Exchange Visit Grant: Scientific Report

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1 Purpose of the visit

The Gaia mission will have major impacts on the science of Solar System Objects and on fundamental physics [Mignard et al., 2007]. Indeed Gaia will provide high precision orbits and dynamical model for several 100,000s asteroids, comets and a few satellites. From such orbits it is possible to derive parameters from a global dynamical modelling as it has been implemented within the Gaia DPAC consortium of data reduction and analysis. For instance, the Gaia data will allow to derive directly and simultaneously the PPN parameter β and the Solar quadrupole J_2 [Hestroffer et al., 2008, 2010]. Nevertheless other data that provide high accuracy astrometry can valuably complement the Gaia data set over longer period of time. This is true with Hipparcos data, and also with ground-based radar data that also provide tests of General Relativity [Margot and Giorgini, 2010].

One purpose of my visit at the IMCCE/Paris Observatory is to investigate the outcome of the scientific exploitation of the Gaia data in terms of tests of General Relativity. Another purpose of my visit is to validate the JAVA software developed in order to reduce astrometric observations of Solar System Objects (SSO). Finally, the extension of this code to include extended tests of General Relativity has been performed.

2 Description of the work carried out

2.1 Sensitivity study of different tests of General Relativity

To assess precisely the different possibility to test the gravitation theory with SSO, I developed a software dedicated to simulate diverse observations (GAIA astrometric observations but also radar observations). This software integrates the equations of motion of the different bodies and compute the astrometric and range observables. It also performs the inversion of the system by performing a least-square fit of the initial conditions of the bodies and of global parameters: Sun J_2, parameters characterizing alternative theories of gravitation, ...

Different terms have been included in this software:

- the quadrupolar momment of the Sun (J_2).

- the Sun Lense-Thirring effect.
- the β PPN parameter [Will, 1993].
- the η Nordtvedt parameter which characterizes a violation of the Strong Equivalence Principle [Nordtvedt, 1968].
- the λ, α parameters which characterize a fifth force deviation from the Newtonian potential [Adelberger et al., 2003].
- a temporal variation of the gravitational constant parametrized by $\dot{G}/G$.
- a periodical variation of the gravitational constant as proposed in Anderson et al. [2015]
- the $\bar{s}_{\mu\nu}$ parameters entering the Standard Model Extension – SME – formalism [Bailey and Kostelecký, 2006].

The corresponding additional accelerations have been included in the equation of motion but also in the variational equations needed in order to perform the least-square fit.

Realistic simulations of SSO observations by GAIA have been performed to assess the sensitivity of observations to the different parameters.

2.2 Completion of the Gaia data with additional observations

Completion of the Gaia data by other ground- or space-based high precision data, over a longer time span, should in principle be profitable. We have started to assess what is the expected improvement by combining Gaia astrometry of SSO to radar data acquired at Arecibo over the last decades (in collaboration with Jean-Luc Margot, UCLA, USA). Simulation of the ground-based data, and implementation of the partial derivatives for echo/ranging data in the global system has been performed. A variance analysis is currently being performed to assess the general improvement.

2.3 Validation of the JAVA software

JAVA codes partly developed at IMCCE within DPAC/DU451 and DU457 are available for both the simulations of the Gaia data (rendez-vous dates and precision) and the global inversion and orbit reconstruction (through numerical integration of the equations of motion, partial derivatives, and least-squares inversion). The JAVA software has been carefully validated by comparing results of the integration with an independent software I developed. The equations of motion have been validated, the variational equations as well as the determination of the measure function.

Besides, the execution time of the software has been drastically improved.

