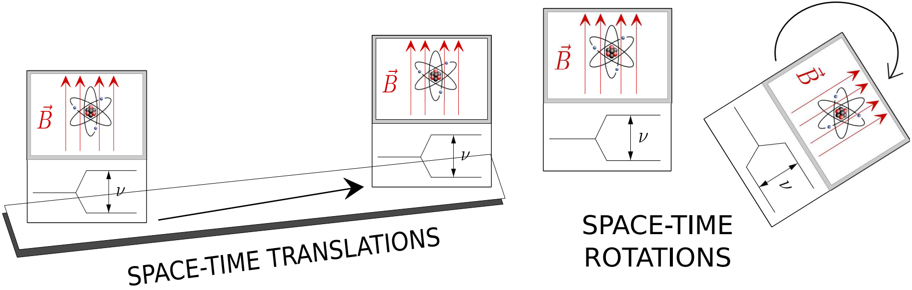
First results from a test of Lorentz Invariance with the MICROSCOPE mission

- ACES Workshop 2018 -

Hélène Pihan-Le Bars[1], C. Guerlin[2,1], Quentin Bailey[3], Geoffrey Mo[4], Jay Tasson[4], Peter Wolf[1]

1 SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, France
2 LKB, ENS, Université PSL, CNRS, Sorbonne Université, Collége de France, France
3 Embry-Riddle Aeronautical University, Arizona, USA
4 Carleton College, Minnesota, USA

Space-time symetries

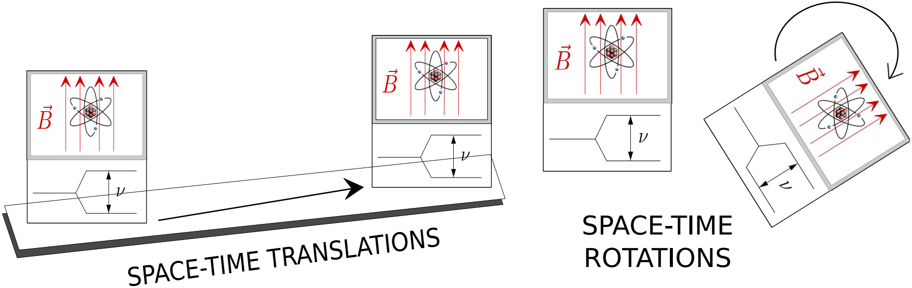


Homogeneous and isotropic space-time

Physical laws are the same:

- ◇ whatever you choose as spacetime coordinates → **observer invariance**
- ◇ whatever boost or orientation changes you realize in a given inertial frame → **particle invariance**

Space-time symetries



Homogeneous and isotropic space-time

Physical laws are the same:

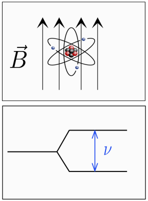
- whatever you choose as spacetime coordinates $\rightarrow$ **observer invariance**
- **whatever boost or orientation changes you realize in a given inertial frame $\rightarrow$ particle invariance**

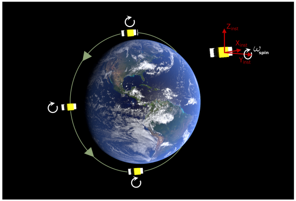
The Lorentz symmetry group

Local Lorentz Invariance Principle

The results of a non-gravitational experiment is independent of the boost and orientation changes encountered by the free-falling laboratory frame.

C. Will, 1993





Lorentz symmetry in physics

- ◇ General Relativity → directly related to space-time geometry
- ◇ Standard Model → affect the space-time in which particles interact

Lorentz symmetry in alternative theories

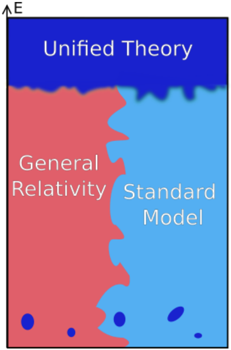
Some theories beyond General Relativity and Standard Model consider the possibility of Lorentz symmetry breaking at high energy (*e.g.* some string theories, Horava gravity...)

