9.4 Orbital and Rotational Dynamics as constraints on planetary bodies

A. Context and state of the art

In the frame of the very accurate study of planetary dynamics (INPOP planetary ephemerides), the role of the knowledge of the interior of planets is crucial. As it was demonstrated in [1] and in [2], the constraints on the possible location of the ninth planet in the solar system or on possible violations of general relativity strongly rely on radio science data. In the other hand, the radio science data are deeply related to our knowledge of the interior of planets and natural satellites. This latest can be reached by indirect observations such as the static gravity field and its variation in space, the moment of inertia, the tidal effect on an orbiter, and the precession, nutations or librations of the planetary spin axis. These informations can be obtained through geodesic experiments from radio tracking of flying by, orbiting or landed s/c or by observing directly the rotational motion of bodies. The gravitational interaction of the planets and moons with the close and/or massive celestial bodies perturbs their rotation generating variations of the rotation period (librations in longitude and the associated length-of-day changes) and modifying the orientation of the rotation axis with respect to a given point on the planet's surface (polar motion) and in space (libration in latitude and precession/nutation). In addition, the presence of fluid layers at the surface (atmosphere, hydrosphere, and ocean) and/or at the planetary interior (such as a liquid core) varies the amplitude response of rotational variations. The aim of this project is to improve our modelization of planet and satellite rotation by including more complete interior structure model in order to improve the dynamical modeling of the bodies.

B. Current activity

Since 2006, INPOP has become an international reference for space navigation and for scientific research in dynamics of the solar system objects and in fundamental physics. With ESA provided VEX and MEX data, use of LLR observations and the development of new ephemeris models and new adjustments for the planets and the Moon, INPOP10a [3] have established INPOP at the forefront of global planetary ephemerides. This version is the official Gaia planetary ephemeris used for the Gaia navigation as well as for the scientific exploitation of the mission. The member of the project team are also involved in the preparation of Bepi-Colombo and JUICE missions. Planetary ephemerides are used as a very efficient tool for several scientific applications : from solar physics and asteroid mass determination [3], tests of general relativity [1,4] to the localisation of the nith planet in the solar system [2]. INPOP gives the most accurate constraints for PPN parameters, but also for MOND alternative theory of gravity [5]. Planetary ephemerides largely depend on the range bias observations deduced from space missions (56%) and this will increase with the continuous addition of s/c and lander data (Opportunity etc...). In 2013, the members of the project have analysed raw radio science data of the mission MESSENGER leading to the construction of a new planetary ephemerides INPOP13a and new constraints for general relativity. Very recently, [2] have used the Cassini radio science implemented in the construction of the planetary ephemerides INPOP15a for constraining the localisation the ninth planet of the solar system.

The rotational motion of the Moon is measured at the milli-second levels thanks to the LLR measurement of the round-trip travel time between an observatory on the Earth and one of the five corner cube retroreflector arrays on the Moon. The LLR data processing is a very sophisticated and challenging task with 180 parameters involved in the INPOP solution. The unprecedented accuracy in modeling the Moon's Dynamics at the centimeter and milli-arcsecond level is the result of recent developments in the laser station (Grasse, Apache point) and in the data processing. With data span over more than 30 years, the analysis of LLR data provides complementary informations to GRAIL results on the lunar interior and solid-body tides [6], indicating that the lunar core is liquid [7] which has been confirmed by seismological studies. In addition, the lunar rotational variations have strong sensitivity to moments of inertia and gravity field. The contributions to observations from tidal variations are sensitive to the interior structure of the Moon, its physical properties, and the energy dissipation inside the Moon are now at detectable level. As an example of the sensitivity of the LLR observations to the Moon dynamical model, one can see on Figure 1 the DE430 residuals for 7 nights and stations, and for different reflectors. The noticeable offsets between reflectors can be compensate by empirical corrections of the Moon orientation model. This indicates an obvious lack in the present Moon rotation model even in including gravity field coefficients deduced from the GRAIL mission.

