Lunar Dynamical Modeling with Improved IR Lunar Laser Ranging data

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Overview

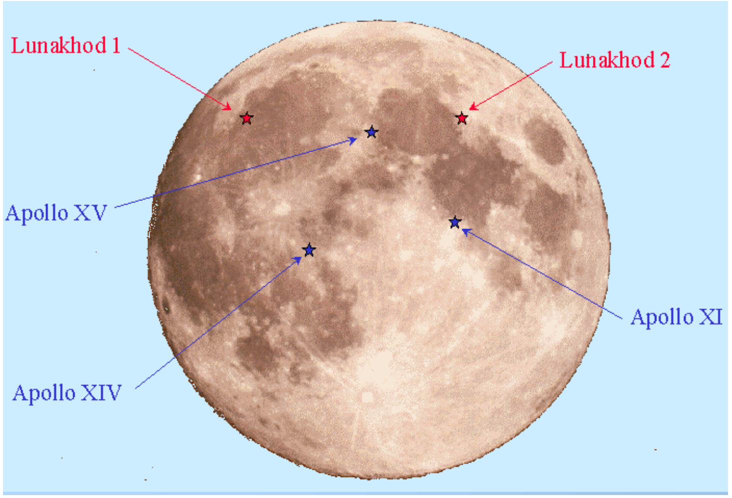
1. New Dataset
   - IR (1064nm) Lunar Laser Ranging at OCA
     - advantages
     - impact on tests of general relativity

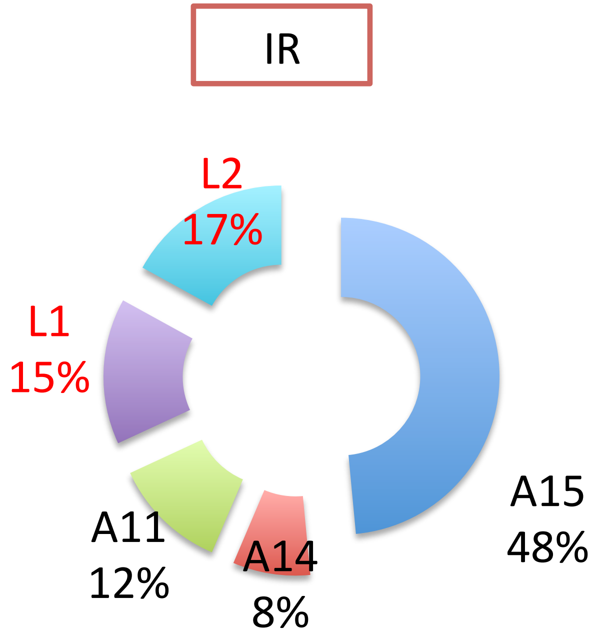
2. Improved dynamical model
   - INPOP Planetary and Lunar Ephemeris
     - description
     - latest residuals comparison with DE430 ephemeris
     - preliminary estimates

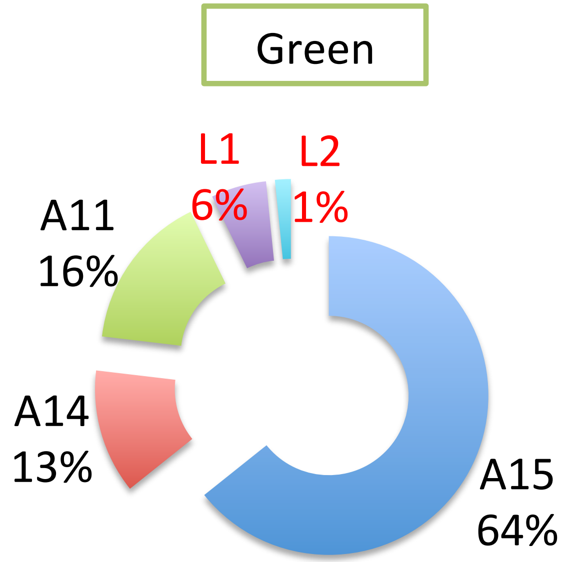
3. Conclusion + Future work
   - Multitechnique at MeO-OCA
     - SLR + LLR
     - Hydrology loading

Improved IR LLR data

- LASER : Infrared wavelength (1064nm)
- **Advantages[7]**:
  - ✓ Better atmospheric transmission
  - ✓ Observations round the clock (high SNR)
  - ✓ **Diversification of observed reflectors**