High energy effects (10^{19} GeV)

- Not accessible by experiments
- No low-energy experimental observable

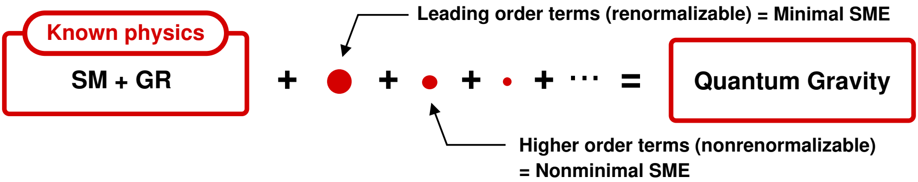
Solution: the Standard Model Extension (SME)

- Research of tiny low-energy signatures
- General theoretical framework: enable to derive obervables for a large range of experiments

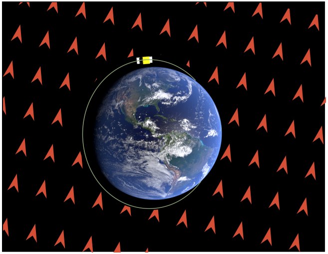


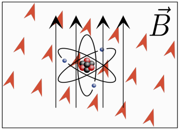
The Standard Model Extension

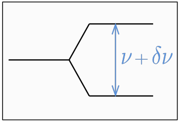
- Effective theory parametrizing all possible particle Lorentz violations
- Build from SM fields (fermions, photon, quark... sectors)
- Include violations arising from spacetime metric and curvature through a gravitational sector
- Amplitude of violations quantified by SME coefficients corresponding to components of SME tensors



The Standard Model Extension







- SME tensors are fixed in space and time and define a "preferred orientation" of space-time
- CONVENTION: SME coefficients expressed in Sun Centered Frame (inertiel over thousand of years)

Kostelecky et al., PRD 51, 1995, Kostelecky et al., PRD 58, 1998

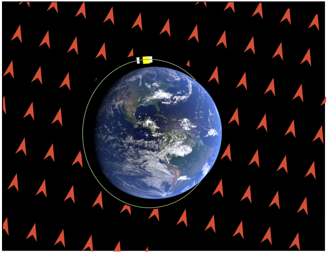
How to test Lorentz invariance

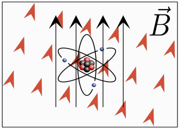
Requirements

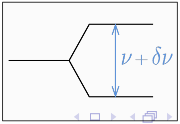
- Experiment with a preferred orientation
- Experiment with long term stability

Signals: shape and dependance

- Search of periodic signals related to the experiment orientation changes with respect to SME background fields
  - ◇ spatial orientation
  - ◇ boost $\beta = v/c$





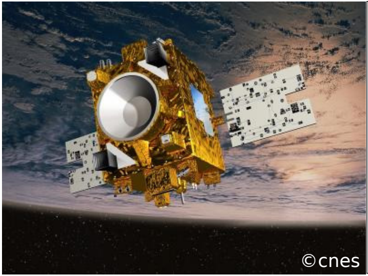


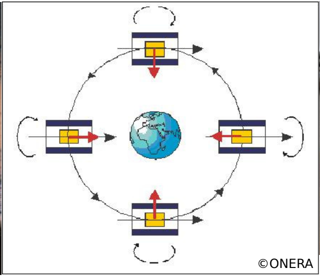
MICROSCOPE mission

Goal

Test of universality of free fall (UFF), with a precision of 10^{-15} on the Eötvös parameter δ.

