





#### 18<sup>th</sup> International Workshop on Laser Ranging

FujiYoshida 10-15 November 2013

# Lunar Laser Ranging: Recent activities of POLAC

Sébastien Bouquillon et al.

Service Polac / SYRTE / Observatoire de Paris In collaboration with the INPOP Group and the MéO laser Station (IMCCE Observatoire de Paris /GeoAzur, Observatoire de la Côte d'Azur)

# Lunar Laser Ranging: Recent activities of POLAC

#### <u>Contents</u>

Overview of POLAC history and activities.

POLAC recent activities:

- Support for LLR observers:
  - Improvements of "Prediction and Validation" tools
  - Validation of LLR Observations by e-mail
- Support for LLR DATA users:
  - Critical analyse of an extended LLR data gathering.

POLAC projects.

# Overview of POLAC history activities.

#### Paris Observatory Lunar Analysis Center (since 1996)

#### In SyRTE division of Paris Observatory

- <u>Current members</u>: S. Bouquillon & C. Le Poncin-Lafitte
- Founding members: J. Chapront, M. Chapront-Touzé & G. Francou
- Main collaborators: H. Manche(IMCCE), J-M Torre(OCA), D. Feraudy(OCA)
  - C. Lhotka(Roma University)

#### Specificities of this service:

- LLR data reduction based on two semi-analytical Lunar theories:
  - \* ELP(Ephéméride Lunaire Parisienne) J.Chapront & M.Chapront-Touzé
  - The Lunar Libration Theory developed by M.Moons
- Implications with EOP-PC and ICRS-PC (products centers of IERS)
- Close Cooperation with the Grasse Station(MeO).
- Collaboration (since 2006) with the group in charge of the development of INPOP (Intégration Numérique Planétaire de l'Observatoire de Paris)
- Recent interactions with the Team "Theory & Metrology" of SyRTE divison of Paris Observatory

# POLAC recent activities: Support for LLR observers.

#### Improvement of "Prediction & Validation" Tools

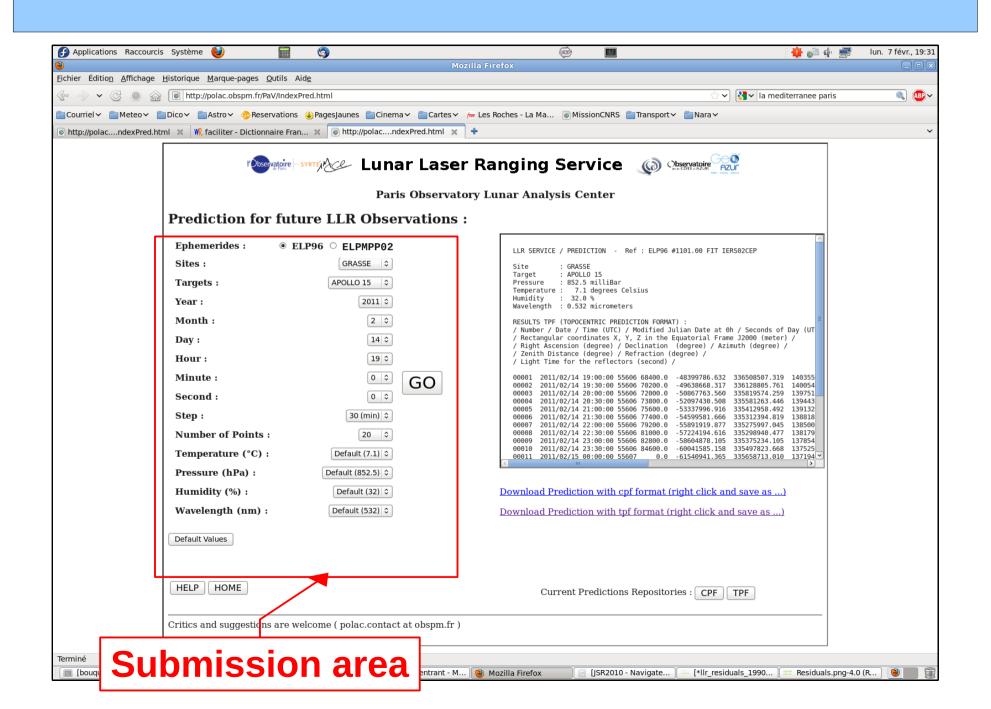
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# Improvement of "Prediction & Validation" Tools