Distribution of observation

Improved IR LLR data

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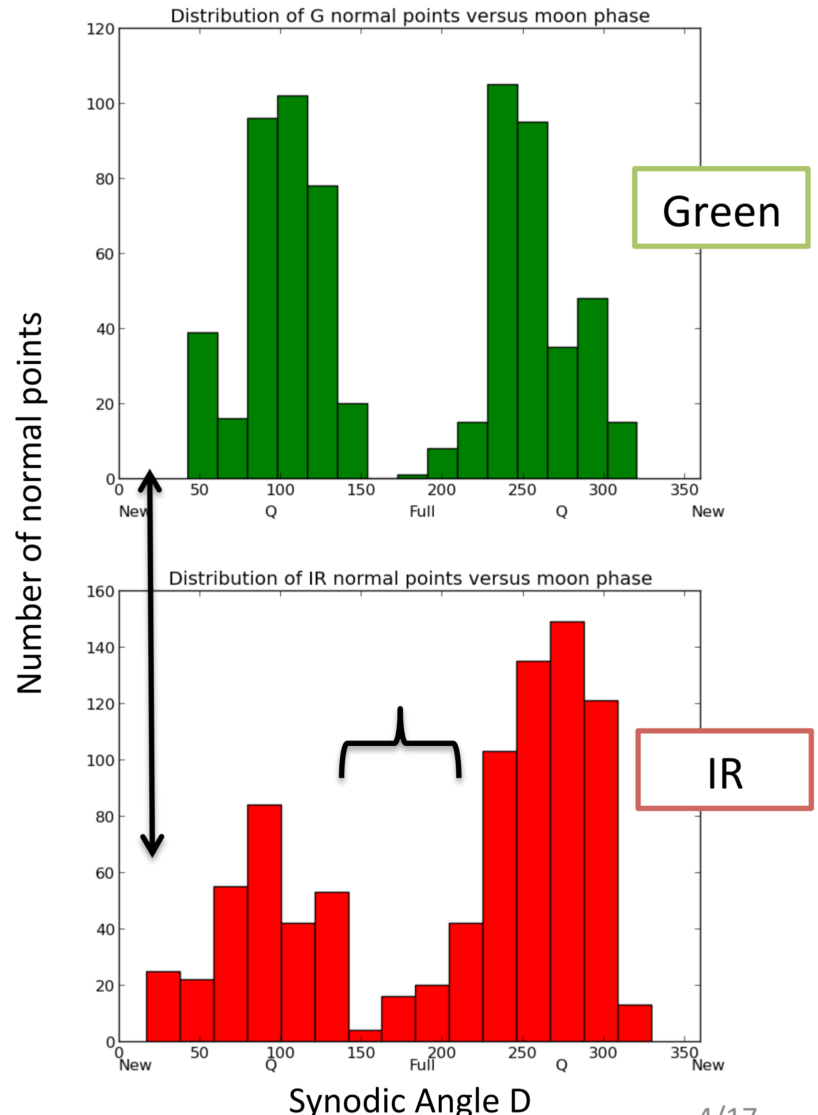
  - ✓ **Observations during new and full moon**

Maximum sensitivity for tests of **EP : cos(D)**



Improved IR LLR data

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- **Advantages**[7]:
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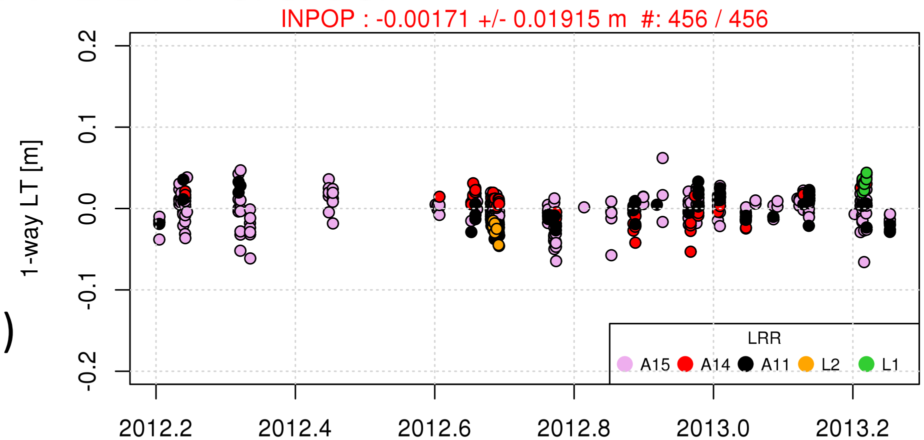
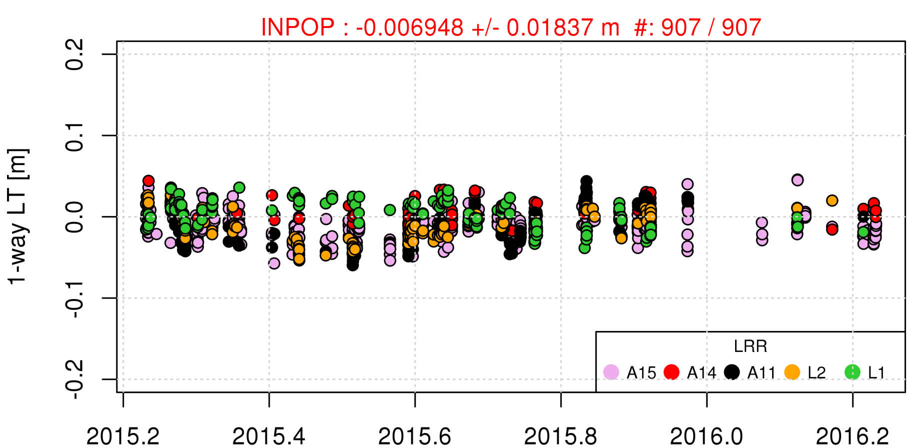
  - ✓ Observations round the clock (high SNR)
  - ✓ Diversification of observed reflectors
  - ✓ Observations during new and full moon
  - ✓ **Dense observations**