$$\delta(A,B) \sim \frac{m_{g,1}}{m_{i,1}} - \frac{m_{g,2}}{m_{i,2}}$$





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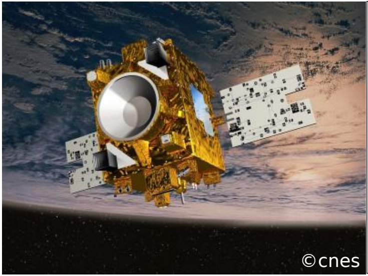
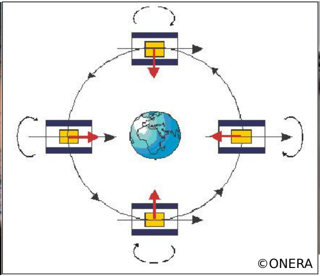
MICROSCOPE mission

Instrument and measurements

- Twin electrostatic accelerometer T-SAGE
- Measures the differential acceleration of two test masses (Ti/Pt) ou (Pt/Pt)





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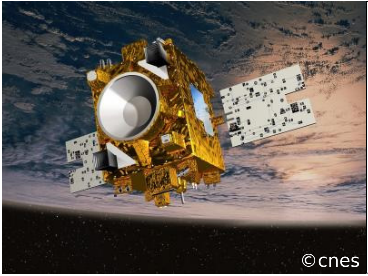
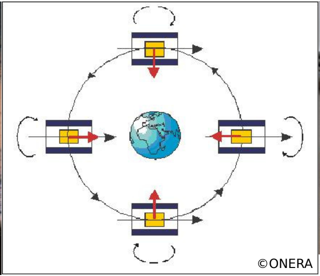
MICROSCOPE mission

Satellite

- Micro-satellite provided by CNES
- Sun-synchronous circular orbit (altitude $\sim$ 700 km)
- Launched in Avril 2016, de-orbiting ongoing





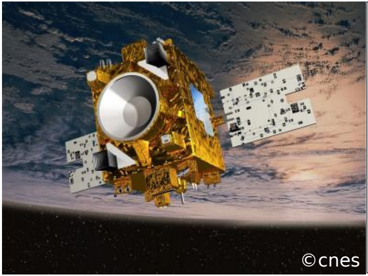
MICROSCOPE mission

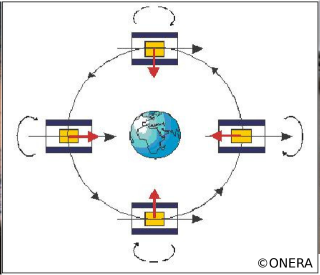
First results

Obtained by the analysis of 120 orbits:

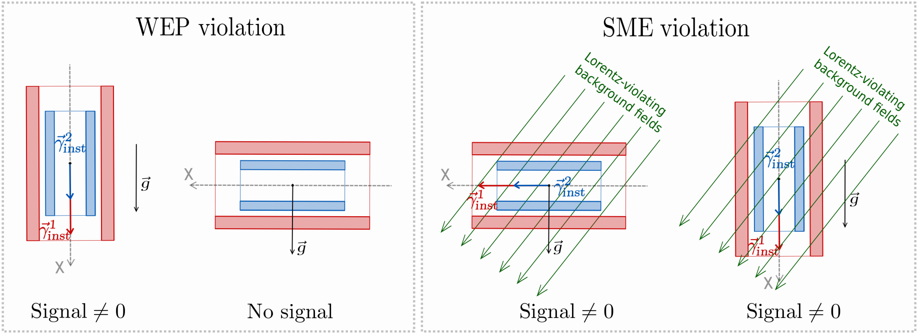
$$\delta = [-1 \pm 9\ \text{(stat)}\ \pm 9\ \text{(syst)}] \times 10^{-15}$$

