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OBSERVATOIRE DE LA CÔTE D'AZUR
UNIVERSITÉ CÔTE D'AZUR

22nd International Workshop on Laser Ranging, Guadalajara, Spain

PARIS OBSERVATORY LUNAR ANALYSIS CENTER:
from LLR predictions to tests of fundamental Physics

polac

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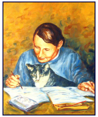
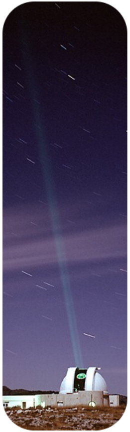
November 11th, 2022

POLAC : brief history to recent activities

Paris **O**bservatory **L**unar **A**nalysis **C**enter
ILRS lunar analysis center since 1997
[http://polac.obspm.fr]

SYRTE (UMR 8630), Observatoire de Paris (ILRS)





① Brief history :

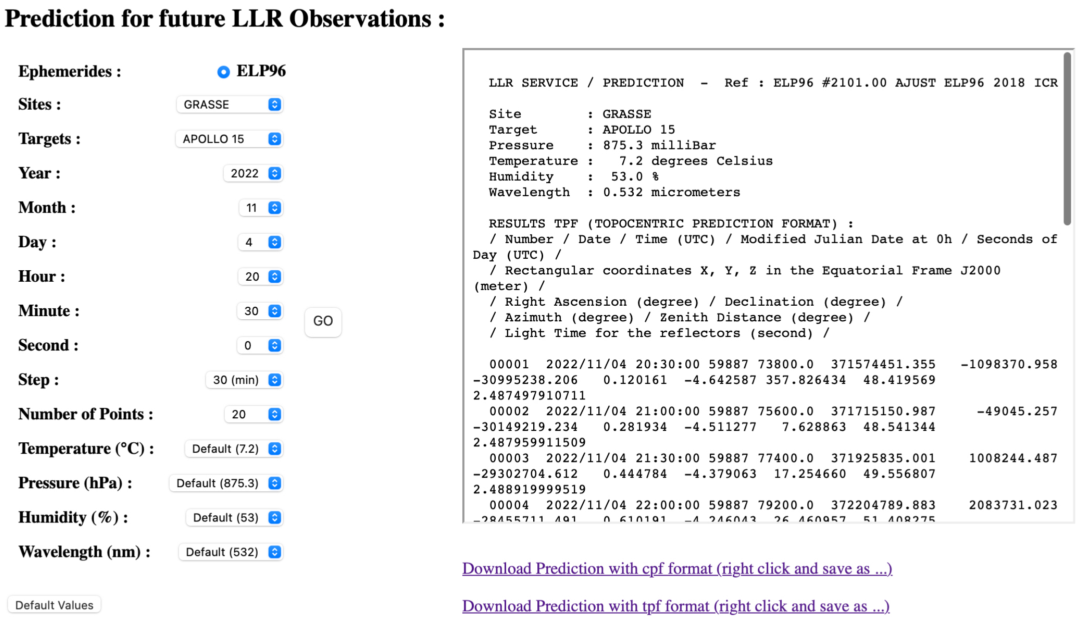
- *Founding members* : J. Chapront, M. Chapront-Touzé, and G. Francou
- *Current members* : S. Bouquillon, A. Bourgoin, and G. Francou
- *Support members* : T. Carlucci, A. Hees, and C. Le Poncin-Lafitte
- *Numerical tools* :
  $\Longrightarrow$ **ELP** : semi-analytical series (orbital and rotational motion)
  $\Longrightarrow$ **CAROLL** : LLR data reduction software
- *Fields of research* : celestial reference frames, Earth orientation parameters, tidal effects, etc.

② Current activities :

- *Day to day tasks* : collect, distribution, and LLR data processing
- *Support for LLR observers* : prediction and validation tools for ranging experiments
- *Numerical tools* :
  $\Longrightarrow$ **ELPN** : numerical lunar solution (orbital and rotational motion)
  $\Longrightarrow$ **CAROLL** : updated to receive **ELPN** solutions
- *Fields of research* : tests of fundamental physics, modeling of tropospheric delays, etc.

