Networks and Engineering standing Committe (NESC)

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Towards a Lunar Laser Ranging at the sub-centimetric level

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Science with LLR; past and future [Viswanathan *et al.*, **BAAS** (2021)]

- Lunar Physics and deep lunar interior

  Past: Fluid lunar core dimension, triaxiality of the fluid lunar core [Viswanathan *et al.*, **GRL** (2019); Rambaux *et al.*, **JSRS** (2019)]
  Future: Presence of a solid inner core? It could explain the presence of a long lasting dynamo field [Laneuville *et al.*, **EPSL** (2014)]. New retroreflectors could enable a detection

- Dissipation within the Earth-Moon system

  Past: Earth tidal dissipation [Folkner *et al.*, **INPR** (2014)]. Friction at the CMB [Williams *et al.*, **JGR** (2001)]. Dissipation controls the long-term evolution of the Earth-Moon system. Presence of an unexplained secular drift in eccentricity 10^{-12}/years [Williams *et al.*, **CMDA** (2016)].
  Future: How to improve the constraints? Better determination of Love numbers, core size, and moment of inertia. New retroreflectors? More LLR stations for more favorable geometry to observe librations?

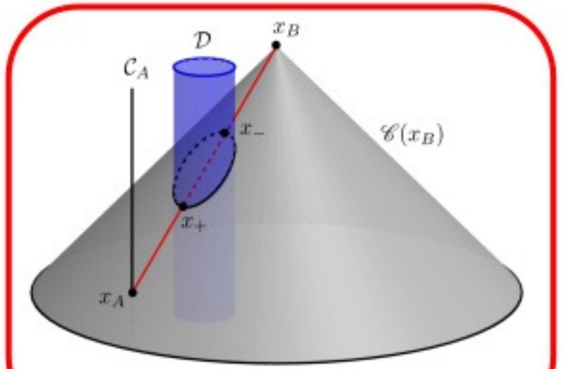
- Earth Orientation Parameters

  Past: Modern data seems to be able to measure EOPs (few **mas** for the terrestrial pole offsets, few ***μs*** for the Earth Rotation phase) [Vijay Singh *et al.*, **ASR** (2021)] (see also Friday's presentations by Hannover team)
  Future: Can LLR contribute efficiently to EOP determination? Simultaneous observations at a fixed latitude? More LLR stations in the south hemisphere for a better determination of precession and nutations?

- Fundamental Physics (LLR is still one of the best probe to test GR)

  Past: SEP and WEP [Williams *et al.*, **IJMPD** (2009)], geodetic precession and gravito-magnetism [Soffel *et al.*, **PRD** (2008)], variation of the gravitational constant [Hofmann *et al.*, **CQG** (2018)], Lorentz symmetry violations [Bourgoin *et al.*, **PRL** (2016), **PRL** (2017), **PRD** (2021)], etc.
  Future: How to improve the constraints? Modeling improvements and new data points at new and full moon [Müller *et al.*, **PRD** (1998)]. IR observations important in the context of fundamental Physics.

How to improve LLR data processing pipelines?

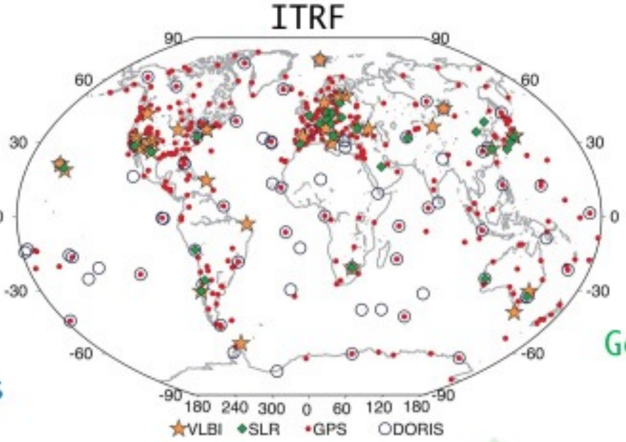


Bourgoin, PRL (2020)