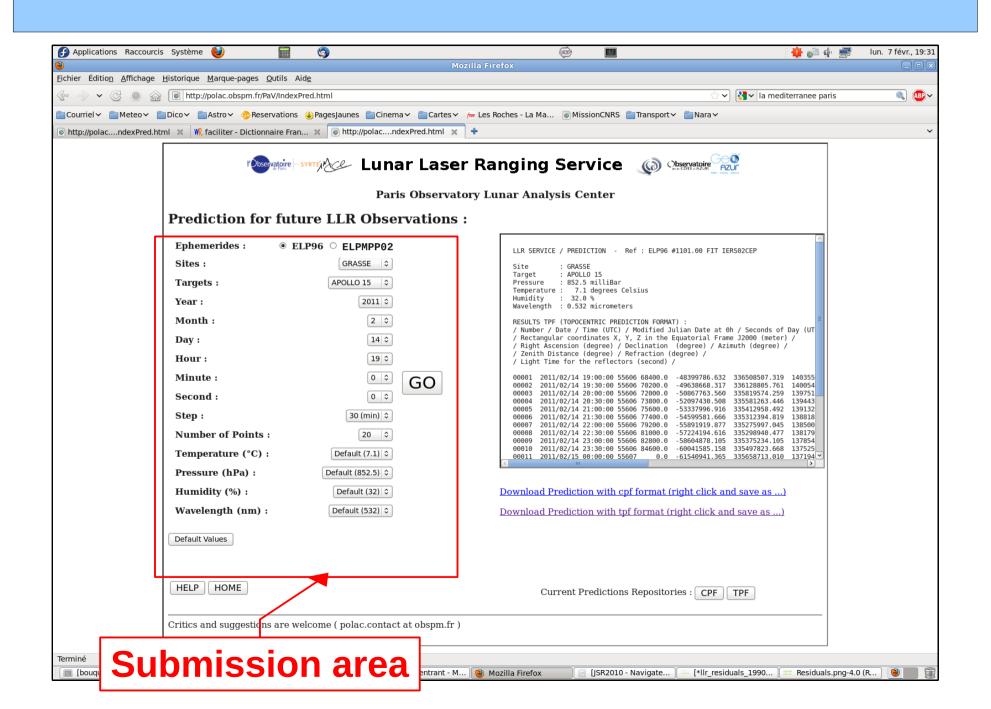
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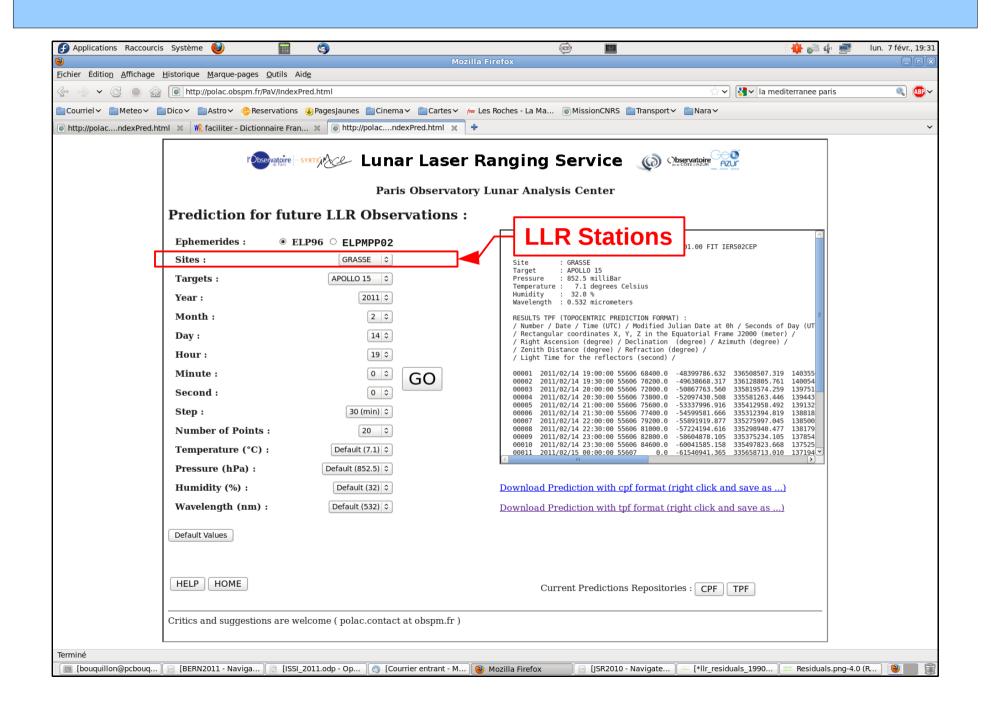
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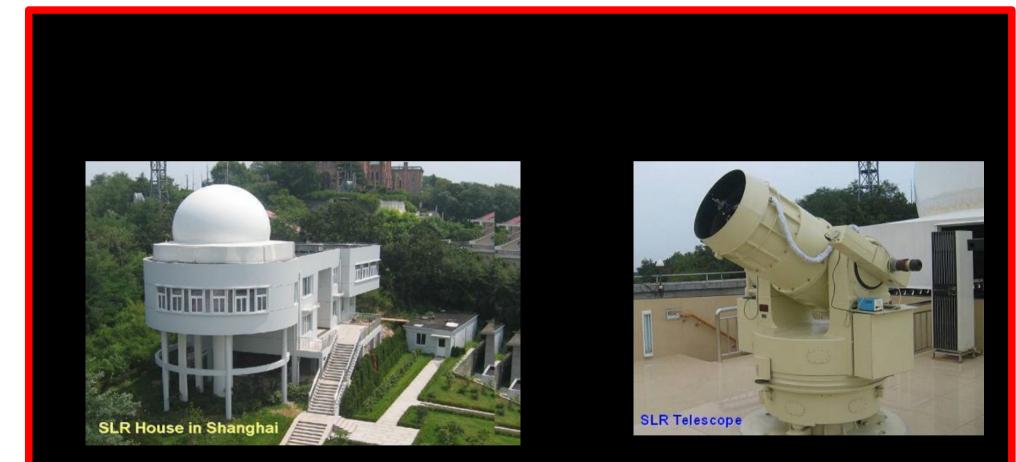




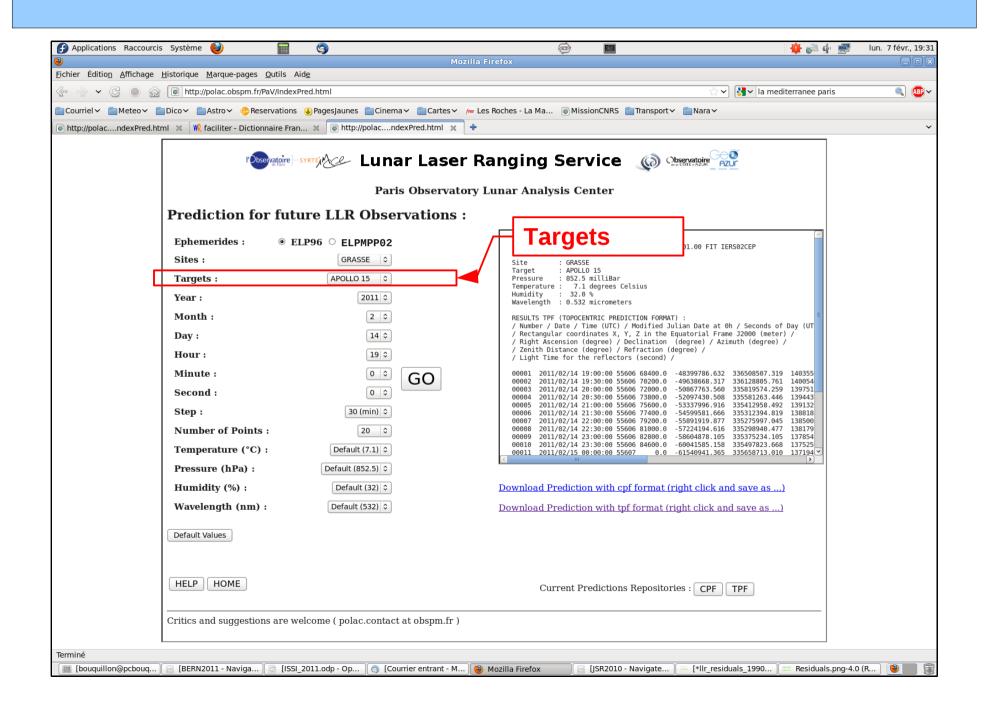
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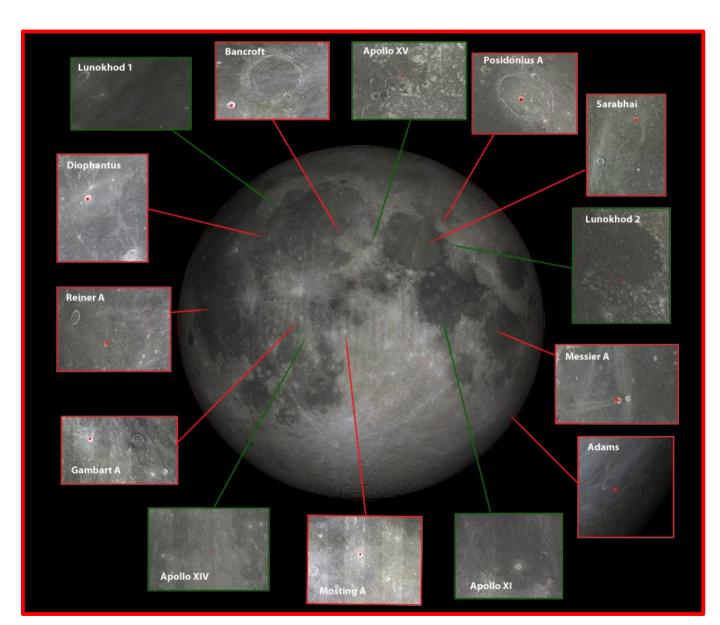
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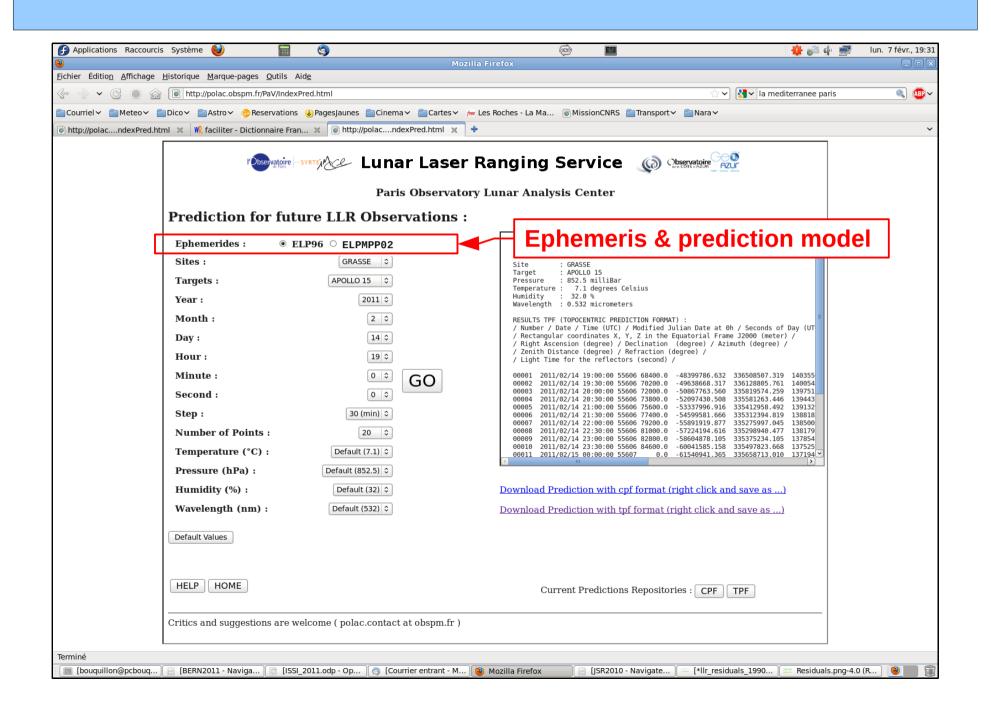