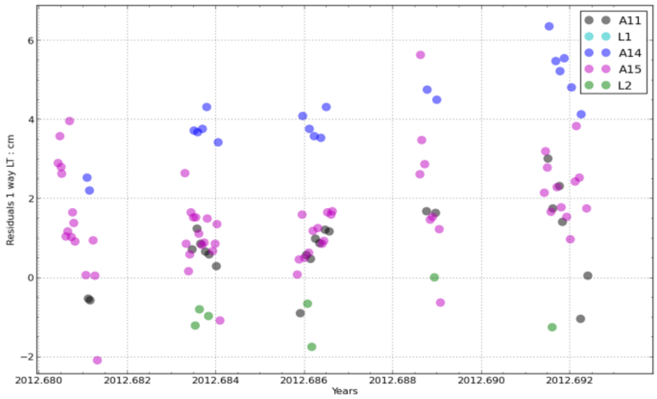

Figure 1: LLR one-way residuals in cm obtained with DE430 versus time. The offset for each reflector is a well known effect of the lacks in the moon internal structure modelisation

The altimeter measurments can be converted to both gridded and spherical harmonic models for the topography and shape of the planet (Mars, Moon, etc.). They generally have vertical and radial accuracies of around 1 m with respect to the planet's center of mass. This level is suitable for geophysical, geological, and also atmospheric circulation studies. As an example, the LOLA altimetric observations have been used to improve the lunar geodetic grid to around 10 m radial and ~100 m spatial accuracy with respect to the Moon' s center of mass. But measurement precision degrades due to surface roughness and off-nadir pointing of the orbiting spacecraft.
The precision of individual altimeter measurements collected so far is ~12 cm on flat surfaces. By combining the 1-way range to ground points with the reconstructed orbit of the spacecraft, the radius of the planet can be calculated. Topography is thus determined by subtracting a sphere of given radius (e.g. 1737.4 km for the Moon) from each radius measurement.
Errors in the gravity field model used in the computation of spacecraft orbits cause geographically correlated errors in spacecraft position that cannot be removed by including additional tracking data. Such errors have been observed for Earth-orbiting spacecraft as well as for MGS. Orbital crossover analysis is a method for using altimetry as an observation type for non topographic purposes. Crossovers are locations on the surface of a planet where the groundtrack of an orbit crosses over a previous track. At these locations a measure of the radius of the planet is obtainable from both orbits. The crossover observations are sensitive to orbital errors and can therefore be used as an observation of the spacecraft radial position in the orbit determination process. Thus crossovers can be combined with the Doppler tracking of the spacecraft to improve knowledge of the orbit and laser beam pointing angle and, simultaneously, to estimate changes in the topography or shape of the planet due to seasonal mass redistribution between the polar caps and atmosphere, tides, and other effects. Experience of the Astrogeo team with the use of crossovers in satellite geodesy includes Earth-orbiting radar altimeter satellites, such as TOPEX and Jason. Crossovers have been used for the first time on a planetary spacecraft for MGS and have resulted in demonstrated improvements in radial, along-track, and across-track orbit components.
Based on earth experiments (GRACE, GOCE, CHAMP, etc…), the use of an accelerometer on board of a s/c was a key element for transporting the geodesy and geophysics as the XXIth century. Crucial discoveries were obtained thanks to these missions.
Proposals are regularly made for installing the CHAMP type accelerometers on board of planetary missions (ODYSSEY, Uranus Pathfinder). However because of constraints on the localization of the accelerometer at the barycenter of the platform, these propositions were

never really considered despite the significant increase of the science case due to the accurate measurements of non-gravitational accelerations which can be done by such instrumentation. As it was described in [8] the use of an accelerometer will bring better constraints on the non-gravitational accelerations over the s/c orbiting and fly-bying the planet, and will then reduce the uncertainties on the s/c orbit reconstruction leading to J2 determination during far away flybys (Uranus case). The members of the project are directly involved in the most challenging space accelerometry mission over the past ten years : MICROSCOPE. The MICROSCOPE experiment is an attempt to test the Equivalence principle with a resolution of 10^{-15} by measuring the relative acceleration of two masses of different composition in free motion in a drag compensated satellite, in orbit in the Earth's gravitational field. This experiment requires measuring accelerations less than a femto-g, a particularly stable on-board environment and an extremely thorough analysis of perturbations in orbit.