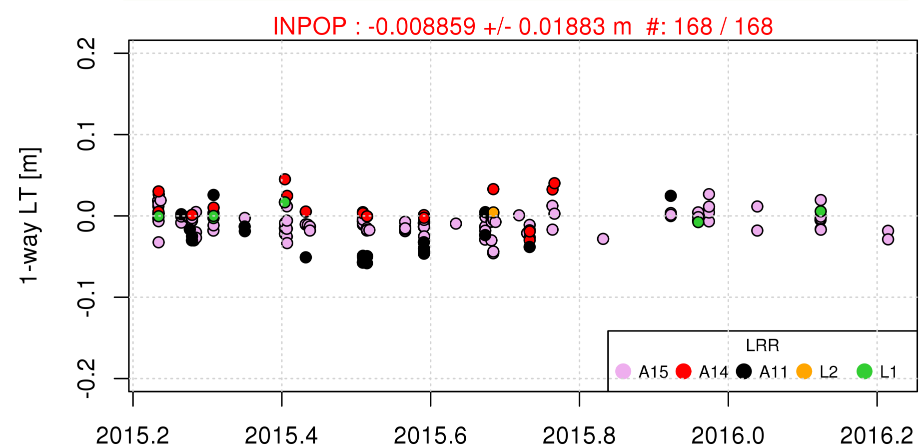
1 year GR (2012-2013) @ Calern: # 456

1 year IR (2015-2016)@ Calern : # **907**



Residuals (m) vs time (year)

1 year GR (2015-2016) @ Calern: # 168



Residuals (m) vs time (year)

Lunar Dynamical model

INPOP

Intégrateur **N**umérique **P**lanétaire de l'**O**bservatoire de **P**aris

- Uses Numerical integration of the (Einstein-Imfeld-Hoffmann, c^{-4} PPN approximation) equations of motion
- Adams-Cowell integrator in extended precision
- 8 planets + Pluto + Moon + asteroids (point-mass, ring), GR, J_2^{sun}, Earth rotation (Euler angles)

$$\ddot{x}_{Planet} = \sum_{A \neq B} \mu_B \frac{r_{AB}}{\|r_{AB}\|^3} + \ddot{x}_{GR}(\beta, \gamma, c^{-4}) + \ddot{x}_{AST,300} + \ddot{x}_{J_2^{\odot}}$$

- Moon: orbit and librations
- Simultaneous numerical integration TT-TDB, TCG-TCB
- *Fit to observations in ICRS over 1 cy (1914-2016)*
- *GAIA ESA planetary ephemerides*
- *Asteroid physics, Tests of gravity, solar physics*

INPOP15b Lunar dynamical model description:

Simplified, differentiated **2 layer** model

a. Solid mantle

b. Liquid core :

- Axial symmetry (C22 Core = 0)
- Non-differential rotation
- Shape constrained by core-mantle boundary

Perturbations on lunar orbit :

a. Interaction - <u>Moon's figure</u> and point masses :

- Earth, Sun, Venus, Jupiter

b. Interaction - <u>Earth's figure</u> and point masses :

- Moon, Sun, Venus, Jupiter

c. Interaction - <u>distorted</u> part of Earth and Moon :
(acceleration + 5 time delays)

- **Distortions**:
  - Solid tides raised by Moon and Sun
  - Deformation due to spin
- Force exerted on the Moon

Interactions at Lunar Core-Mantle Boundary (CMB) :

✓ **Dissipation** : Viscous drag of core fluid flowing past boundary

- Torque on the mantle due to coupling (no topography at CMB)