Touboul ***et al.****, PRL, 119, 231101 (2017)*



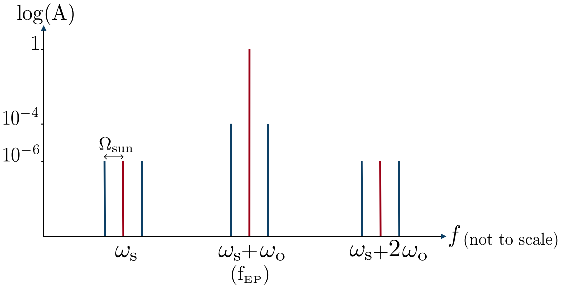


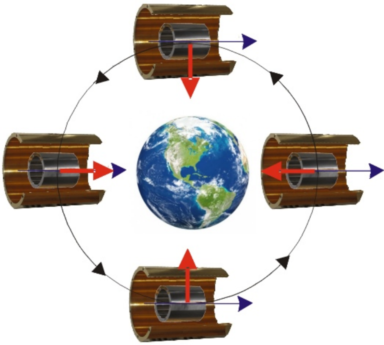
Relation between WEP and SME test



- Test in the sector of couplings between matter and gravitation. Constraints on $\alpha\,(\bar{a}_{\text{eff}})^{w}_{\mu}$ components.
- $\alpha\,(\bar{a}_{\text{eff}})^{w}_{\mu}$ quantifies a modification massive bodies trajectories depending on their respective composition.

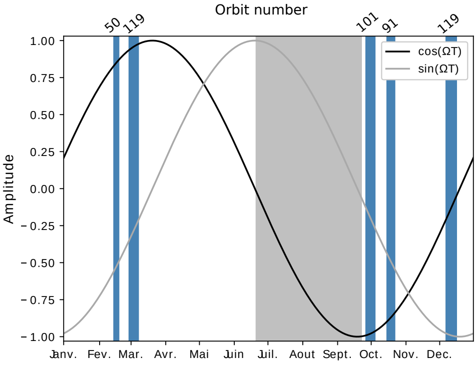
What sort of signals can we expect?



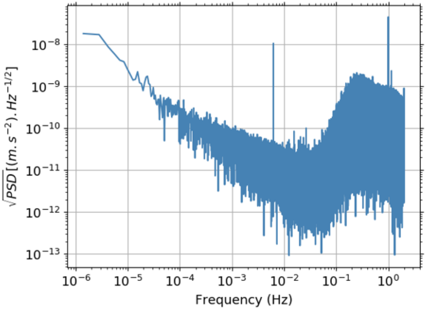


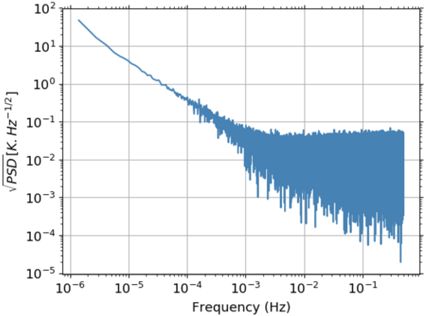
- Variation of the relative acceleration depending on the orientation of the sensitive axis
- Annual modulation due to the motion of the satellite with respect to the Sun.

Data used for the analysis



Temporal repartition of the data (durng year 2017)