C. Future steps

1. The terrestrial planets

In the coming years, the Exomars and the Insight missions will provide new lander data from the Mars surface and the ESA Bepi-Colombo mission will reach Mercury. These two types of mission are very promising tools for improving the planetary dynamics together with better constraining the internal structure of these two bodies. The data of communication between landers and orbiters are some interesting measures for the study of the dynamics of Mars since they allow to constrain the rotation of the planet on the one hand and measure the lander - orbiter - land distances on the other hand. But the constraints on planetary rotation allow to have access to the overall internal structure of Mars. Especially INSIGHT mission that will be launched in 2018 plans to ship the instruments of seismic measurements to direct studies of the rheology of Mars and a band radio transponder X (RISE experience) that will improve the link lander / orbiter .
The project is to associate the expected improvements on our knowledge of Mars internal structure obtained with the seismologic measurements (see section 3.3) with a new modeling of its rotation based on the analysis of the radio data in X-band between the lander and the orbiter.
The modeling of the internal structure of the planet and its rotation are essential to be able to include radio data landers in the global construction of the Mars orbit. By using the radio science data from ExoMars and INSIGHT into the INPOP construction, one expects:
i) the improvement of the orbit of Mars. Our knowledge of the Mars orbit is currently limited by the perturbations induced by main belt asteroids. Any improvement in the Mars orbit will directly impact our knowledge about asteroid masses perturbing the planet. ii) The second consequence is then the improvement of the asteroid mass determination that are deduced from their perturbations of the Mars orbit. Because of their non-negligible perturbations over the Mars orbits, about 200 asteroids have their masses obtained during the construction of planetary ephemerides such as INPOP. In 2019, Gaia will also obtain accurate masses for the biggest asteroids of the main belt. By using these Gaia masses inside the INPOP planetary ephemerides adjusted to ExoMars and INSIGHT radio science data, it will be then possible determine masses for smaller objects. Furthermore with the release of the Gaia stellar catalogue, it will become easier to observe stellar occultations solar system objects and then to determine asteroid radii (see the section "Ground based observations of small bodies"). In combining INPOP mass determinations with Gaia stellar occultations, about several hundreds of asteroid densities will then estimated with great accuracy constraining strongly formation models.
The member of this project are also member of the Bepi-Colombo SWG. They are involved in the analysis of the radio-science data for the improvement of the s/c orbit determination and then the gravity field determination. A specific activity has been started by the members of this project for increasing the science return of the mission with the use of Bepi-Colombo radio science data in the INPOP planetary ephemerides. As it was demonstrated in [4], the use of Bepi-Colombo range data will push forward the limit of possible violation of general relativity by a factor 10 in the frame of the global dynamics in the solar system. Such limit will make dilaton-

type theories detectable (i.e. [9]). In the other hand, for achieving such an accuracy, a developed model of internal structure of Mercury is required for assessing a highly precise orbit. To obtain a factor 10 improvement for the RG tests, one required an accuracy of 2 cm on the orbit [4]. The usage of inner structure modellings for Mercury and Mars issued from the work of the C4PO project called “Internal structure of Terrestrial planets (Insight, BepiColombo, Juice) ” will be crucial for the aims of this project when simultaneously, the orbit analysis of Bepi-Colombo and Mars orbiters proposed in this project will be important constraints for the developments proposed in section “Internal structure of Terrestrial planets”.
We also propose in this project to apply the technics of crossovers altimetry for i) the improvements of s/c determination and then for planetary orbit computation ii) a better estimation of topography to be combined with determination proposed in section 3.4 in the frame of solar system exploration. The construction of a reduction pipeline can be set up in using MGS altimeter (MOLA) data which are already avalaible. Seasonal and loadings effects can then be measured with the altimeter measurements.

2. The Earth-Moon system

In this project, we propose to work on the combination of GRAIL results with the long-term data of LLR produced by GéoAzur at the Calern facility. The aim here is double : first to estimate the dissipation coefficient Q2 of the Moon and of the Earth. These parameters will give us indication about the cooling rate of the two bodies and the secular evolution of their internal structure. Second, to make equivalence principal test in using the Moon and the Earth as test-mass falling freely into the sun direction. Up to now, the accuracy of such a test is limited by our lack of modelisation of the Moon internal structure as illustrated in figure 1. Furthermore, the crossover method can be applied to the LOLA measurements obtained by the LRO mission in order to improve LRO orbit reconstruction. As LRO was equipped with a retroreflector, the Grasse station was able to laser track the mission for several years. The combination of LRO laser tracking data and the LLR data is a unique opportunity to tie reference frames but the accuracy of the altimetry is mandatory for obtaining a convincing accuracy [10].