#### • New site added last year : Shanghai SLR station (07821)



• Reflectors and Craters currently available in the web interface





• Lunar solutions & reduction models available to compute predictions:

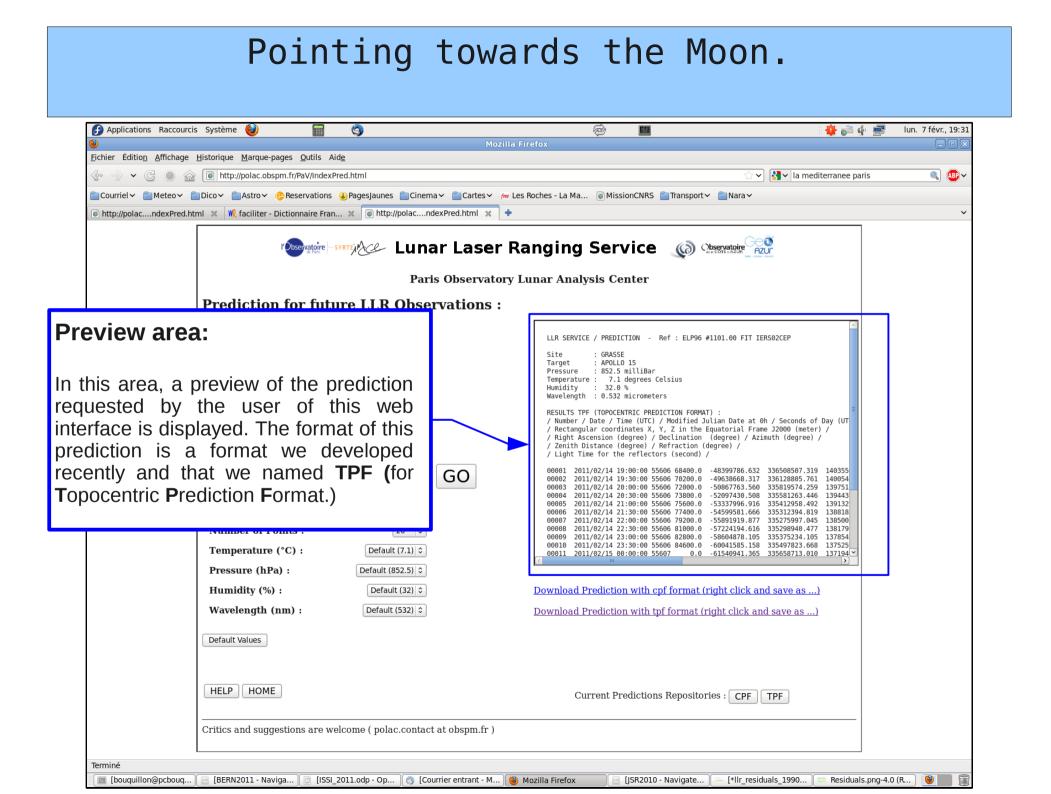
**ELP96:** It is an improved version of the analytical solution of the Moon ELP2000-82B (Chapront-Touzé M. & Chapront J., 1988, 1997). The numerical ephemeris DE245 (JPL) is used for the motion of the Earth-Moon barycenter and for numerical complements to the lunar librations and orbital motion. Initially, the lunar coordinates given by this solution are referred to the dynamical mean ecliptic of the date. The change to the equatorial frame of the Celestial Ephemeris Pole (J2000) is carried out by analytical expressions of the precession-nutation. This solution is fitted to the Lunar Laser Ranging observations made from 1972 until 2010 (Chapront J. & Francou G., 2002)

**ELPMPP02**: The main differences from the previous solution 'ELP96' is the use of the new planetary perturbations MPP01 (Bidart, 2001). The numerical ephemeris DE405 is used for the motion of the Earth-Moon barycenter and for numerical complements to the lunar librations and orbital motion. This solution is fitted to the Lunar Laser Ranging observations made from 20/08/1969 until 30/05/2013. The initial positions of station are given in ITRF 2008 and the transformation between terrestrial reference frame and celestial reference frame is done with the help of SOFA routines (consistent with IERS Conventions 2003)

#### **New Ephemeris and New Reduction Model**

Bidart, P., 2001, A&A,366,351B. Chapront-Touzé, M., Chapront, J., 1988, A&A, 190, 342. Chapront-Touzé, M., Chapront, J., 1996, Celest.Mech., 66, 31. Chapront-Touzé, M., Chapront, J., Francou, G., 1997, Celest.Mech., 66, 31. Chapront, J., Chapront-Tousé, M., Francou G., 2002, A&A, 387, 700.