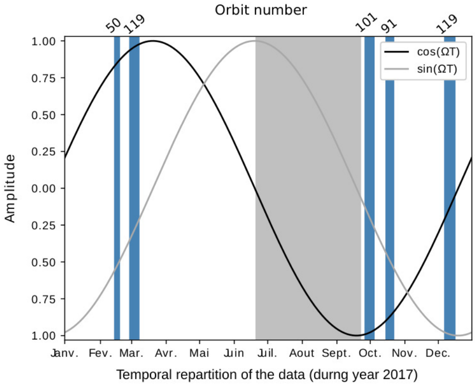


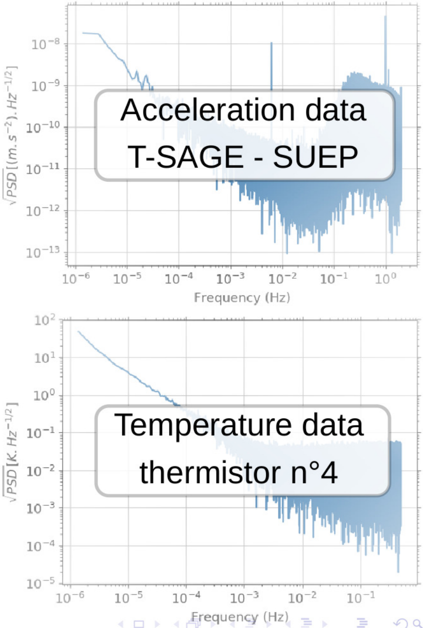
5 sessions - 480 orbits

30 days of cumulated data

gap $< 10^{-3}$ %

Data used for the analysis





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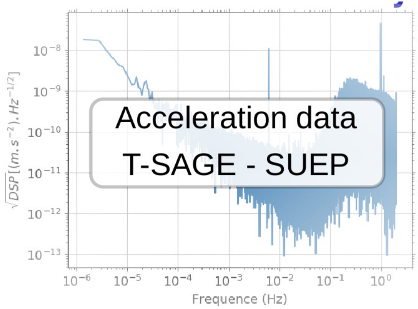
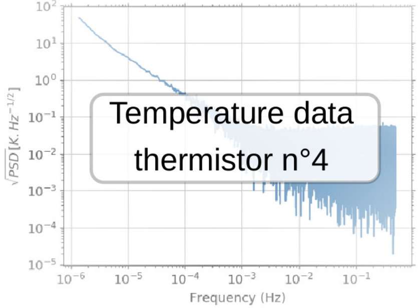
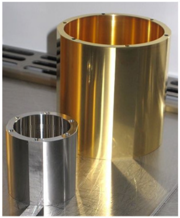




Titanum

Platinum



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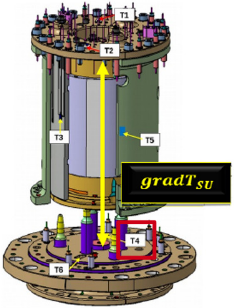

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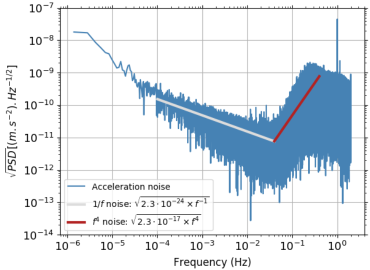
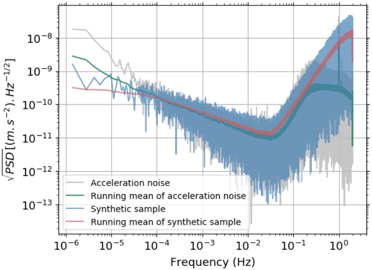
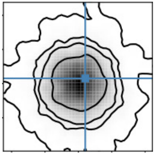
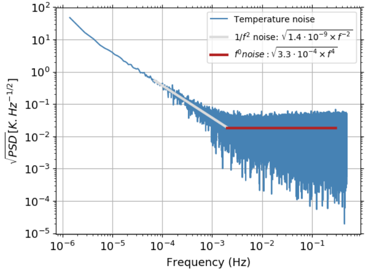
Analysis method: Least-squares Monte Carlo (LSMC) method