③ Official predictions for ILRS since 2019

POLAC : prediction [http://polac.obspm.fr/PaV/PaVb4/IndexPred.html]



Prediction for future LLR Observations :

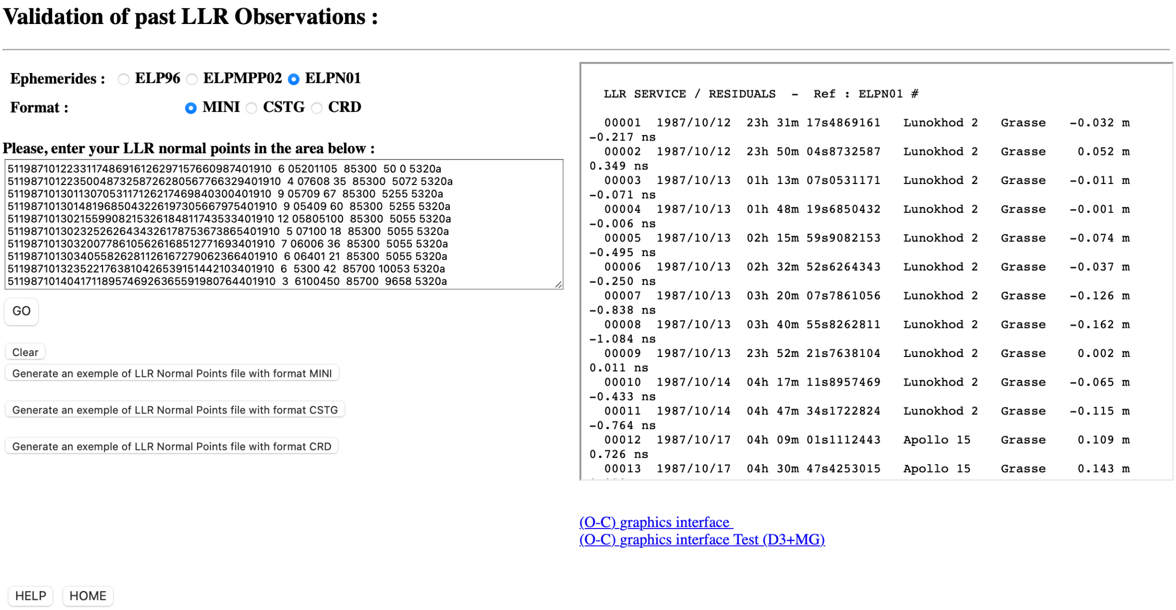
Ephemerides : ● ELP96
Sites : GRASSE
Targets : APOLLO 15
Year : 2022
Month : 11
Day : 4
Hour : 20
Minute : 30
Second : 0
Step : 30 (min)
Number of Points : 20
Temperature (°C) : Default (7.2)
Pressure (hPa) : Default (875.3)
Humidity (%) : Default (53)
Wavelength (nm) : Default (532)

```
  LLR SERVICE / PREDICTION  -  Ref : ELP96 #2101.00 AJUST ELP96 2018 ICR

  Site        : GRASSE
  Target      : APOLLO 15
  Pressure    : 875.3 milliBar
  Temperature :   7.2 degrees Celsius
  Humidity    :  53.0 %
  Wavelength  : 0.532 micrometers

  RESULTS TPF (TOPOCENTRIC PREDICTION FORMAT) :
  / Number / Date / Time (UTC) / Modified Julian Date at 0h / Seconds of
Day (UTC) /
  / Rectangular coordinates X, Y, Z in the Equatorial Frame J2000
(meter) /
  / Right Ascension (degree) / Declination (degree) /
  / Azimuth (degree) / Zenith Distance (degree) /
  / Light Time for the reflectors (second) /

  00001  2022/11/04 20:30:00 59887 73800.0  371574451.355   -1098370.958
-30995238.206   0.120161  -4.642587 357.826434  48.419569
2.487497910711
  00002  2022/11/04 21:00:00 59887 75600.0  371715150.987     -49045.257
-30149219.234   0.281934  -4.511277   7.628863  48.541344
2.487959911509
  00003  2022/11/04 21:30:00 59887 77400.0  371925835.001    1008244.487
-29302704.612   0.444784  -4.379063  17.254660  49.556807
2.488919999519
  00004  2022/11/04 22:00:00 59887 79200.0  372204789.883    2083731.023
-28455711.491   0.610191  -4.246043  26.460957  51.408275
```

[Download Prediction with cpf format (right click and save as ...)]