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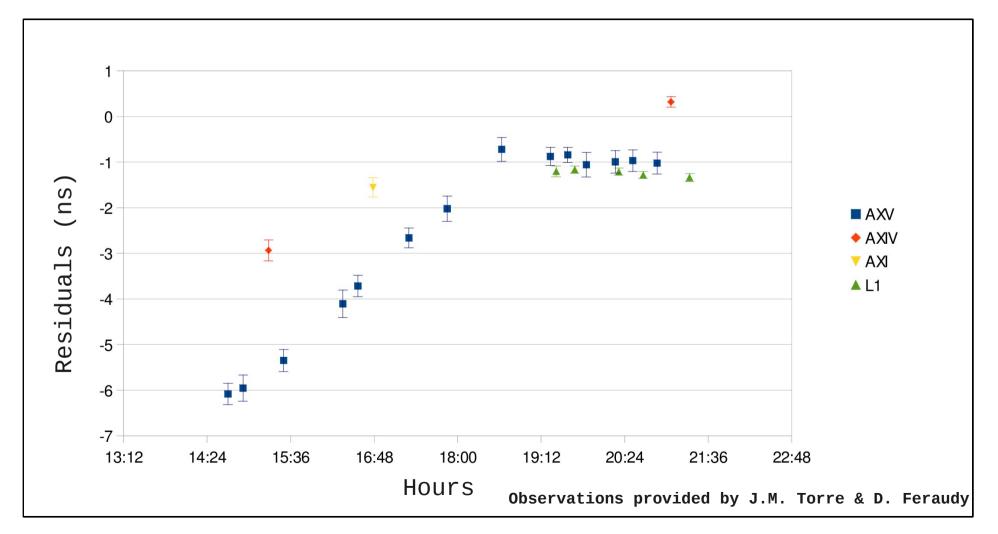


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Ephemerides : • ELP96 • ELPMPP02   Sites : GRASSE •   Targets : APOLLO 15 •   Year : 2011 •   Month : 2 •   Day : 14 •   Hour : 19 •   Minute : 0 •   Second : 0 •   Step : 30 (min) •   Number of Points : 20 •   Temperature (°C) : Default (7.1) •	LLR SERVICE / PREDICTION - Ref : ELP96 #1101.00 FIT IERS02CEP Site : GRASSE Target : APOLLO 15 Pressure : 852.5 milliBar Temperature : 7.1 degrees Celsius Humidity : 32.0 % Wavelength : 0.532 micrometers RESULTS TPF (TOPOCENTRIC PREDICTION FORMAT) : / Number / Date / Time (UTC) / Modified Julian Date at 0h / Seconds of Day (UT / Rectangular coordinates X, Y, Z in the Equatorial Frame J2000 (meter) / / Regtangular coordinates X, Y, Z in the Equatorial Frame J2000 (meter) / / Reight Ascension (degree) / Declination (degree) / Azimuth (degree) / / Zenith Distance (degree) / Refraction (degree) / Azimuth (degree) / / Light Time for the reflectors (second) / 00001 2011/02/14 19:30:00 55606 7200.0 - 40633668.317 33612805.761 140054 00003 2011/02/14 19:30:00 55606 7200.0 - 5086776.3560 335812574.259 139751 00004 2011/02/14 20:00:00 55606 73000.0 - 52097430.508 335581263.446 139443 00005 2011/02/14 21:30:00 55606 7200.0 - 54599581.666 33512394.819 13818 00007 2011/02/14 21:30:00 55606 7200.0 - 554599581.666 335312394.819 13818 00007 2011/02/14 22:30:00 55606 7200.0 - 554599581.666 335312394.819 13818 00007 2011/02/14 22:30:00 55606 8200.0 - 52097430.508 335581234.415 138580 00008 2011/02/14 22:30:00 55606 7200.0 - 554599581.666 335312394.819 13818 00007 2011/02/14 22:30:00 55606 8200.0 - 52097430.5158 33575234.105 137854 00010 2011/02/14 22:30:00 55606 8200.0 - 52097430.5158 335497823.668 137525 00011 2011/02/14 23:30:00 55606 8200.0 - 5000478.105 33537524.105 137854 00010 2011/02/14 23:30:00 55606 8200.0 - 60041585.158 335497823.668 137525 00011 2011/02/14 23:30:00 55606 8200.0 - 60041585.158 335497823.668 137525 00011 2011/02/14 23:30:00 55606 700.0 0.0 - 61540941.365 335658713.010 137194 ×
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his area, daily predictions are available under or TPF format for all the lunar targets. They computed for 3 days since the current date a step of 30 min and they are updated each at 10:30am (Paris Local time) just after the daily solution produced by IERS EOP product	Current Predictions Repositories : CPF TPF

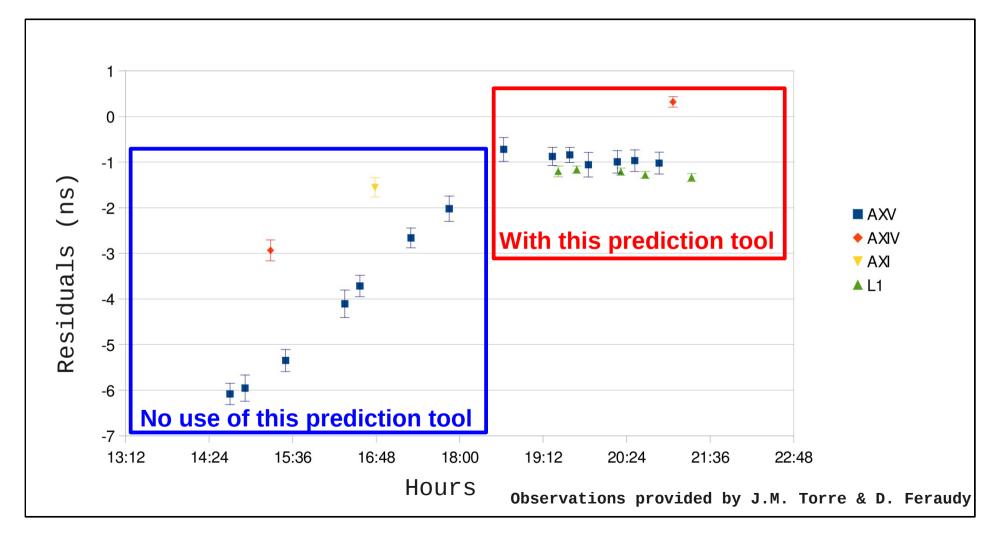
#### Example of Prediction done with this tool: First Detection of Lunokhod 1 with MeO Night 19<sup>th</sup>/20<sup>th</sup> of March 2013

• LLR NP Residuals obtained during the night



#### Example of Prediction done with this tool: First Detection of Lunokhod 1 with MeO Night 19<sup>th</sup>/20<sup>th</sup> of March 2013

