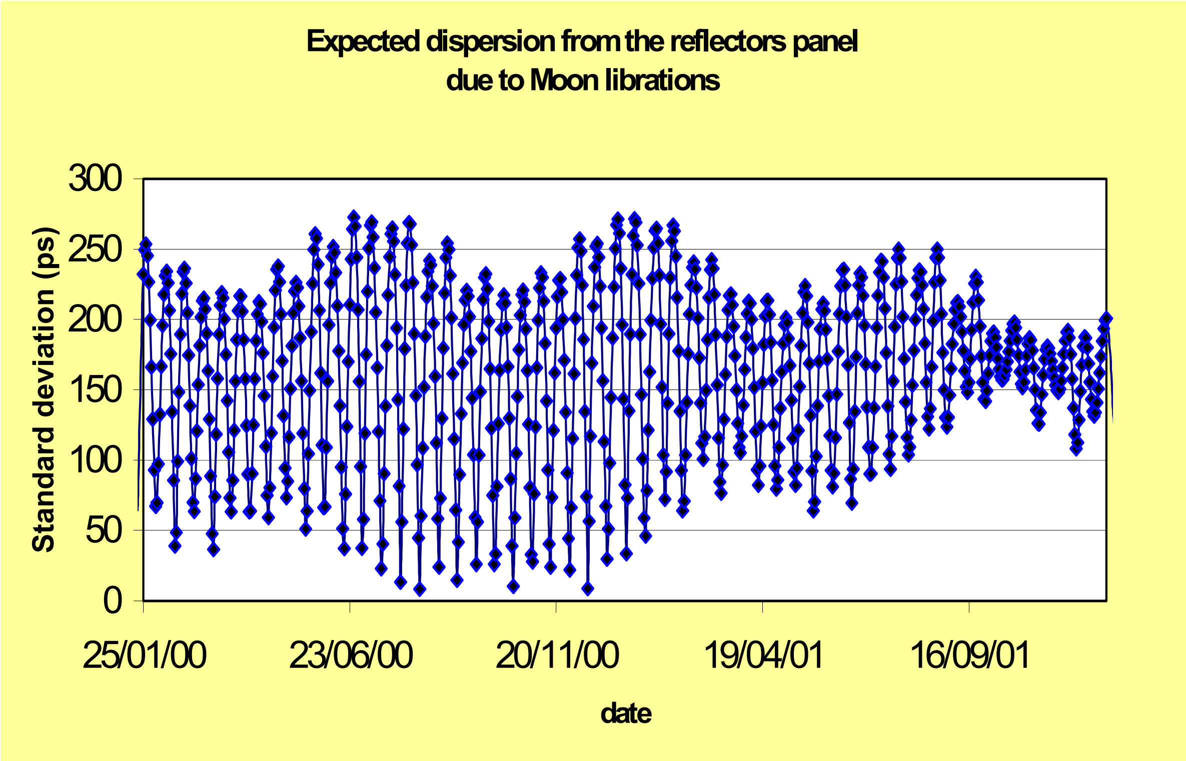
Figures 3a and 3b





About the accuracy of Normal Points on Apollo XV with LLR at Grasse

It depends essentially, on the dispersion of the panel and on the precision of the station.



The dispersion from the reflectors panel is variable with librations. Now the accuracy on one corner cube is about 150 ps ($\sigma_{station}$). *It depends on the pulse width of the laser.*

Therefore the precision of the normal point is generally* : $\sigma / (N)^{1/2}$ with

N : number of returns in 10 min (normal point duration),

σ : standard deviation of raw data

often $\sigma = (\sigma_{station}{}^{2} + \sigma_{panel}{}^{2})^{½}$,

rarely σ_{panel} is smaller than $\sigma_{station}$

and N increases with the width of the laser pulse.

* It is supposed that N is large enough, therefore that the ratio signal on noise is raised.
Consequently, I choose a 300 ps width of laser pulse for the Moon.

Why the results have been so much improved since 1996 ?