[Download Prediction with tpf format (right click and save as ...)]

POLAC : validation [http://polac.obspm.fr/PaV/PaVb4/IndexValid.html]



Validation of past LLR Observations :

Ephemerides : ○ ELP96 ○ ELPMPP02 ● ELPN01

Format : ● MINI ○ CSTG ○ CRD

Please, enter your LLR normal points in the area below :

```
5119871012233117486916126297157660987401910  6 05201105  85300  50 0 5320a
5119871012235004873258726280567766329401910  4 07608 35  85300  5072 5320a
5119871013011307053117126217469840300401910  9 05709 67  85300  5255 5320a
5119871013014819685043226197305667975401910  9 05409 60  85300  5255 5320a
5119871013021559908215326184811743533401910 12 05805100  85300  5055 5320a
5119871013023252626434326178753673865401910  5 07100 18  85300  5055 5320a
5119871013032007786105626168512771693401910  7 06006 36  85300  5055 5320a
5119871013034055826281126167279062366401910  6 06401 21  85300  5055 5320a
5119871013235221763810426539151442103401910  6  5300 42  85700 10053 5320a
5119871014041711895746926365591980764401910  3  6100450  85700  9658 5320a
```

```
 LLR SERVICE / RESIDUALS  -  Ref : ELPN01 #

 00001  1987/10/12  23h 31m 17s4869161   Lunokhod 2   Grasse   -0.032 m
-0.217 ns
 00002  1987/10/12  23h 50m 04s8732587   Lunokhod 2   Grasse    0.052 m
0.349 ns
 00003  1987/10/13  01h 13m 07s0531171   Lunokhod 2   Grasse   -0.011 m
-0.071 ns
 00004  1987/10/13  01h 48m 19s6850432   Lunokhod 2   Grasse   -0.001 m
-0.006 ns
 00005  1987/10/13  02h 15m 59s9082153   Lunokhod 2   Grasse   -0.074 m
-0.495 ns
 00006  1987/10/13  02h 32m 52s6264343   Lunokhod 2   Grasse   -0.037 m
-0.250 ns
 00007  1987/10/13  03h 20m 07s7861056   Lunokhod 2   Grasse   -0.126 m
-0.838 ns
 00008  1987/10/13  03h 40m 55s8262811   Lunokhod 2   Grasse   -0.162 m
-1.084 ns
 00009  1987/10/13  23h 52m 21s7638104   Lunokhod 2   Grasse    0.002 m
0.011 ns
 00010  1987/10/14  04h 17m 11s8957469   Lunokhod 2   Grasse   -0.065 m
-0.433 ns
 00011  1987/10/14  04h 47m 34s1722824   Lunokhod 2   Grasse   -0.115 m
-0.764 ns
 00012  1987/10/17  04h 09m 01s1112443   Apollo 15    Grasse    0.109 m
0.726 ns
 00013  1987/10/17  04h 30m 47s4253015   Apollo 15    Grasse    0.143 m
```

[(O-C) graphics interface](#)
[(O-C) graphics interface Test (D3+MG)](#)

POLAC, a partner of the Grasse LLR station

Stations de Télémétrie Laser
ILRS lunar and satellite data center
[`https://meo.cnrs.fr`]
Géoazur (UMR 7329), Université Côte d'Azur, OCA

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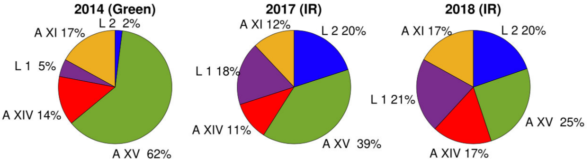
① Grasse LLR station in brief :

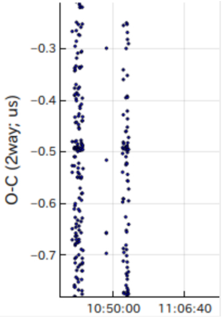
- *Current members* : J. Chabé, C. Courde, J.-M. Torre, H. Mariey, M. Aimar, D. H. Phung, etc.
- *Founding and past members* : J.-F. Mangin, E. Samain, C. Veillet, etc.
- *The oldest still in activity* : 1984-1986 (Rubis), 1986-2006 (YAG), 2009-2022 (MéO, green and IR)
- *The most active* : more than 50% of LLR NPs