• LLR NP Residuals obtained during the night



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Ephemerides : O ELP96  ELPMPP02 O INPOP10e	LLR SERVICE / RESIDUALS - RET : ELP96 #1101.00 FIT IERS02CEP	$\sim$
Format :	00001 1987/10/12 23h 31m 17s4869161 Lunakhod 2 Grasse -0.043 m -0.284 ns	
Please, enter your LLR normal points in the area below :	00002         1987/10/12         23h 50m 04s8732587         Lunakhod 2         Grasse         0.043 m         0.290 ns           00003         1987/10/13         01h 13m 07s0531171         Lunakhod 2         Grasse         -0.017 m         -0.115 ns           00004         1987/10/13         01h 44m 19s6650432         Lunakhod 2         Grasse         -0.007 m         -0.149 ns	
5119871012233117486916126297157660987401910 6 05201105 85300 50 0 5320a 5119871012235004873258726280567766329401910 4 07608 35 85300 5072 5320a	00004 1937/10/13 02h 15m 595005422 Lunakhod 2 Grasse -0.081 m -0.538 ns 00006 1987/10/13 02h 32m 52s6264343 Lunakhod 2 Grasse -0.044 m -0.294 ns	
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GO	00016 1987/10/18 03h 12m 14s4013468 Apollo 15 Grasse -0.042 m -0.283 ns 00017 1987/10/18 03h 34m 46s1977089 Apollo 15 Grasse 0.110 m 0.733 ns	
GO	00018         1987/10/18         03h         47m         29s1821324         Apollo         15         Grasse         0.090 m         0.604 ns           00019         1987/10/18         03h         59m         54s8907994         Lunakhod 2         Grasse         0.072 m         0.479 ns           00020         1987/10/18         04h         21m         50s2436903         Apollo         15         Grasse         0.075 m         0.498 ns	
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Generate an exemple of LLR Normal Points file with format MINI	Wrong (***) : 00000 Limit: 1.000 m	~
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• Lunar solutions & reduction models available to compute Validation :

**ELP96 & ELPMPP02:** Same Ephemeris and Reduction Model than the ones used in the prediction tool.

**INPOP10e**: It is the latest version of the planetary and lunar ephemeris INPOP, developed at the Observatory of Paris (IMCCE). This numerical solution is fitted on both planetary and LLR observations. It is available at http://www.imcce.fr/inpop, and is used to estimate new initial conditions and librations parameters as well as tests for inner Moon (Fienga et al., 2008, 2009,2011). The LLR observations are reduced with a model consistent with IERS Conventions 2003, including tectonic plate motion, solid tides effects, ocean and atmospheric loading, polar tide, relativistic light deviation and tropospheric time delay.

Fienga, A., et al., 2008, A&A, 477, 315. Fienga, A., et al., 2009, A&A, 507, 1675. Fienga, A., et al., 2011, Celest.Mech., 111, 363.

**New Ephemeris and New Reduction Model** 

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Ephemerides : ELP96    Errmat : MINI    CSTG  CRD   Please, enter your LLR normal points in the area below :   9999   0000103000137845780153200016425400003001942764103991391   731186731431513503424764000039908732271005500260223000   99999   000010300013784578015320001642900003002202463164725071   06240862323490806689182000047308099279804500050260394   99999   00010300015784578015320001642990003002242764103901351   75115130925943607557020600003908768274406300740221500   9999   000103000157845780153200016433300003002272764103621261   Telar Clear Generate an exemple of LLR Normal Points file with format MIN Generate an exemple of LLR Normal Points file with format CSTG	00006       1910       3       20000116       184600.3949065       2.40179423740305       0.0049m       0.0325ns         00007       1910       2       20000116       185710.3422887       2.4010547531250s       0.0233m       0.1557ns         00008       1910       3       20000116       199651.0404788       2.4004875736110s       0.0127m       0.0128m       0.1257ns         00010       1910       2       20000116       193966.0778061       2.3998737730405       0.0176m       0.1174ns         00011       1910       2       20000116       201365.535845       2.4001330005080s       0.0370m       0.2465ns         00013       1910       3       20000116       203823.8612687       2.400448179700s       0.0177m       0.1181ns         00014       1910       2       20000116       203823.8612687       2.400336372420s       0.0079m       0.0526ns         00015       1910       3       20000116       20122.145014       2.400937863280s       -0.0097m       0.0526ns         00016       1910       3       20000117       182164.347673       2.3781317753930s       -0.0025m       0.0177m       0.0187ns         00017       7112.3       20000117       182164.347673	
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area gives for the LLR observations cted by the user the bias and the standard ation of the residuals for all the retro- ectors and for each one of them.	Global : 19 obs. Bias: 0.028 m St.dev.: 0.069 m 0.188 ns 0.457 ns (O-C) graphics interface	Ţ

Critics and suggestions are welcome ( polac.contact at obspm.fr )

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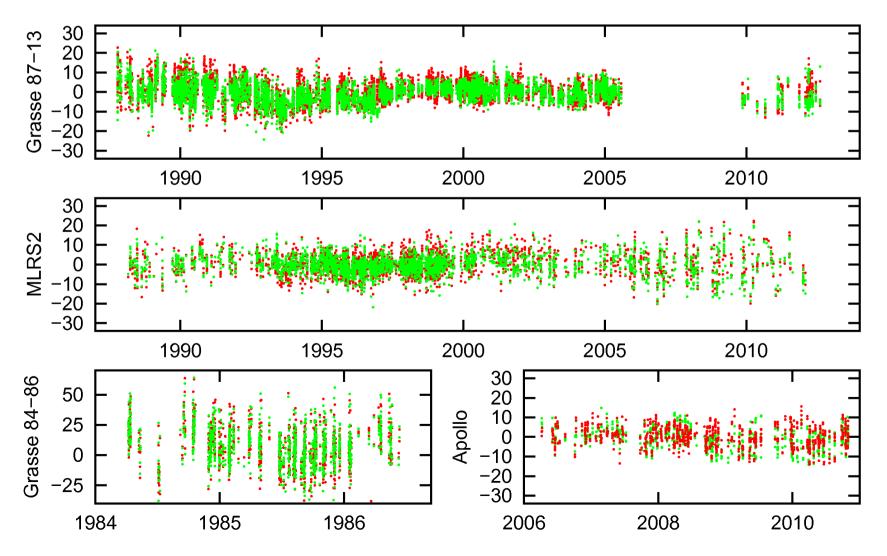
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reflectors, the time and residuals units.	
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#### Reduction of All LLR normal Points since 1984 carry out with this interface:

0-C plots for two different models: INPOP10e and ELPMPP02

**INPOP10e** and **ELPMPP02**: residuals in cm



Reduction of All LLR normal Points since 1984 carry out with this interface:

0-C Statistics for **INPOP10e** & **ELPMPP02** models

INPOP10e and ELPMPP02: RMS of residuals in cm

Stations (periods)	INPOP10e	ELPMPP02
GRASSE (1984-1986)	15,89	15,41
GRASSE (1987-1995)	6,35	5,48
GRASSE (1995-2012)	4,01	3,82
MLRS2 (1985-1996)	4,71	4,29
MLRS2 (1996-2012)	5,59	5,08
Apollo (2006-2012)	5,22	5,34

## POLAC recent activities: Support for LLR observers.

# Validation of LLR Observations by e-mail polac.processing at obspm.fr

#### Validation of LLR Observations by e-mail

E-mail Format Example for the Submission of LLR Observations to Validate:

TO : <b>polac.processing at obspm.fr</b> Subject : <b>##LLR-VALIDATION##</b>	
DISPLAYOMC=1 DISPLAYOBS=1 DISPLAYPLOT=1 DISPLAYSTAT=1 EPHEM=1	
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## Validation of LLR Observations by e-mail

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Validation of past LLR Observations :				
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Generate an exemple of LLR Normal Points file with format CSTG (O-C) graph	h <u>ics interface</u>			
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Critics and suggestions are welcome ( polac.contact at obspm.fr )				
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## POLAC recent activities: Support for LLR data users.