The reasons are :

- a better reliability of optical adjustments of coude focus.
- perhaps a better quality of laser image with the removal of the 12 mm rod, which was the cause of some thermal problems.
- especially a better calibration, which is steadier, nearer from the paths used on measurements to the Moon, *and achieved in real time.*

Global diagram of the station

One can see details concerning the calibration in real time

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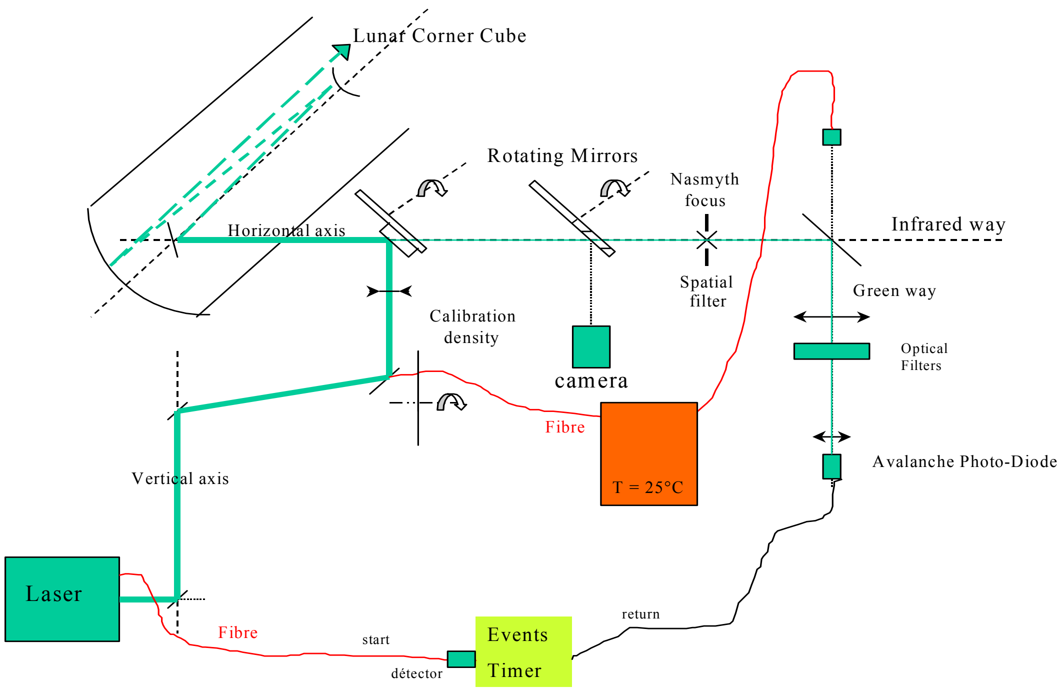
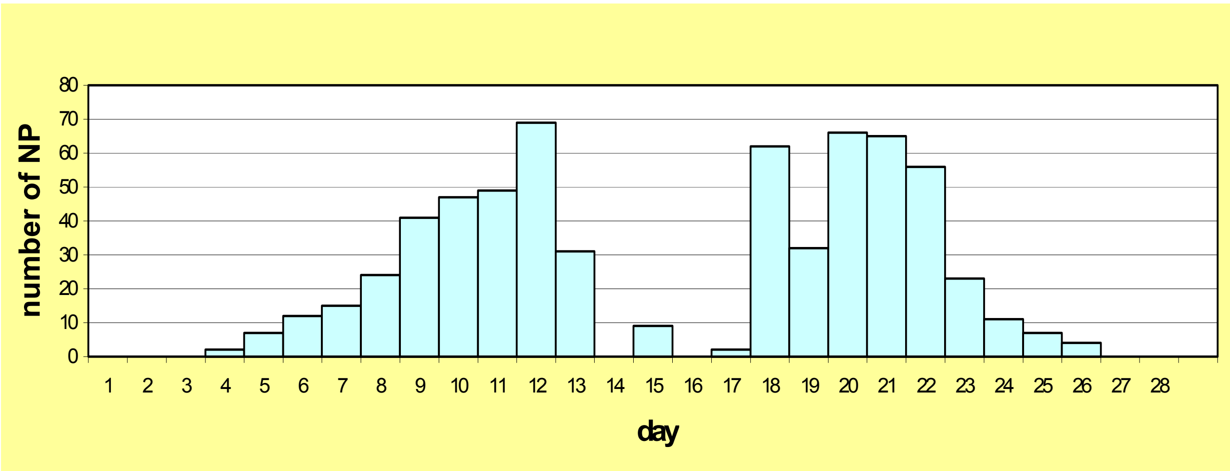