② MéO station highlights : (cf. presentations by H. Mariey, D. H. Phung, and J. Chabé)

- *Since 2015* : link budget improved thanks to IR and new optical tuning of MéO telescope
  $\Longrightarrow$ homogeneous observations of all retroreflectors [Chabé *et. al*, **ESS** (2020)]



  $\Longrightarrow$ observations all along the lunar cycle
- *Sept. 2020* : two-way laser ranging to LRO (NASA Goddard) [Mazarico *et. al*, **EPS** (2020)]
- *Dec. 2020* : laser ranging to Hayabusa2 on 6 millions of km (JAXA) [`https://meo.cnrs.fr`]



Echos at -0.5 μs from Hayabusa2

Collaboration between POLAC & MéO

- **Hindsight analysis** :

  ⟹ avoid issues (e.g., calibration, NPs format, etc.) before insertion into ILRS database

- **Prediction for ranging to artificial satellites** :

  ⟹ LRO two-way laser ranging campaign [Mazarico *et. al*, **EPS** (2020)]

- **Improvement of prediction and validation tools to support LLR observers** :

  ⟹ scheduling of observations to reach scientific objectives (method developed for observations of stars around Sgr A*) [Hees *et. al*, **APJ** (2019)]

  ⟹ adding new LLR stations and new retroreflectors [Porcelli *et. al*, **NAS** (2021)]

- **Precision of LLR NPs and residuals**

- **Improvement in modeling tropospheric delay** :

  ⟹ covariant formalism based on TTF and optical metric (recently applied for radio atmospheric occultations experiments)

  [Bourgoin, **PRD** (2020) ; Bourgoin *et al.*, **A&A** (2021) ; Bourgoin *et al.*, **ASR** (2022)]

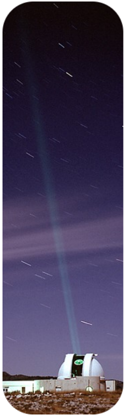
  ⟹ see also J. Chabé's presentation (atmospheric turbulence)

- **Improvement in testing fundamental physics** :

  ⟹ impact of IR observations on test of the SEP

  ⟹ tests of Lorentz symmetry (gravity sector, matter sector, mass dimension 5)

  [Bourgoin *et al.*, **PRL** (2016) ; Bourgoin *et al.*, **PRL** (2017) ; Bourgoin *et al.*, **PRD** (2021)]



POLAC LLR residuals in GR framework with ELPN

- **ELPN** : a numerical lunar solution
  - $\Longrightarrow$ barycentric solution for center-of-masses
  - $\Longrightarrow$ quadruple precision, more than 8500 Eqs.
- **CAROLL** : a fitting procedure
  - $\Longrightarrow$ turns ELPN's predictions into a UTC computed light-time
  - $\Longrightarrow$ finds ELPN's parameters minimising LLR residuals

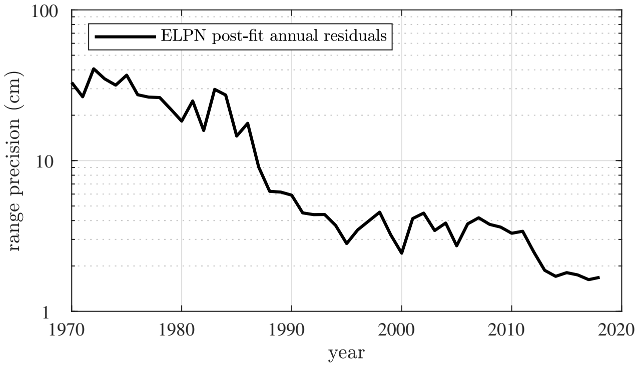


TABLE III. ELPN (in pure GR) postfit residuals per LLR station and instrument. The mean and the standard deviation of the residuals are denoted by μ and σ, respectively. For each station or instrument, N is the number of available observations and N_r the number of rejected observations ($> 3\sigma$).