# critical analysis of an extended LLR data gathering

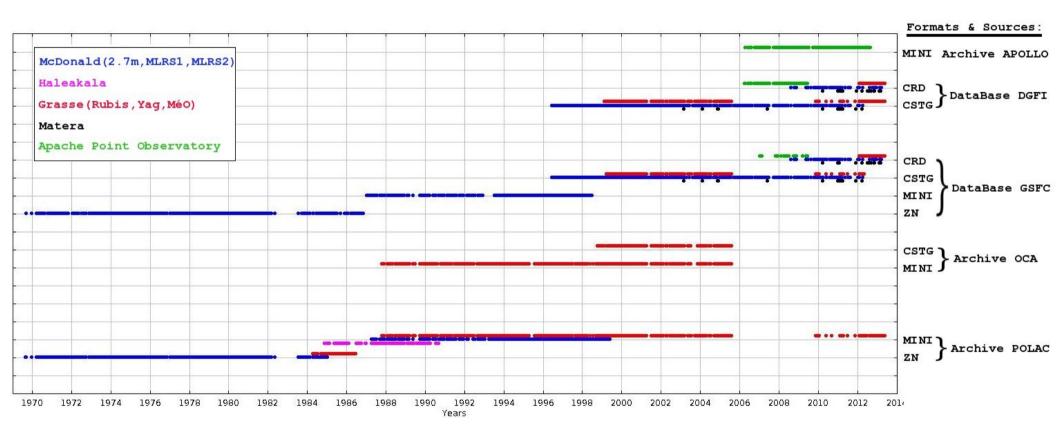
ftp://polac.obspm.fr/pub/LLR\_Observations/

#### LLR Data Sources:

- Archive POLAC
- Archive of Grasse laser station (Observatoire de la Côte d'Azur, MéO)
- Archive of APOLLO laser station (Apache Point Observatory Lunar Laser-ranging Operation)
- ILRS DataBase :
  - GSFC (Goddard Space Flight Center)
  - DGFI (Deutsches Geodätisches Forshung Institut)

#### <u>LLR Data Formats:</u>

- ZN Original Format, COSPAR Working Group 1, (Mulholland, 1971)
- MINI Mini Normal Point Record, NASA Management/Operations Working Group on LLR, (COSPAR Information Bulletin No. 108, April, 1987.)
- CSTG Coordination of Space Techniques for Geodesy and Geodynamics, ILRS Normal Point Format since March 1997
- CRD Consolidated Laser Ranging Data Format, ILRS Normal Point Format since 2009, (R.L. Ricklefs, C.J. Moore, October 2009).



Distribution of All LLR Observations per Archive Center & per Format

Main Steps of LLR Data gathering and Critical analysis Method:

#### First Step: DATA NORMALIZATION

#### FOR EACH DATABASE:

- Split LLR data by LLR station and by format
- Check the consistency of each data (values, format nomenclature, etc.) <u>Example:</u>

**Original data:** 1346774929284703469653230000105087922826**250**00560222200

Error for format of Humidity => correction 250 -> 025 :

Modified data: 134677492928470346965323000010508792282602500560222200

- Erase redundant data (only strictly identical Normal Points)
- Change the data format in the LLR standard Format "MINI"
- Check this new file consistency
- Sort Chronologically
- For each Normal Point keep a trace of Original Archive and Format <u>Example:</u>

5 201305131633071529333266516406199301 1910 42 1949 16 87344 13556 5321 0673 DGFI-CRD

Normal Point in "MINI" format

Archive and Format Name

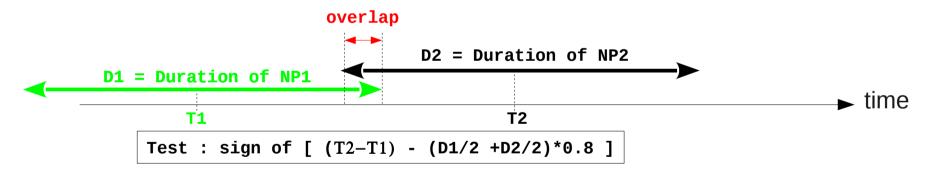
Main Steps of LLR Data gathering and Critical analysis Method:

Second Step: ERASE DATA WITH RESIDUALS LARGER THAN 100 METERS

Third Step: IDENTIFICATION OF DATA DUPLICATIONS AND SELECTION

METHOD FOR IDENTIFICATION OF DATA DUPLICATIONS:

2 Normal Points are considered as data duplications if there is a temporal overlap Larger than 20% of the sum of their half-duration.

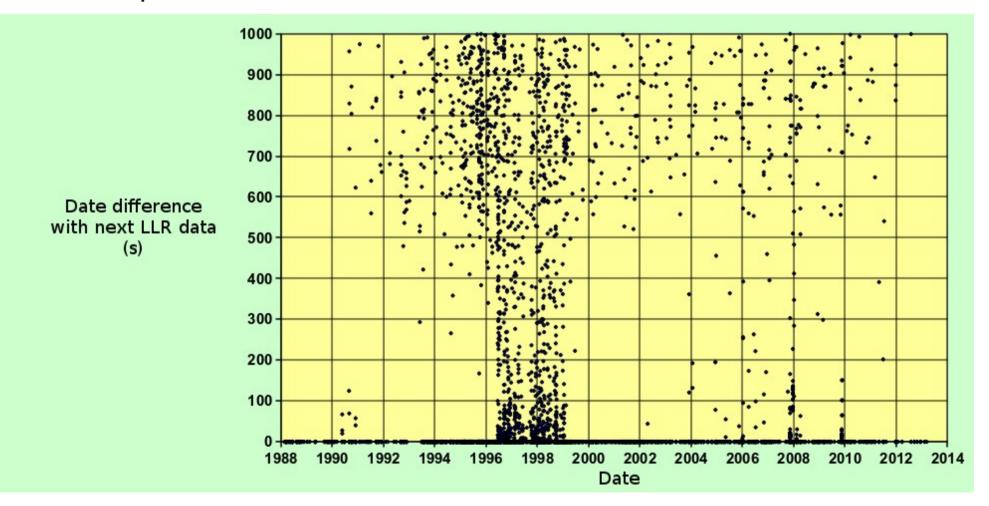


If LLR Normal point duration is not given, we fix it to 3 minutes.

METHOD OF DATA SELECTION IN CASE OF DUPLICATION:

- The selection of one observation in case of duplication is based on the criteria listed below:
  - The Residual [0-C] (weight = 2)
  - The Echoes Number (weight = 1)
  - The Uncertainty (weight = 1)
  - The Signal to Noise Ratio (weight = 1)
  - $\rightarrow$  The duration (weight = 1).