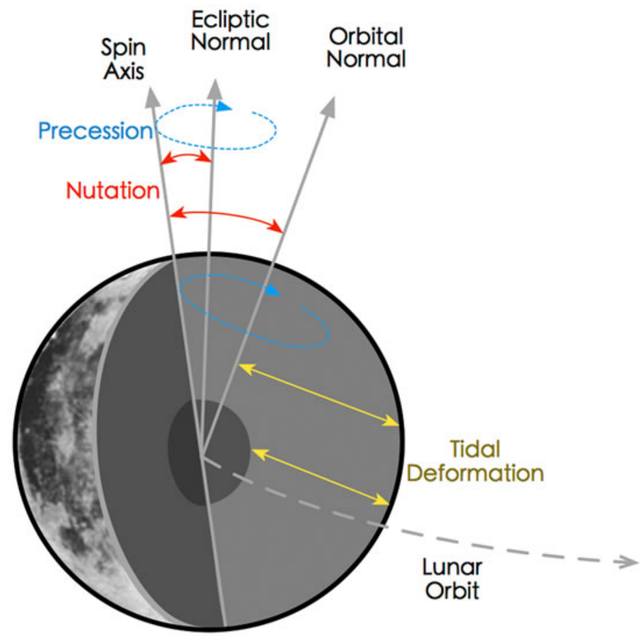


Illustration Credit: LPI

LLR Reduction Model

Calern : A Multi-Technique Station

- GINS Reduction Model
- Calern => SLR + LLR
- GINS allows SLR + LLR processing
- Calibration of SLR/LLR reduction procedure with LAGEOS
- Under study : Hydrology loading and horizontal gradients in the troposphere

What is GINS ?

(Géodésie par Intégrations Numériques Simultanées)

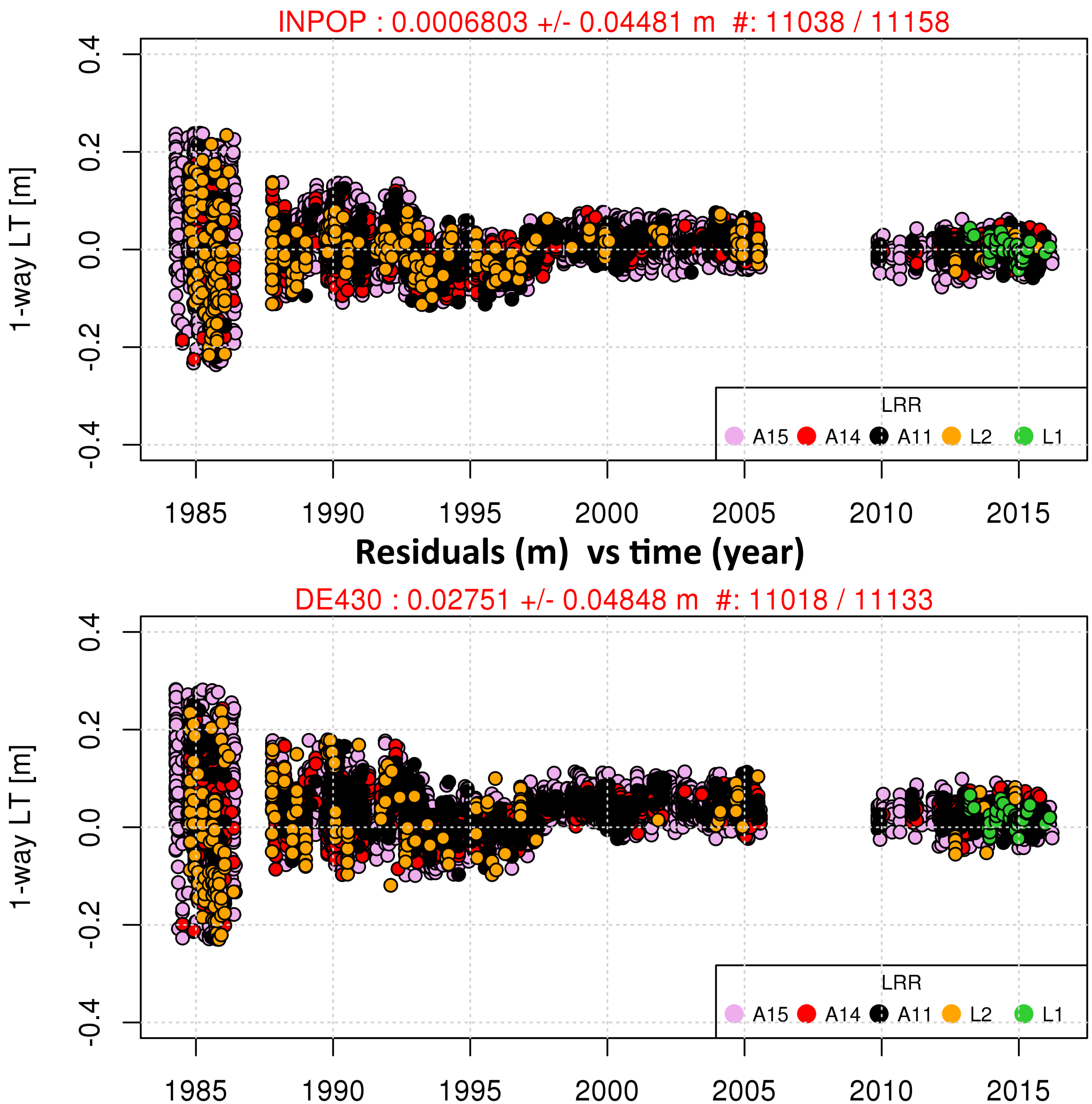
- Precise Orbit determination applied to space geodesy
- Developed and maintained by **OCA-GRGS-CNES**
- Time of flight (photon) to Residuals
- Planetary and lunar ephemeris (libration angles)
- Earth orientation (IERS C04 / JPL KEOF)
- Tides and loading
- Tropospheric delay
- Crustal deformation (Love & Shida numbers)
- Relativistic effects
- Under study : Hydrology loading