Station (instrument)	Period	N	N_r	μ (cm)	σ (cm)
McDonald (2.7-m)	1969–1985	3604	92	14.0	34.7
McDonald (MLRS1)	1983–1988	631	74	7.3	29.3
McDonald (MLRS2)	1988–2015	3670	467	−1.0	5.5
Grasse (Rubis)	1984–1986	1188	21	4.5	16.0
Grasse (Yag)	1987–2005	8324	51	0.0	4.1
Grasse (MeO green)	2009–2018	1937	23	0.2	1.8
Grasse (MeO IR)	2015–2018	3837	25	−0.2	1.7
Haleakala	1984–1990	770	23	−2.8	8.1
Matera	2003–2018	224	15	−0.4	4.7
Apache Point (P1)	2006–2010	941	2	0.9	2.2
Apache Point (P2)	2010–2012	513	15	0.9	2.9
Apache Point (P3)	2012–2013	360	9	0.7	2.3
Apache Point (P4)	2013–2016	834	7	1.0	1.7
Wettzell	2018–2018	22	0	1.7	1.2

Lorentz symmetry in the SME framework

1. **Total action in gravity and matter sectors** : $\boxed{S_{\text{tot}} = S_m + S_{mg} + S_g}$

[Bailey *et al.*, **PRD** (2006); Kostelecký *et al.*, **PRD** (2011); Bailey *et al.*, **PRD** (2017)]

- *Matter* : $S_m = S_m\left[\Psi_A, g_{\mu\nu}, s^{\mu\nu}, (a_{\text{eff}})_\mu, q^{\mu\rho\alpha\nu\beta\sigma\gamma}\right]$,
- *Matter-gravity couplings* : $S_{mg} = -c\int \mathrm{d}\lambda\, (a_{\text{eff}})_\mu u^\mu$,
- *Field* (dim. 4 and 5) : $S_g = \dfrac{c^4}{16\pi G}\displaystyle\int \mathrm{d}^4x\sqrt{-g}\Big[\underbrace{R + s^{\mu\nu}\left(R_{\mu\nu} - \tfrac{1}{4}g_{\mu\nu}R\right)}_{\text{dim. 4}} \underbrace{- \frac{1}{4}g_{\mu\nu}q^{\mu\rho\alpha\nu\beta\sigma\gamma}\nabla_\beta R_{\rho\alpha\sigma\gamma}}_{\text{dim. 5}}\Big]$.

2. **Physical implications of Lorentz symmetry breaking** :

- Modified field equations (dim. 4 and 5)
  $\Longrightarrow$ Lorentz symmetry violations in the way spacetime metric is generated by matter fields Ψ_A
  $\Longrightarrow$ violations of the SEP
- Ψ_A not minimally coupled to $g_{\mu\nu}$ (because of S_{mg})
  $\Longrightarrow$ Lorentz symmetry violations in the way matter fields is responding to the spacetime metric
  $\Longrightarrow$ violations of the WEP $\Longrightarrow$ no geodesics

3. **Constraints with LLR**

[Bourgoin *et al.*, **PRL** (2016); Bourgoin *et al.*, **PRL** (2017); Bourgoin *et al.*, **PRD** (2021)]

- Insertion of Lorentz symmetry violations in **ELPN** and **CAROLL**
- LLR data processing within the SME framework

Constraints on mass dimension 5 operators

1. **Theoretical grounds** :

[Bailey *et al.*, **PRD** (2017)]

$$\mathcal{L}_g = \mathcal{L}_g^{(4)} + \mathcal{L}_g^{(5)} + \dots \qquad \text{with} \qquad \mathcal{L}_g^{(5)} = -\frac{c^4}{128\pi G} h_{\mu\nu} q^{\mu\rho\alpha\nu\beta\sigma\gamma} \partial_\beta R_{\rho\alpha\sigma\gamma}$$

- Dimension 4 terms highly studied and constrained with many techniques
- Dimension 5 terms break both Lorentz and CPT symmetries
- The higher the dimension the shorter the range of action $\Longrightarrow$ better constrained by laboratory experiments
- New phenomenological signatures e.g., two-body system terms $\propto v/r^3$ $\Longrightarrow$ LLR and binary pulsars

[Shao *et al.*, **PRD** (2018)]

2. **Dynamics of the Earth-Moon system** :

- 60 independent $q^{\mu\rho\alpha\nu\beta\sigma\gamma}$'s to be constrained ! $\Longrightarrow$ orbital dynamics provide only 15 canonical K_{jklm}'s
- Equations of motion of the two-body problem :

$$\left[\frac{\mathrm{d}^2 r^j}{\mathrm{d}t^2}\right]_{(d=5)} = \frac{GM}{r^3}\frac{v^k}{c}\left(15 n_{[j}K_{k]lmn} n^l n^m n^n - 3K_{[jk]ll} + 9K_{[jk]lm} n^l n^m - 9 n_{[j}K_{k]llm} n^m\right)$$

- Signatures really different than GR corrections, PPN, violation UFF, LS-breakings of dim. 4, etc.