Attempts to get returns for different lunar phases

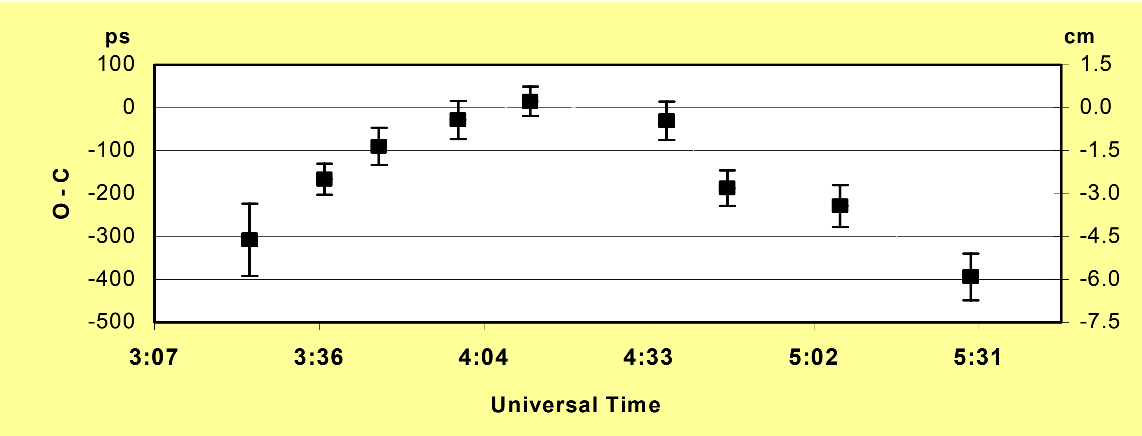
1. Tests have been led to control the precision of the photodiode in Infrared. It permits to reduce the noise for day's shootings to reflectors in darkness, near the New Moon (Atmospheric diffusion). Nevertheless, the temporal scattering of the diode (EGG 30954) is too large (350 ps) to be used.
2. Tests have been made in green with some interesting results.