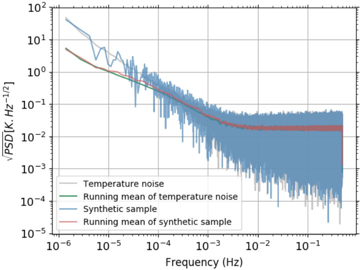




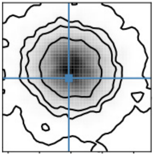
ACCÉLÉRATION



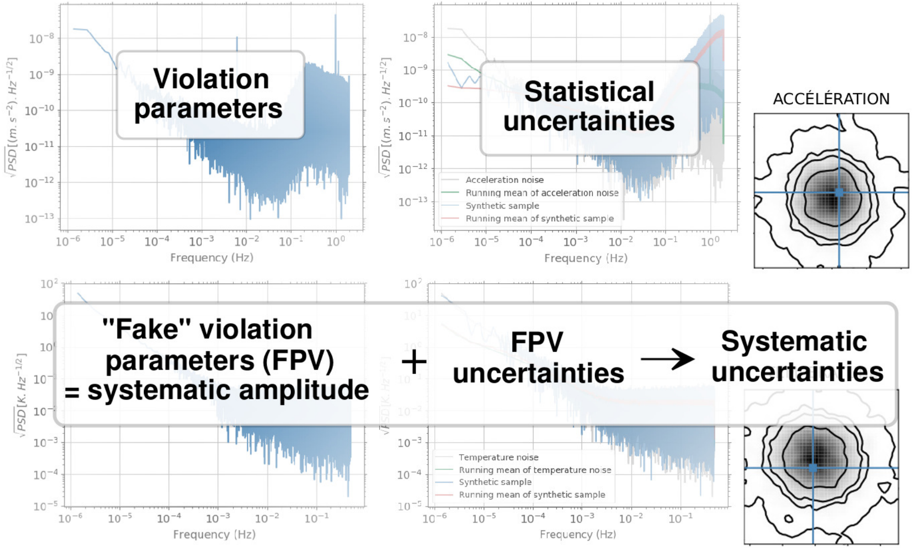




TEMPERATURE



Analysis method: Least-squares Monte Carlo (LSMC) method



Validation of the method

LSMC vs optimal General Least-squares (GLS)

- Similated test-data (1000 data points) with realistic noise
- LSMC performances ware about a factor 1.4 worse than GLS

WEP analysis with LSMC vs *Touboul et al., PRL, 119, 231101 (2017)*

- LSMC leads to conservative estimation of parameters bounds
- Overall factor 2 between LSMC and the analysis realized in Touboul2017

Parameter	Value and uncertainties		unit
	This analysis	Touboul 2017	
δ	$(-1.3 \pm 2.2 \pm 2.2) \times 10^{-14}$	$(-0.1 \pm 0.9 \pm 0.9) \times 10^{-14}$	–

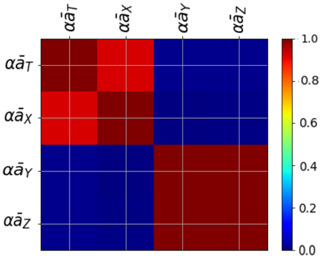
Room for improvement...

Résults of the SME combined analysis

$$\alpha(a^{(d)}_{\text{eff}})_\mu = A\,\alpha(a^{(n)}_{\text{eff}})_\mu + B\,\alpha(a^{(e+p)}_{\text{eff}})_\mu$$

with $A = 0.47\ \text{GeV}^{-1}$ and $B = 0.29\ \text{GeV}^{-1}$

Parameters	Value and uncertainties	Unit	Maximal sensitivities			Unit
			e	p	n	
$\alpha(a^{(d)}_{\text{eff}})_T$	$(0.4 \pm 1.5)(1.1)(1.0) \times 10^{-14}$	–	$10^{-13(\mathbf{2})}$	$10^{-13(\mathbf{2})}$	$10^{-13(\mathbf{2})}$	GeV
$\alpha(a^{(d)}_{\text{eff}})_X$	$(0.6 \pm 2.2)(1.3)(1.8) \times 10^{-10}$	–	$10^{-9(\mathbf{3})}$	$10^{-9(\mathbf{3})}$	$10^{-9(\mathbf{4})}$	GeV
$\alpha(a^{(d)}_{\text{eff}})_Y$	$(0.3 \pm 2.5)(1.1)(2.2) \times 10^{-8}$	–	$10^{-7(\mathbf{2})}$	$10^{-7(\mathbf{2})}$	$10^{-7(\mathbf{2})}$	GeV
$\alpha(a^{(d)}_{\text{eff}})_Z$	$(-0.7 \pm 5.8)(2.5)(5.2) \times 10^{-8}$	–	$10^{-6(\mathbf{1})}$	$10^{-6(\mathbf{1})}$	$10^{-7(\mathbf{2})}$	GeV