3. **LLR data processing** :

- **ELPN** for solving the barycentric motions and **CAROLL** for the light-time between station and retroreflector
- Fitting 83 parameters : Newtonian parameters (degree 2, and 3 of the Moon, etc.) and relativistic ones

[Viswanathan *et al.*, **AGU** (2019)]

Constraints on mass dimension 5 operators

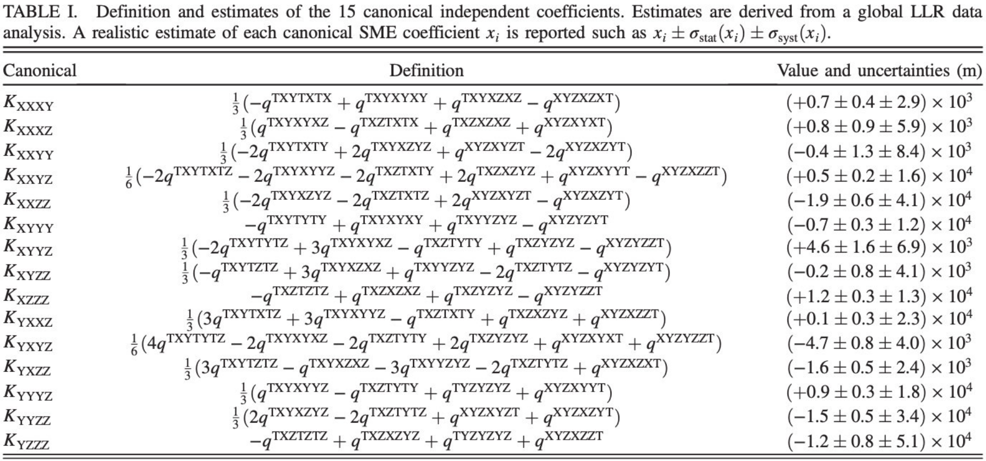


TABLE I. Definition and estimates of the 15 canonical independent coefficients. Estimates are derived from a global LLR data analysis. A realistic estimate of each canonical SME coefficient x_i is reported such as $x_i \pm \sigma_{\rm stat}(x_i) \pm \sigma_{\rm syst}(x_i)$.