New solution : INPOP15b

- INPOP dynamical modeling
- fitted over LLR observations 1969-2016
- inclusion of IR LLR dataset
- GINS LLR reduction model
- Model differences between DE430 and INPOP

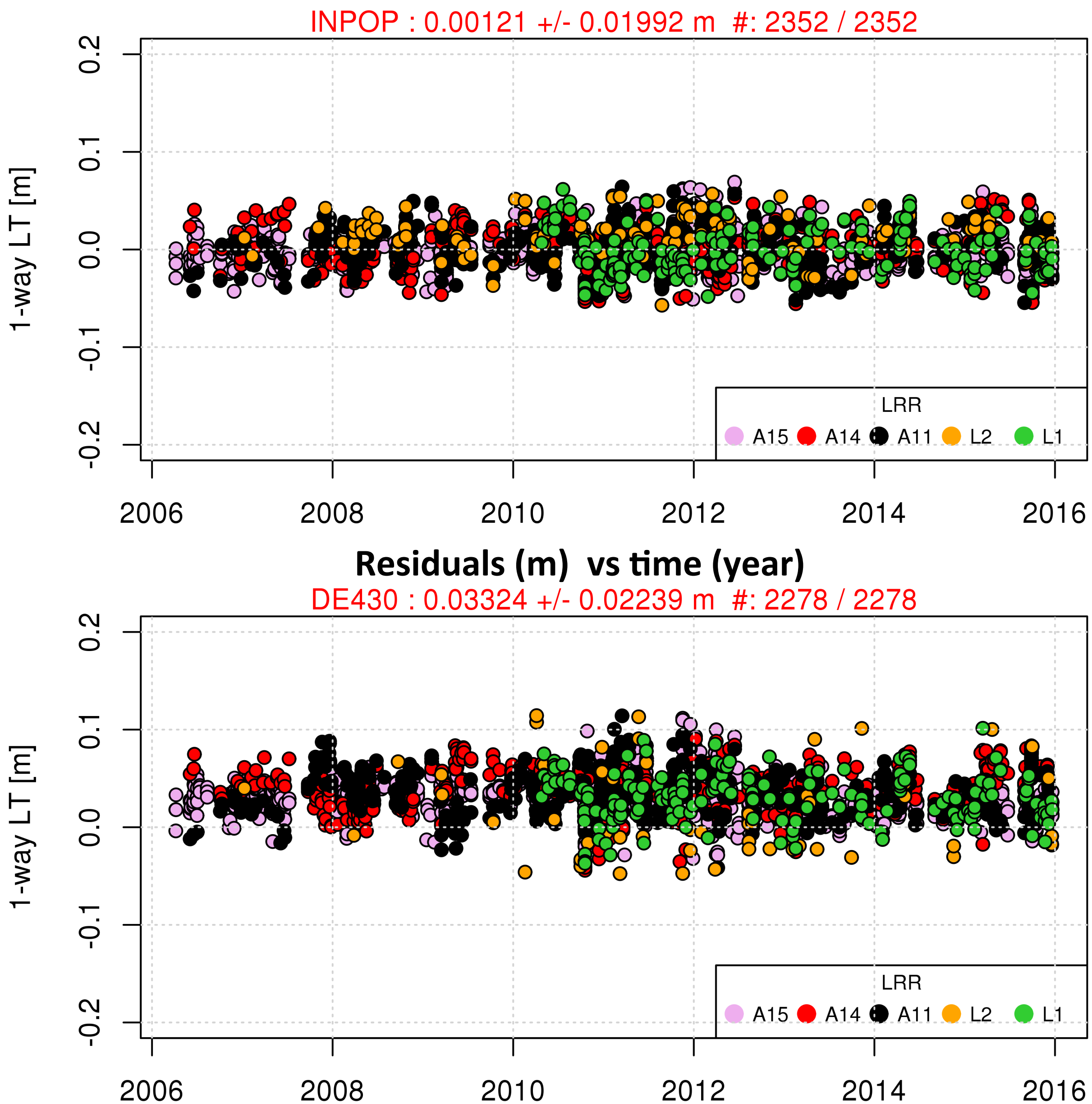
	DE430[1][2]	INPOP13c[3]	INPOP15b*
Shape of Moon	C20 β = (C-A)/B γ = (B-A)/C C22 (derived) C/MR^2 (derived)	C20 C22 C/MR^2	C20 C22 C/MR^2
Shape of fluid core	CMB flattening f	-	C20 Core C/MR^2 Core
Fluid Moment ratio	fixed	-	derived from: C/MR^2 , f and C20 Core
Symmetry of core	Axisymmetric	-	Axisymmetric
Additional longitude libration (Δτ)	A1 A2 A3	-	-
Lunar Gravity field	GRAIL660b[5]	LP150[4]	GRAIL660b[5]