3. The outer planet satellites

As co-Pi experience of radio science 3GM on board of the ESA JUICE mission, the member of the project actively participate in the preparation of the mission in collaboration with the PI team from the University of La Sapienza in Rome. This included a joint project of iterative simulations for the determination of Ganymede gravity field, the orbital parameters of the probe and the barycentric orbit of Jupiter. As it has been indeed experimented during the Cassini mission, uncertainties in the orbit of Saturn induce very significant bias on the determinations of the long-period coefficients of the potential of the planet and satellites.
A combined improvement of the s/c orbit together with the barycenter of the planetary system orbit is then required for obtaining consistent estimations of long periodic gravity field coefficients. The current uncertainty in the orbit of Jupiter is still greater than that of Saturn's orbit when the Cassini mission, it is reasonable to think that the same problem will arise for JUICE in the Galilean system. Therefore, we initiate with our colleagues from Rome simulations to develop a pipeline of adjustment within the JUICE mission. Simulations based on the analysis of Cassini data during its flybys phases of Titan and Enceladus are also planned. The aim of this work is to set up a pipeline for combining simultaneously the improvement of the s/c dynamics and of the planetary system in its whole thanks to the implementation of Cassini range data in the INPOP construction. In this context, the development of an accurate and global dynamical modeling of the Saturnian and Jovian systems is planed for starting next September. This development will be done inside the INPOP planetary ephemerides in order to ensure consistency between the dynamics of the barycenter of the satellite system and the satellite orbits themselves. Adjustments to the Cassini data are also planned giving then an unique opportunity to constraint new internal structure model for Titan and Enceladus.

The crossover method can also be simulated in the case of Ganymede observations by the JUICE altimeter. GALA. In this case, the simulations would include seasonal and loadings effects.

4. New accelerometry concept for planetary missions

In this project we propose to make realistic simulations in order to identify specifications in terms of accuracy, precision but also constraints for the mission and the platform in the frame of a possible mission to either an asteroid or a terrestrial planet (Venus) or an outer planet (Uranus). This analysis could then be used by industrial partners for the commissioning of the new generation of accelerometers and for being ready to reply to the new ESA/NASA calls of missions.

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D. International collaborations

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F. Most significant publications of the team

[1]Fienga, A., Laskar, J., Manche, H., Gastineau, M. Constraints on P9 localization, A&A (2016)
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Short CV of participants

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Mark Wieczorek (CNRS Director of Research, laboratory Lagrange) Expert in using geophysical data to decipher the interior structure and geologic evolution of the terrestrial planets. Co-PI on NASA's lunar gravity mapping mission GRAIL, NASA's martian geophysical station InSight, and the laser altimeters on ESA BepiColombo and JUICE missions. Former editor-in-chief of the *Journal of Geophysical Research Planets*, and has published over 66 papers and book chapters.

M. Delbo CNRS research scientist, expert of the physical characterisation of asteroids, ground- and space-based astronomical observations, modelling, and laboratory experiments on meteorites and other asteroid analogs. CoI of space missions: ESA's Gaia (with responsibility of asteroid spectroscopy) and NASA's asteroid sample return OSIRIS-REx mission (with responsibility of asteroid thermal mod- elling). Author of 80 reviewed publications.

P. Exertier, CNRS research director. Expert of satellite dynamics, altimetry and time transfer by laser. Director of the Astrogeo team (SLR / LLR station). 50 referred publications.

A. Mémin, Associate professor. Expert in using space-based geodetic observations to understand the spatio-temporal Earth's response to geophysical processes. Co-chair of the IAG-IERS joint working group on modelling environmental loading effects for Reference Frame realizations, 8 referred publications.

P. Tanga, Astronomer . Chevalier de l'Ordre des Palmes Academiques. Leader of the Solar System data processing for the Gaia mission (ESA). Expertise on physical properties of asteroids, planetary atmospheres and their investigation by transit/occultations (WP manager in the EuroVenus FP7 project). Polarimetry, spectroscopy, astrometry of Solar System objects. Co-manager of the MP3C data base for physical properties of asteroids. 73 refereed publications.