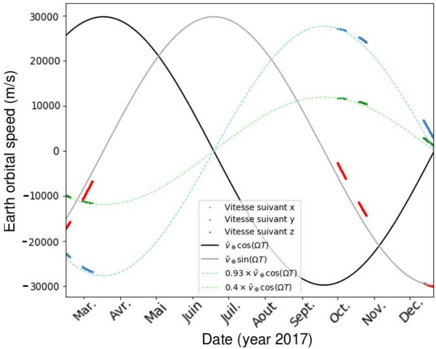
- Combined analysis of 5 sessions
- **No signatures of Lorentz violation detected**
- Improvement by 1 to 4 orders of magnitude on the limites of $\alpha\,(\bar{a}_{\text{eff}})^w_\mu$

This work has been carried out in collaboration with the teams of OCA and ONERA involved in the MICROSCOPE mission, in particular:

G. Métris (OCA), J. Bergé (ONERA) and M. Rodrigues (ONERA)

Thank you for your attention

Correlations in SME analysis



β_X ~ constant > T and X components correlated

β_Y & β_Z vary identically > Y and Z 100 % correlated

$$
\begin{aligned}
2\gamma^{(d)}_{app,\hat{x}} &= S_{\hat{x}\hat{x}}\boldsymbol{\Delta}_{\hat{x}} + \left(S_{\hat{x}\hat{y}} + \dot{\Omega}_z\right)\Delta_{\hat{y}} + \left(S_{\hat{x}\hat{z}} - \dot{\Omega}_y\right)\boldsymbol{\Delta}_{\hat{z}} \qquad (2.43)\\
&+ g_{\hat{x}}\left[2\alpha(\mathrm{a}^{(\mathrm{d})}_{\mathrm{eff}})_{\mathrm{T}} + \beta_{\mathrm{X}}2\alpha(\mathrm{a}^{(\mathrm{d})}_{\mathrm{eff}})_{\mathrm{X}} + \beta_{\mathrm{Y}}2\alpha(\mathrm{a}^{(\mathrm{d})}_{\mathrm{eff}})_{\mathrm{Y}} + \beta_{\mathrm{Z}}2\alpha(\mathrm{a}^{(\mathrm{d})}_{\mathrm{eff}})_{\mathrm{Z}}\right]\\
&- \frac{3Gm^{\mathrm{S}}R_{\oplus}^2}{5cr^5}\left(R_{\hat{x}\tilde{x}}\tilde{x}^{\mathrm{orb}} + R_{\hat{x}\tilde{y}}\tilde{y}^{\mathrm{orb}} + R_{\hat{x}\tilde{z}}\tilde{z}^{\mathrm{orb}}\right)\left(\tilde{x}^{\mathrm{orb}}2\alpha(\mathrm{a}^{(\mathrm{d})}_{\mathrm{eff}})_{\mathrm{Y}} - \tilde{y}^{\mathrm{orb}}2\alpha(\mathrm{a}^{(\mathrm{d})}_{\mathrm{eff}})_{\mathrm{X}}\right)\omega_{\tilde{z}}\\
&+ \frac{Gm^{\mathrm{S}}R_{\oplus}^2}{5cr^3}\left(2\alpha(\mathrm{a}^{(\mathrm{d})}_{\mathrm{eff}})_{\mathrm{Y}}R_{\hat{x}\tilde{x}} - 2\alpha(\mathrm{a}^{(\mathrm{d})}_{\mathrm{eff}})_{\mathrm{X}}R_{\hat{x}\tilde{y}}\right)\omega_{\tilde{z}}
\end{aligned}
$$

Mission data
INPOP
Estimated in our analysis