Post-fit residual comparison : INPOP15b vs DE430 (5 sigma filtered)



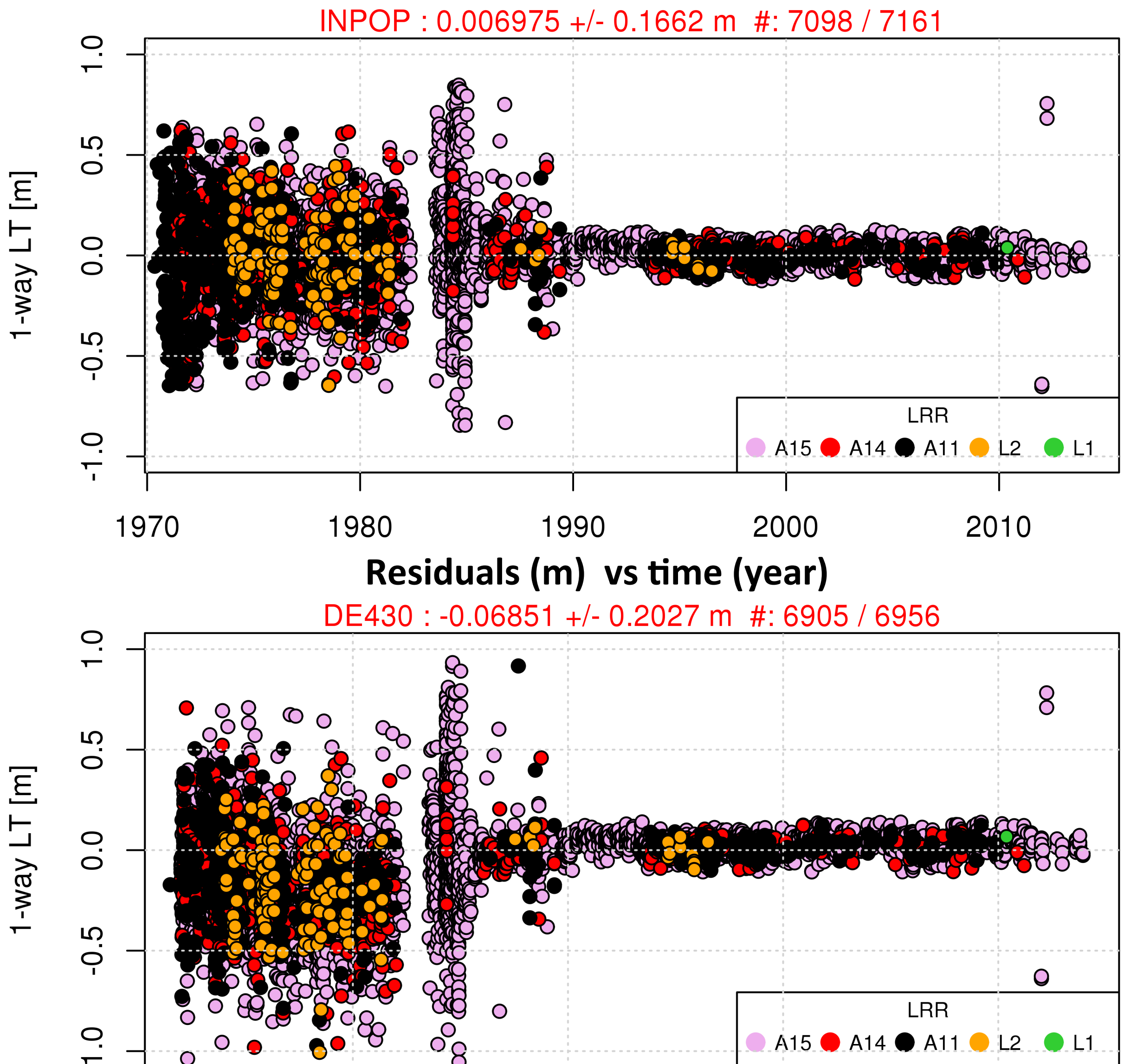
CALERN station (Green)

Post-fit residual comparison : INPOP15b vs DE430 (5 sigma filtered)