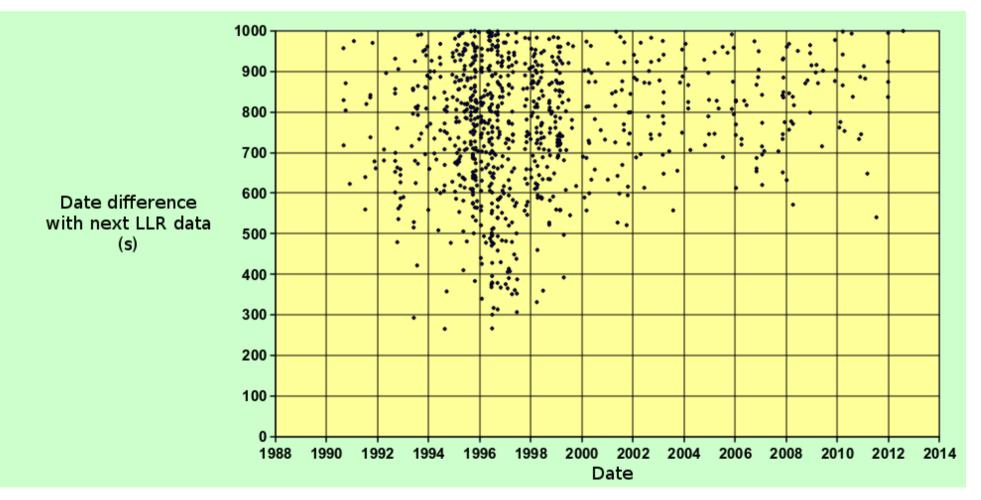
Main Steps of LLR Data gathering and Critical analysis Method: Third Step : IDENTIFICATION OF DATA DUPLICATIONS AND SELECTION



This plot shows for each LLR data gathering for the MLRS2 station, the observation date in X axis and the date difference with the next data in second in Y axis **with data duplications**.

Main Steps of LLR Data gathering and Critical analysis Method:

Second Step : IDENTIFICATION OF DATA DUPLICATIONS AND SELECTION



This plot shows for each LLR data gathering for the MLRS2 station, the observation date in X axis and the date difference with the next data in second in Y axis with no data duplications.

#### LLR Resulting Data Set:

ftp://polac.obspm.fr/pub/1\_llr\_analysis/2\_llr\_residuals/observationsUpdate/

DATA SETS OF LLF	OBSERVATIONS BY STATION AND PERIOD				
🔶 OMCD6985.DAT	:	3604	Observations	(20/08/1969	- 30/06/1985)
OMCD8388.DAT	:	631	observations	(02/08/1983	- 27/01/1988)
OMCD8813.DAT	:	3653	observations	(29/02/1988	- 20/03/2013)
🔶 OGRA8486.DAT	:	1188	observations	(07/04/1984	- 12/06/1986)
🔶 OGRA8705.DAT	:	8324	observations	(22/01/1987	- 30/07/2005)
🔶 OGRA0913.DAT	:	654	observations	(11/11/2009	- 20/05/2013)
🔶 OHAL8490.DAT					- 30/08/1990)
🔶 OMAT0313.DAT	:	83	observations	(22/02/2003	- 05/03/2013)
OAP00612.DAT	' <b>:</b>	1564	observations	(07/04/2006	- 28/08/2012)

DATA SETS FOR ALL THE LLR OBSERVATIONS FROM 1969 AUGUST 20 TO 2013 MAY 30

- TOTALOBS6913.DAT : Valid Observations (20471) (Format MINI)
- TOTALOBS6913.xml : Valid Observations (20471) (Format VOTABLE)
- TOTALSUP6913.DAT : Observations with residuals > 100m

Grasse	103
McDonald	305
Matera	3
Haleakala	Θ
Apollo	Θ
Total	411

TOTALDBL6913.DAT : DUPLIACATED DATA (28615)

### Planed improvements.

For Prediction Tool

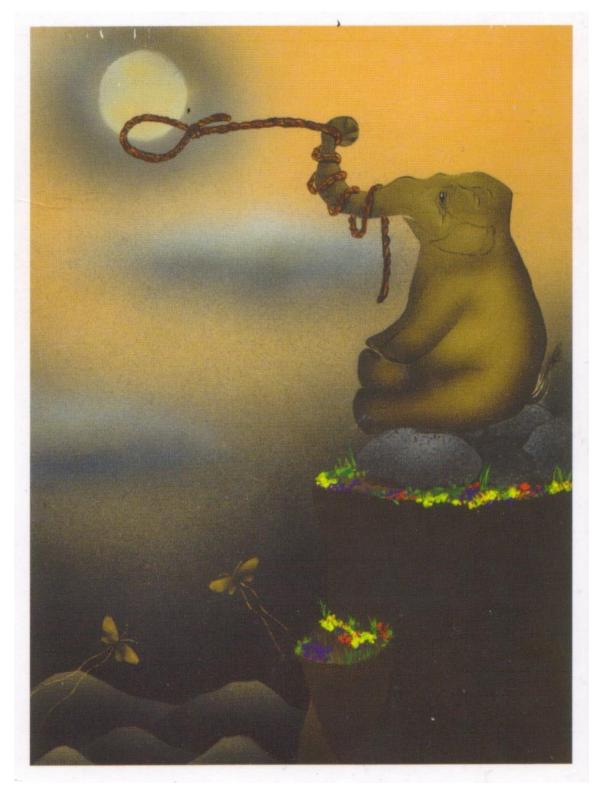
 add some helpful information for reflectors (as their libration angle, their sun illumination, etc.)

#### For Validation Tool

- Implementation of other lunar solutions or other reduction processes:
  - JPL lunar solution (DE421)
  - FESG/IFE Lunar solution
  - ?
  - => Useful for unification of LLR observation reduction process=> Useful for comparison of different lunar solutions
- Improvement of speed of PaV Tools when using ELP (by using a tabulated version of ELP Ephemeris instead of Poissons Series) DONE
- Separate for the interface user the choice of Reduction Model to the choice of the Moon Ephemeris

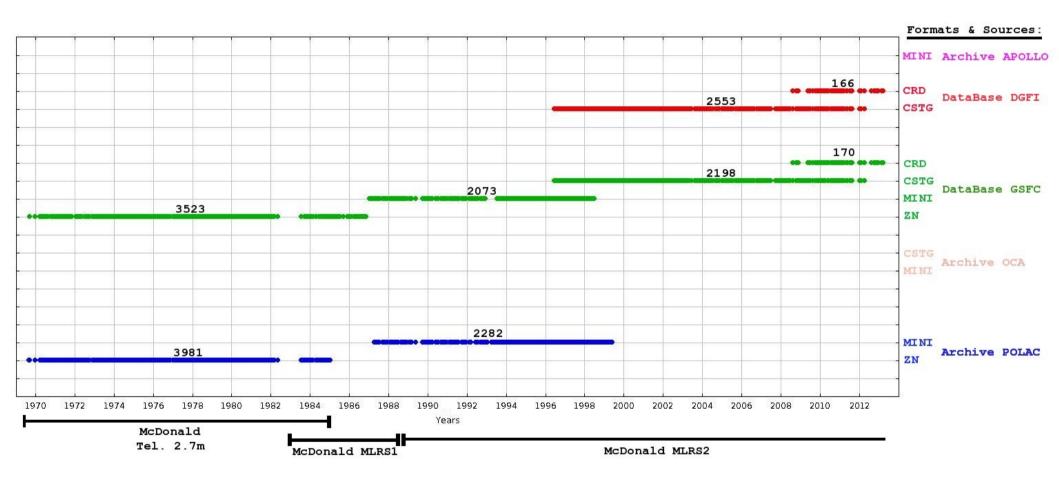
#### For LLR Data Set

- Regularly update this data set
- Method Improvement for the Identification of LLR Data duplications