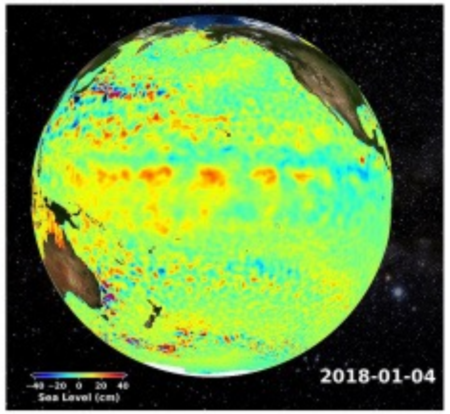
Earth atmosphere modeling

Hulley *et al.*, **JGR** (2004)

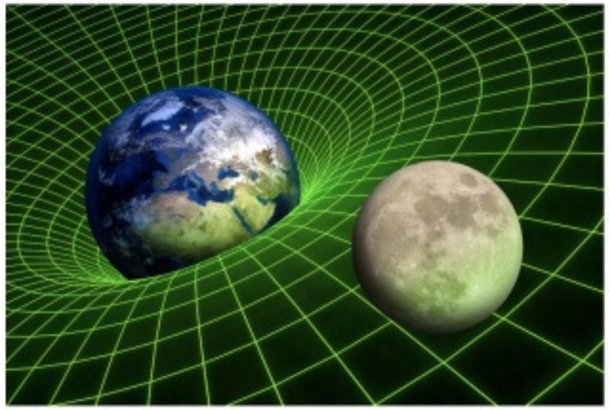
Astro-geodétic techniques



Global Geophysical changes



Tests of fundamental Physics



- Tropospheric delays

  Currently: Effect on the light-time @ **1m** and up to **10m**. IERS recommend spherical symmetry models [Mendes *et al.*, **GRL** (2004)]. Impact of horizontal gradients @ **30cm** [Hulley *et al.*, **JGR** (2004)]. Reabsorbed in other parameters…

  Future: Need for more robust models of tropospheric delays. SLR models with horizontal gradients [Drozdzewski *et al.*, **JoG** (2019)]. New models in the framework of relativistic geometrical optics? [Bourgoin **PRD** (2020)]

How to improve LLR data processing pipelines?

- Incompatibility between GRAIL gravity field and LLR data

Currently: Imposing GRAIL gravity field during LLR data analysis generates strong signatures in residuals [Viswanathan *et al.*, **AGU** (2019)]. Need to fit C_{32}, S_{32} and C_{33} (cf. Figure, with permission of Vishnu Viswanathan). Cause unknown yet.

Future: Need to solve for this issue, GRAIL provides better constraints. Unmodeled dissipation? Tidal model not accurate enough? Reference frames issue (selenocentric for GRAIL and barycentric for LLR)?