Apache station

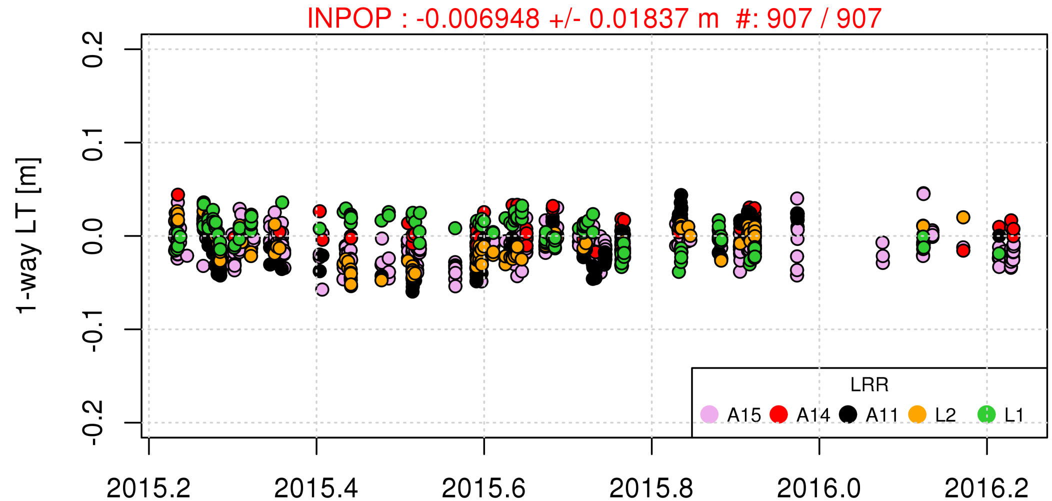
Post-fit residual comparison : INPOP15b vs DE430 (5 sigma filtered)



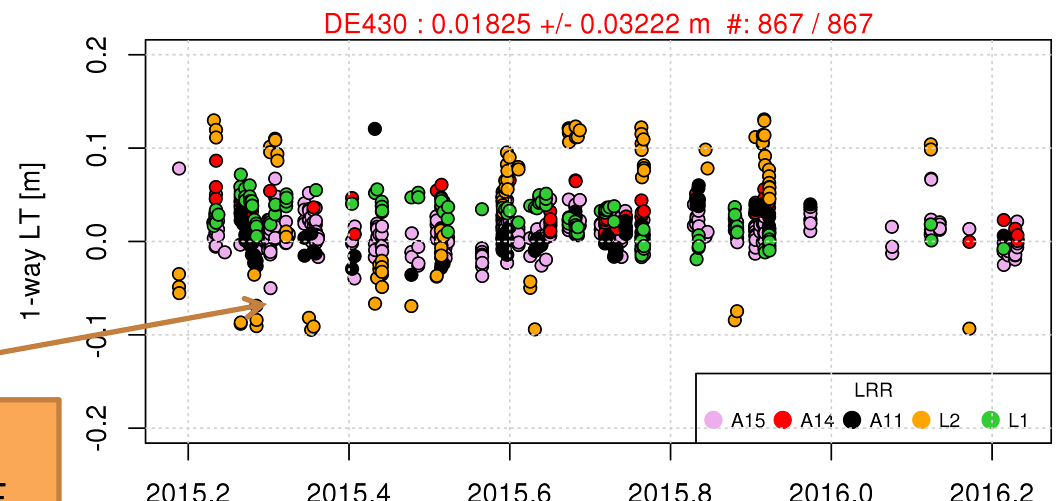
3 McDonald stations

OCA IR Post-fit Residuals

Reflector-wise σ(m) after 5σ filter		
Reflector	***INPOP15b****	***DE430***
A15	0.015	0.016
A14	0.017	0.018
A11	0.026	0.026
L1	0.017	0.020
L2	0.018	0.070



Residuals (m) vs time (year)



DE430
L2 signature outside the DE fitted data interval

Preliminary estimates with formal uncertainties from INPOP15b WLS fit

Parameter	INPOP15b	DE430[1][2]
Radius Moon km	**1.738E+03**	**1.738E+03**
EMRAT	**81.3005718**	**81.3005691±0.0000024**
GM EMB	8.99701141E-10	8.99701139E-10
k2 Moon	2.545E-02 ± 2E-05	**2.4059E-02**
h2 Moon	4.315E-02 ± 9.9E-05	4.76E-02 ± 6.4E-03
l2 Moon	**1.070E-02**	**1.070E-02**
C/MR2 Moon	3.9313E-01 ± 1.331E-06	3.93142E-01
Gravity field coefficients	GRAIL 660b (BVLS 2 x sig)	GRAIL 660b
C(2,0) Core	-4.74E-08 ± 3.052E-10	**-6.78E-08 (computed)**
C/MR2 Core	**2.75E-04**	**2.75E-04 (computed)**
K CMB	6.20E-09 ± 1.167E-11	6.43E-09
Angular velocities	6.241E-03 ± 2.544E-06	**–2.4199E–03**
	-5.136E-04 ± 1.232E-06	**4.110195E-01**
	-1.89E-04 ± 5.090E-06	**–4.630947E-01**
Cf/C ratio	**7.0E-04**	**7.0E-04**