Canonical	Definition	Value and uncertainties (m)
$K_{\rm XXXY}$	$\frac{1}{3}(-q^{\rm TXYTXTX} + q^{\rm TXYXYXY} + q^{\rm TXYXZXZ} - q^{\rm XYZXZXT})$	$(+0.7 \pm 0.4 \pm 2.9) \times 10^3$
$K_{\rm XXXZ}$	$\frac{1}{3}(q^{\rm TXYXYXZ} - q^{\rm TXZTXTX} + q^{\rm TXZXZXZ} + q^{\rm XYZXYXT})$	$(+0.8 \pm 0.9 \pm 5.9) \times 10^3$
$K_{\rm XXYY}$	$\frac{1}{3}(-2q^{\rm TXYTXTY} + 2q^{\rm TXYXZYZ} + q^{\rm XYZXYZT} - 2q^{\rm XYZXZYT})$	$(-0.4 \pm 1.3 \pm 8.4) \times 10^3$
$K_{\rm XXYZ}$	$\frac{1}{6}(-2q^{\rm TXYTXTZ} - 2q^{\rm TXYXYYZ} - 2q^{\rm TXZTXTY} + 2q^{\rm TXZXZYZ} + q^{\rm XYZXYYT} - q^{\rm XYZXZZT})$	$(+0.5 \pm 0.2 \pm 1.6) \times 10^4$
$K_{\rm XXZZ}$	$\frac{1}{3}(-2q^{\rm TXYXZYZ} - 2q^{\rm TXZTXTZ} + 2q^{\rm XYZXYZT} - q^{\rm XYZXZYT})$	$(-1.9 \pm 0.6 \pm 4.1) \times 10^4$
$K_{\rm XYYY}$	$-q^{\rm TXYTYTY} + q^{\rm TXYXYXY} + q^{\rm TXYYZYZ} - q^{\rm XYZYZYT}$	$(-0.7 \pm 0.3 \pm 1.2) \times 10^4$
$K_{\rm XYYZ}$	$\frac{1}{3}(-2q^{\rm TXYTYTZ} + 3q^{\rm TXYXYXZ} - q^{\rm TXZTYTY} + q^{\rm TXZYZYZ} - q^{\rm XYZYZZT})$	$(+4.6 \pm 1.6 \pm 6.9) \times 10^3$
$K_{\rm XYZZ}$	$\frac{1}{3}(-q^{\rm TXYTZTZ} + 3q^{\rm TXYXZXZ} + q^{\rm TXYYZYZ} - 2q^{\rm TXZTYTZ} - q^{\rm XYZYZYT})$	$(-0.2 \pm 0.8 \pm 4.1) \times 10^3$
$K_{\rm XZZZ}$	$-q^{\rm TXZTZTZ} + q^{\rm TXZXZXZ} + q^{\rm TXZYZYZ} - q^{\rm XYZYZZT}$	$(+1.2 \pm 0.3 \pm 1.3) \times 10^4$
$K_{\rm YXXZ}$	$\frac{1}{3}(3q^{\rm TXYTXTZ} + 3q^{\rm TXYXYYZ} - q^{\rm TXZTXTY} + q^{\rm TXZXZYZ} + q^{\rm XYZXZZT})$	$(+0.1 \pm 0.3 \pm 2.3) \times 10^4$
$K_{\rm YXYZ}$	$\frac{1}{6}(4q^{\rm TXYTYTZ} - 2q^{\rm TXYXYXZ} - 2q^{\rm TXZTYTY} + 2q^{\rm TXZYZYZ} + q^{\rm XYZXYXT} + q^{\rm XYZYZZT})$	$(-4.7 \pm 0.8 \pm 4.0) \times 10^3$
$K_{\rm YXZZ}$	$\frac{1}{3}(3q^{\rm TXYTZTZ} - q^{\rm TXYXZXZ} - 3q^{\rm TXYYZYZ} - 2q^{\rm TXZTYTZ} + q^{\rm XYZXZXT})$	$(-1.6 \pm 0.5 \pm 2.4) \times 10^3$
$K_{\rm YYYZ}$	$\frac{1}{3}(q^{\rm TXYXYYZ} - q^{\rm TXZTYTY} + q^{\rm TYZYZYZ} + q^{\rm XYZXYYT})$	$(+0.9 \pm 0.3 \pm 1.8) \times 10^4$
$K_{\rm YYZZ}$	$\frac{1}{3}(2q^{\rm TXYXZYZ} - 2q^{\rm TXZTYTZ} + q^{\rm XYZXYZT} + q^{\rm XYZXZYT})$	$(-1.5 \pm 0.5 \pm 3.4) \times 10^4$
$K_{\rm YZZZ}$	$-q^{\rm TXZTZTZ} + q^{\rm TXZXZYZ} + q^{\rm TYZYZYZ} + q^{\rm XYZXZZT}$	$(-1.2 \pm 0.8 \pm 5.1) \times 10^4$

- Jackknife resampling method to assess systematic errors on parameter x_i by stations and retroreflectors :

$$\sigma^2_{\rm real}(x_i) = \sigma^2_{\rm stat}(x_i) + \sigma^2_{\rm syst}(x_i) \qquad \text{with} \qquad \sigma^2_{\rm syst}(x_i) = \sigma^2_{\rm sta}(x_i) + \sigma^2_{\rm ref}(x_i)$$

- Improvements up to **3 orders of magnitues** w.r.t. binary pulsars (cf. K_{XXXY} and K_{YXZZ})

[Shao *et al.*, **PRD** (2018)]