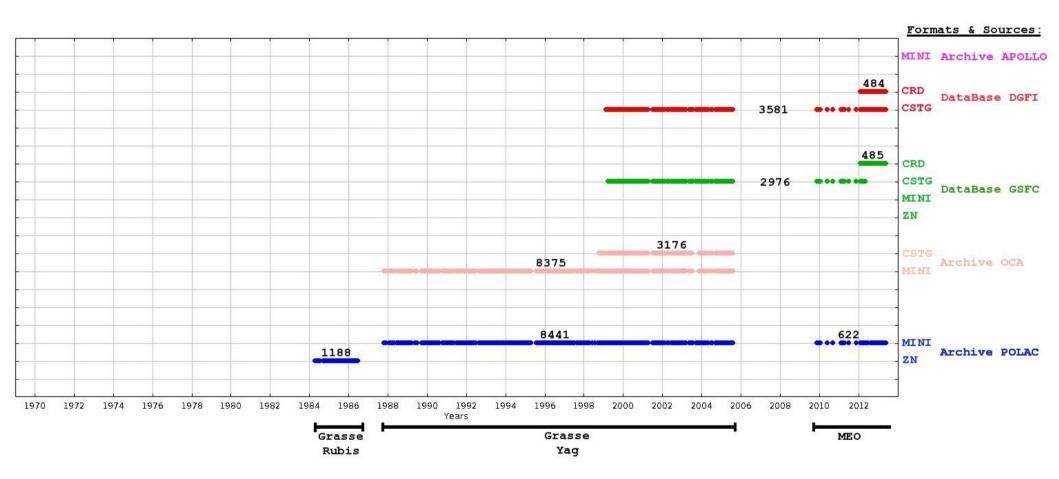


ありがとうございます。

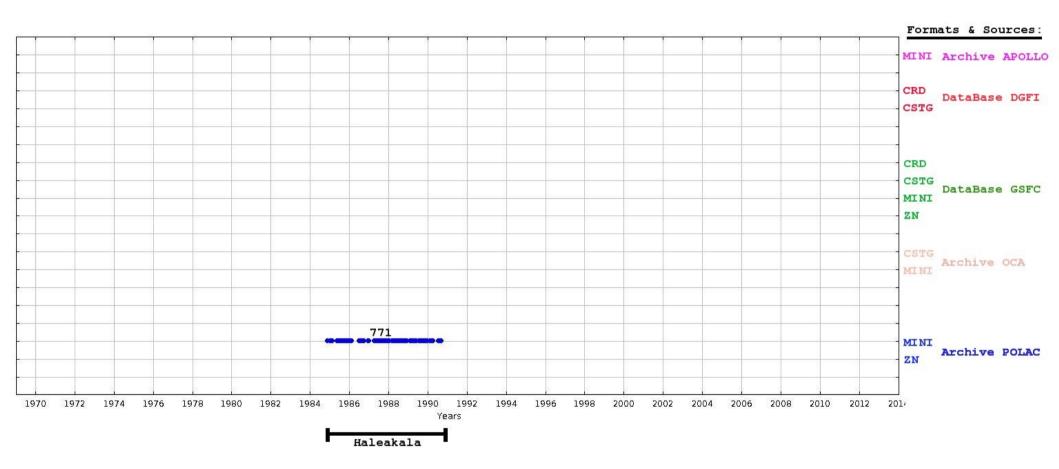
## Extra slides



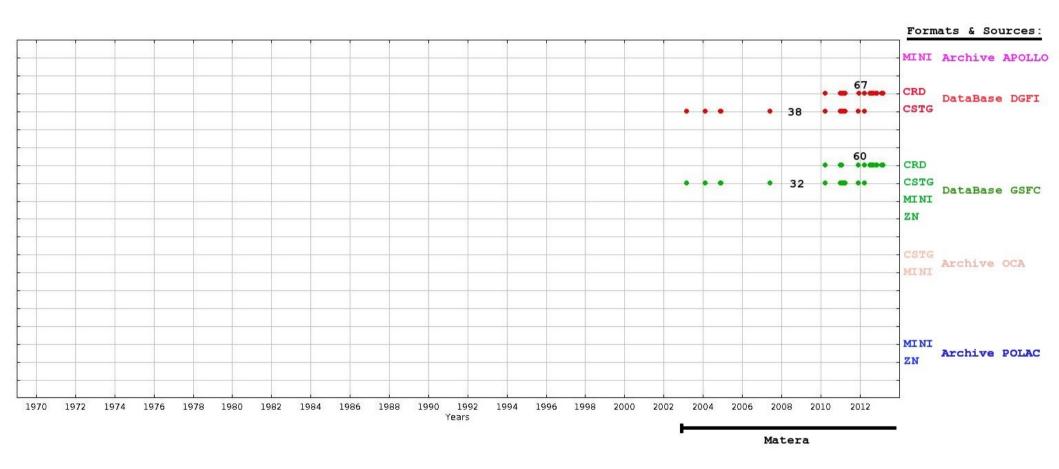
Distribution of McDonald LLR Observations per Archive Center & per Format



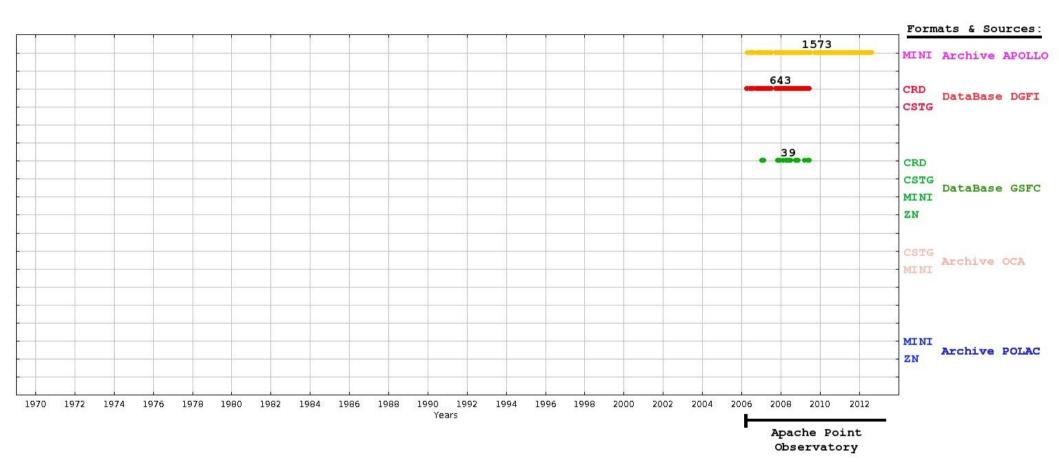
Distribution of Grasse LLR Observations per Archive Center & per Format



Distribution of Haleakala LLR Observations per Archive Center & per Format



Distribution of Matera LLR Observations per Archive Center & per Format



Distribution of APOLLO LLR Observations per Archive Center & per Format