3 Main results obtained

Concerning the sensitivity study of Gaia observations to test the gravitation theory, we have shown that:

- the Sun quadrupolar moment J_2 can be estimated with an accuracy of 10^{-7}.
- the β PPN parameter can be estimated with an accuracy of 7×10^{-4}.
- the η parameter can be estimated with an accuracy of 9×10^{-4}.
- using the relation between η and β (i.e. $\eta = 4\beta - \gamma - 3$) helps to decorrelate the β and J_2 estimates and leads to an improvement of the β estimation to 2×10^{-4}.
- the Lense-Thirring effect is too small to be detected. Nevertheless, not including it in the modeling of the data reduction leads to a bias in the estimation of J_2 of the order of 10^{-8} and a bias in the estimation of β of the order of 5×10^{-5}. A similar conclusion holds for planetary ephemerides.
- the sensitivity on the α, λ parameters from the fifth force formalism is represented by the red curve on Fig. 1.
- a linear variation of the gravitational constant will be constrained at the level of 10^{-12} yr^{-1}.
- a periodic variation of the gravitational constant will be detected and constrained at the (relative) level of 10^{-5}.
- Gaia observations will allow to constrain all the pure gravity SME constants $\bar{s}^{\mu\nu}$. The expected sensitivity on the SME parameters is presented in Table 1. This corresponds to an improvement of around one order of magnitude with respect to existing constraint [Kostelecký and Russell, 2011].

SME Parameter	sensitivity (σ)
$\bar{s}^{XX} - \bar{s}^{YY}$	9×10^{-12}
$\bar{s}^{XX} + \bar{s}^{YY} - \bar{s}^{ZZ}$	2×10^{-11}
$\bar{s}^{XY}$	4×10^{-12}
$\bar{s}^{XZ}$	2×10^{-12}
$\bar{s}^{YZ}$	4×10^{-12}
$\bar{s}^{TX}$	1×10^{-8}
$\bar{s}^{TY}$	2×10^{-8}
$\bar{s}^{TZ}$	4×10^{-8}

Table 1: Expected accuracy on the SME parameters.

The expected improvement provided by additional ground based data is still under study.

On the other hand, several corrections have been applied to the JAVA software developed to reduce GAIA observations. The execution time has also been drastically improved.

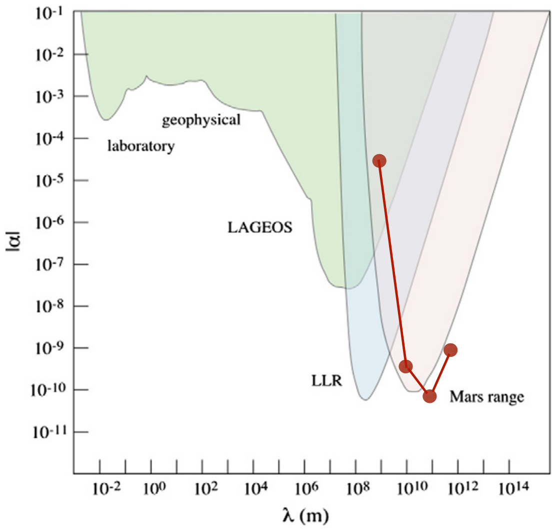

Figure 1: Current constraint on the fifth force formalism (figure from Konopliv et al. [2011]) and in red: estimated sensitivity using Gaia observations

4 Future collaboration with host institution

First of all, at least one paper summarizing all the results obtained during this GREAT exchange will be written. In addition, the collaboration that has started during this exchange is very likely to be pursued in the future. The alternative model of gravitation mentioned in the previous sections will be implemented in the JAVA software used to reduce GAIA observations. This will be done in close collaboration between the IMCCE and myself. The expertise developed during this exchange will also be useful during the data reduction.

In addition, the impact of the inclusion of ground-based data is still under investigation. This project will be pursued in the future in collaboration with the IMCCE but also with J.L. Margot from UCLA, USA. In a very long term, a combined data analysis of both types of data would be highly interesting.

In conclusion, it is very likely that the collaboration initiated with this GREAT exchange will be pursued in the future.

5 Expected publications

The results obtained during this exchange have been presented during the SF2A conference in Toulouse (June 2 2015). The corresponding conference proceedings will contain a summary of the obtained results. A detailed publication of the obtained results will also be written in the near future.

In a longer term, we expect to publish a second paper concerning the possibility of a join analysis of GAIA and UCLA data.

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