Distribution of Normal Points (year 2000) with the age of the Moon



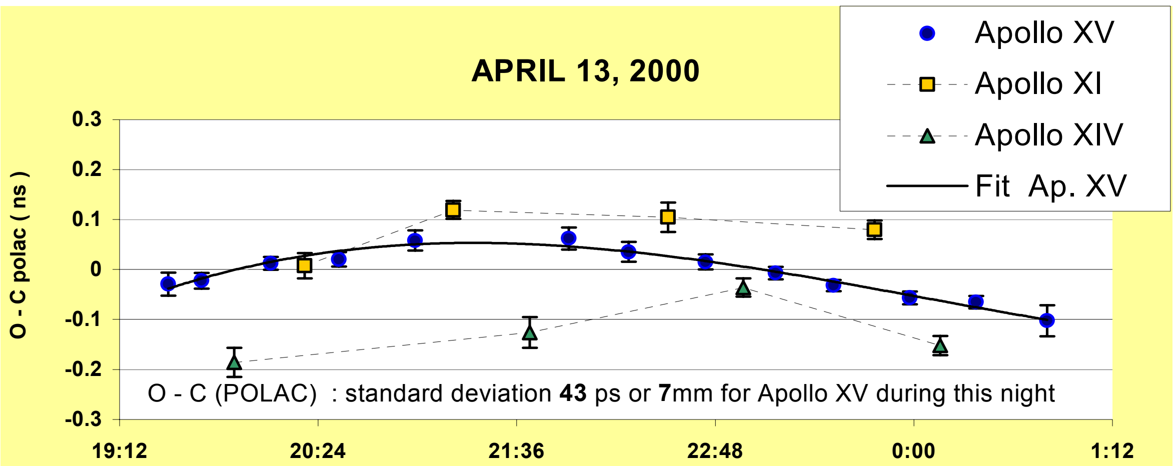
Eclipse January 21, 2000

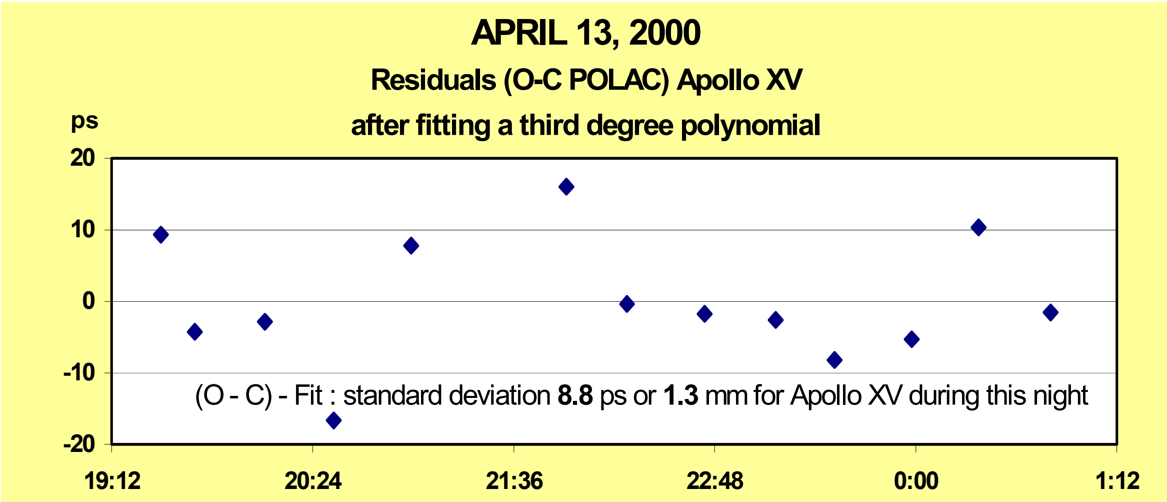
U.Time	Nb returns	O - C	POLAC	RMS	Acc.	calib.	Temp.	Press.	Hyg.
h:mn:ss	mean 30	cm	ps	ps	ps	ns	°C	mB	%
3:23:52	17	-4.6	-308	346	83.9	164.33	0.9	872.2	24
3:36:54	43	-2.5	-167	237	36.1	164.32	1.5	872.2	22
3:46:25	33	-1.4	-90	246	42.8	164.31	1.8	872.2	20
4:00:14	45	-0.4	-29	298	44.4	164.32	2.6	872.2	20
4:12:52	29	0.2	15	182	33.8	164.31	2.3	872.2	20
4:36:41	31	-0.5	-31	248	44.5	164.33	1.6	872.2	20
4:47:15	27	-2.8	-188	216	41.6	164.32	1.6	872.2	20
5:07:00	37	-3.4	-229	296	48.7	164.34	2.6	872.3	20
5:29:49	12	-5.9	-394	189	54.6	164.37	3.2	872.2	20



A very good night in LLR measurements (Grasse)

(average 190 echoes/series)





The ranging method in single photelectron mode permits to get a precision of 1.3 mm, with about 200 returns in 10 mn and with a 300 ps laser width.

Future

- The analysis of the night April 13, 2000 shows that the station is capable to range on a distant target (Moon) with a precision of 1.3 mm, in case of a sufficient number of returns (200) and a steady atmosphere.
- It will be necessary to transform this internal precision in accuracy.
- If transponders are set up on the Moon, with a temporal definition better than 10 ps, the number of returns leads to :

many more data points of better quality

deep impact on lunar and physical science