***bold : fixed parameters**

Current assumptions

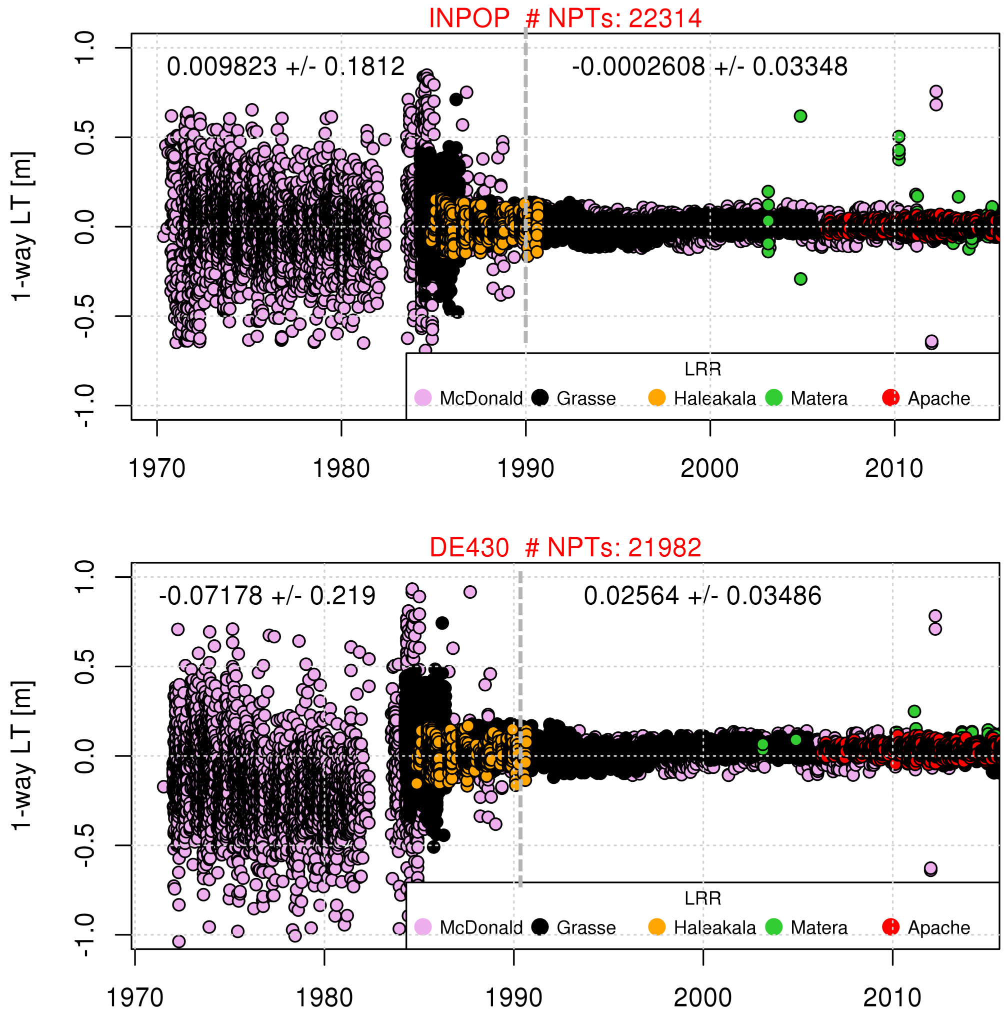
- Axial symmetry of liquid core
- Non-differential rotation
- Shape constrained by CMB
- Only viscous drag at CMB
- No topography at CMB

References :

[1] Folkner,W. M. et al (2014)
[2] Williams, J. G. et al (2014)
[3] Fienga, A. et al (2014)
[4] Konopliv, A. et al (2001)
[5] Konopliv, A. et al (2013)
[6] Viswanathan, V. et al (2016)
[7] Courde, C. et al (2016)*
[8] Wieczorek, M. et al (2016)

Conclusion and Future Work

- ✓ **Reduction model**
  - Hydrology loading
    - EOST/IPGS Loading service
  - Tropospheric delay
    - Horizontal gradients
- ✓ **Multi-technique**
  - Calern : SLR, LLR, GPS
- ✓ **Normal point computation algorithm**
  - Semi-train accumulation



Residuals (m) vs time (year)

Thank you for your attention

Questions?

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OCA LLR Distribution:

http://www.geoazur.fr/astrogeo/?href=observations/donnees/lune/