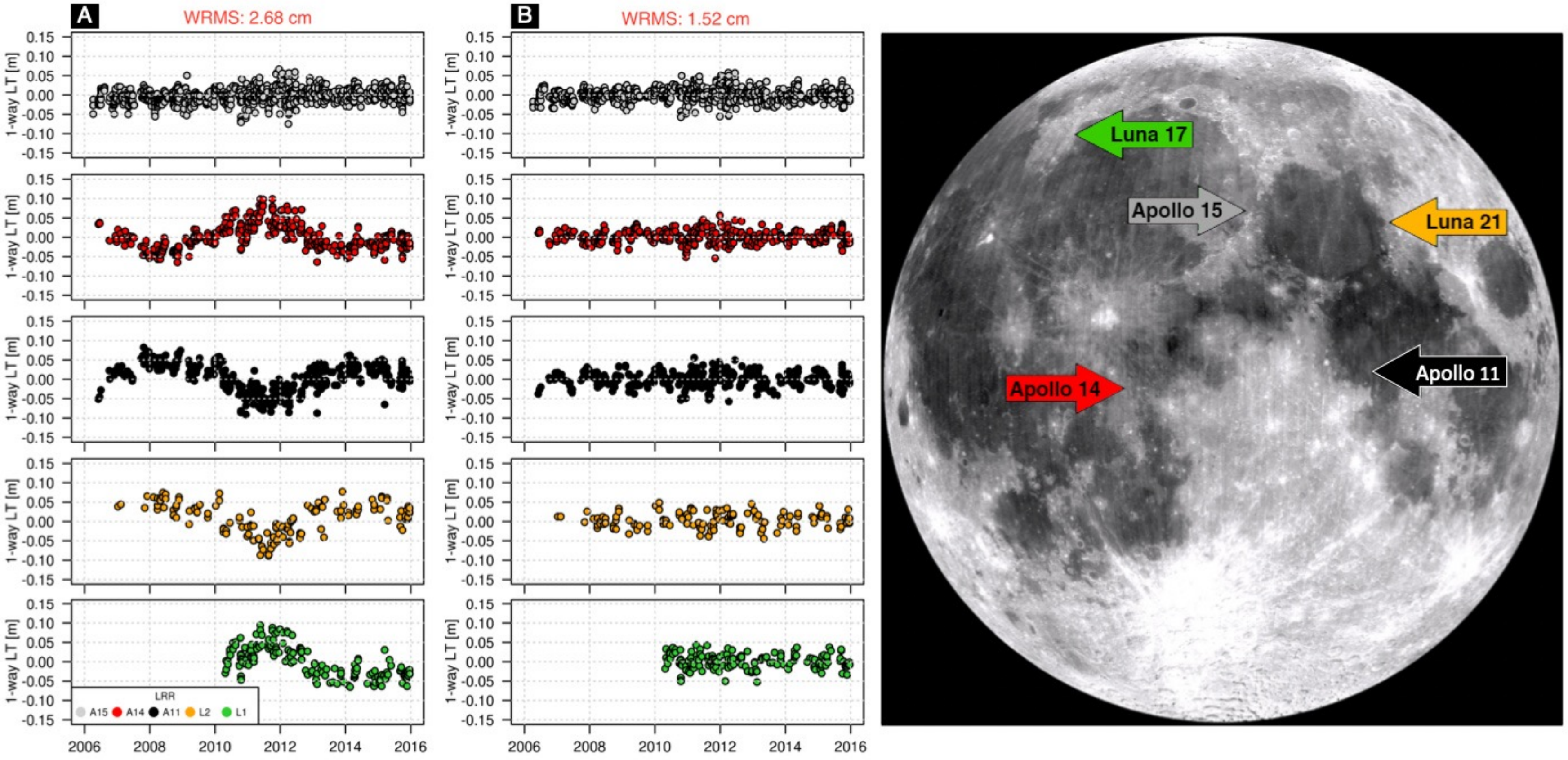


Fig. 3: Impact of deg-3 gravity field on LLR solutions.
A: Solution fixed to GRAIL, **B**: Some degree-3 gravity coefficients allowed to be adjusted.
Adjusting some gravity field coefficients (at 1%) through LLR fits, absorbs this longitude libration signature.

How to improve LLR data processing pipelines?

- Unmodelled systematic errors

Currently: Least squares fitting provides over-optimistic uncertainties. Cannot consider unmodelled systematic errors. Systematics visible with subsets of data [Bourgoin *et al.*, **PRL** (2016); **PRL** (2017); **PRD** (2021)]. Strongly dependent of stations/instruments

Future: Need for more robust modeling with better control on systematics. Provide more realistic uncertainties. Better tests of fundamental Physics.

Station or instrument	Period	N
Haleakala	1984–1990	770
Matera	2003–2015	118
McDonald (2.7m)	1969–1985	3604
McDonald (MLRS1)	1983–1988	631
McDonald (MLRS2)	1988–2015	3670
Grasse (Rubis)	1984–1986	1188
Grasse (Yag)	1987–2005	8324
Grasse (MeO)	2009–2016	1732
Grasse (IR)	2015–2016	1337
Apache Point	2006–2010	941
Apache Point	2010–2012	513
Apache Point	2012–2013	360
Apache Point	2013–2016	834