Constraints on mass dimension 5 operators

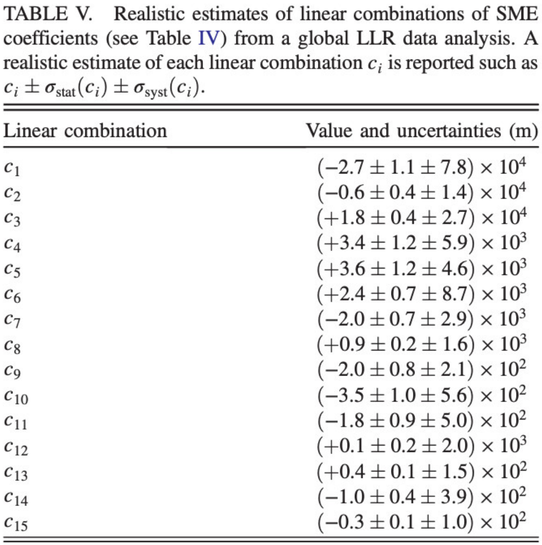


TABLE V. Realistic estimates of linear combinations of SME coefficients (see Table IV) from a global LLR data analysis. A realistic estimate of each linear combination c_i is reported such as $c_i \pm \sigma_{\rm stat}(c_i) \pm \sigma_{\rm syst}(c_i)$.

Linear combination	Value and uncertainties (m)
c_1	$(-2.7 \pm 1.1 \pm 7.8) \times 10^4$
c_2	$(-0.6 \pm 0.4 \pm 1.4) \times 10^4$
c_3	$(+1.8 \pm 0.4 \pm 2.7) \times 10^4$
c_4	$(+3.4 \pm 1.2 \pm 5.9) \times 10^3$
c_5	$(+3.6 \pm 1.2 \pm 4.6) \times 10^3$
c_6	$(+2.4 \pm 0.7 \pm 8.7) \times 10^3$
c_7	$(-2.0 \pm 0.7 \pm 2.9) \times 10^3$
c_8	$(+0.9 \pm 0.2 \pm 1.6) \times 10^3$
c_9	$(-2.0 \pm 0.8 \pm 2.1) \times 10^2$
c_{10}	$(-3.5 \pm 1.0 \pm 5.6) \times 10^2$
c_{11}	$(-1.8 \pm 0.9 \pm 5.0) \times 10^2$
c_{12}	$(+0.1 \pm 0.2 \pm 2.0) \times 10^3$
c_{13}	$(+0.4 \pm 0.1 \pm 1.5) \times 10^2$
c_{14}	$(-1.0 \pm 0.4 \pm 3.9) \times 10^2$
c_{15}	$(-0.3 \pm 0.1 \pm 1.0) \times 10^2$

- High correlations between some of the canonical parameters K_{jklm}.

- SVD decomposition to find the independent linear combinations ($\boldsymbol{c}$) of K_{jklm}'s ($\boldsymbol{x}$) from the covariance matrix ($\boldsymbol{C}$) :

$$\boldsymbol{c} = {}^t\boldsymbol{V}(\boldsymbol{x}) \qquad \text{with} \qquad \boldsymbol{C} = \boldsymbol{V} \circ \boldsymbol{W} \circ {}^t\boldsymbol{V}$$

and $\sigma^2_{\rm stat}(c_i) = W_{ii}$.

$\Longrightarrow$ We report no Lorentz or CPT symmetry breaking !

[Bourgoin *et al.*, **PRD** (2021)]

POLAC : a service dedicated to LLR data processing

Paris **O**bservatory **L**unar **A**nalysis **C**enter
ILRS lunar analysis center since 1997
`http://polac.obspm.fr`
SYRTE (UMR 8630), Observatoire de Paris (ILRS)

1. **Activities** : collect, distribution, and LLR data processing
2. **Support for LLR observers** : prediction and validation tools for ranging experiments
3. **Official predictions for ILRS since 2019**
4. **Close collaboration with Grasse LLR station** :
    - ranging to artificial satellites
    - preparing new observations on new retroreflectors
    - improving the modeling the tropospheric delay
    - impact of IR observations on tests of fundamental physics
5. **Recent highlights** :
    - Data analysis of 50 years of observations at the cm level (**ELPN** in GR)
    - In alternative theory of gravity too (**ELPN** in SME)

$\Longrightarrow$ Improvements up to **three ordres of magnitude** of SME constraints, all techniques considered

[Bourgoin *et al.*, **PRL** (2016) ; Bourgoin *et al.*, **PRL** (2017) ; Bourgoin *et al.*, **PRD** (2021)]