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European Satellite PArtnership for Computing Ephemerides

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Final Report Summary - ESPACE (European Satellite PArtnership for Computing Ephemerides)

Executive Summary:
The activity of ESPaCE (European Satellite PArtnership for Computing Ephemerides) project aims at strengthening the collaborative activities in the domain of the development of ephemerides and reference systems for natural satellites and spacecraft. For this program, teams from seven European institutions have joined their efforts: Paris Observatory- Institut de Mécanique Céleste et de Calcul des Ephémérides (OBSPAR-IMCCE), Royal Observatory of Belgium (ROB), Technische Universität Berlin (TUB), Joint Institute for VLBI in Europe (JIVE), Deutsches Zentrum für Luft- und Raumfahrt (DLR), Centre National d'Etudes Spatiales (CNES), Technical University of Delft (TUD).
All these institutes convened to get benefits from their mutual expertise in order to reach a better knowledge of the dynamics and physics of natural satellites and of spacecraft motions. This program started in June 2011 for a 4-year duration. Twelve work packages have been defined in order to ensure efficient work progress. One particular work package has been introduced for searching and using space and ground-based data useful for astrometric purpose through digitizing of ancient photographic plates and through using space imaging and radioscience data from several space missions. The astrometric imaging data have been archived in a new database: Natural Satellite Data Base (NSDB). This work ensured the evolution toward new highly accurate ephemerides of Martian, Jovian, Saturnian and Uranian satellites by combining the fit of new dynamical models to ground-based and space data. New satellite and spacecraft orbits could be computed and delivered under the format of SPICE kernels.
Besides, this project succeeded to provide new planetary maps, reference systems, gravity models, and rotation models. It allowed us to estimate the performance of the new implementations of VLBI (called PRIDE – Planetary Radio Interferometry and Doppler Experiment) and Laser Ranging techniques for precise positioning of spacecraft. All the results and documents have been progressively made available using standard formats (VO standard, SPICE kernels) for the use by space agencies, planetary scientists, or the public.

Project Context and Objectives:
This project aimed at strengthening the collaborative activities in the domain of the development of ephemerides and reference systems for natural satellites and spacecraft.

Planetary satellites are central to the understanding of the Solar System and its dynamics. Planetary satellites include among others the Earth's Moon, the Martian moons Phobos and Deimos, as well as the numerous (>40) members of the satellite systems of Jupiter and Saturn. Orbits and dynamics of the satellites are particularly complex due to resonances and strong tidal interactions with their parent planets. Complementary exploration of data acquired by spacecraft has been highlighted by discovery of tidally driven volcanic activity of Io, cryogenic activity of Enceladus, or the existence of a probable ocean inside Europa.

Though the study of planetary satellites has a long history, further exploration and analysis of all available data allows us to get a better understanding of physical phenomena and of the dynamic processes that have been discovered. We can enhance our capacity to explore and understand their physical structure, their origin, and their evolution. In order to achieve this goal, linking celestial mechanics, dynamics and astrometry is a powerful strategy. The dynamics modelling of the natural satellites and the orbit analysis of the space probes, combined with high precision observations, allow us to probe the interiors of these celestial bodies from the determination of their gravity field and their tidal dissipation coefficients. Future missions towards planetary satellites (such as the JUICE mission) are currently under study within ESA's Cosmic Vision program.

While studies of planetary geodesy and dynamics in the United States benefit from the coordinated support from several powerful space research facilities, such as NASA's JPL (Jet Propulsion Laboratory) or NASA's GSFC (Goddard Space Flight Center), the relevant activities and the expertise in Europe are scattered over ESA (European Space Agency), several national research institutions, and universities. Our proposal intended to bring together the expertise of seven main European research centers involved in these domains and to initiate a European expertise network in planetary dynamics which could subsequently collaborate on other planetary projects.

Like many aspects of science, spacecraft navigation and satellite ephemerides require accurate observations to constrain the dynamic model based on them. Today, ephemerides achieve a great accuracy. For instance, in the Martian case, we can predict the position of spacecraft and natural satellites up to few meters and few kilometers, respectively.

Owing to the accurate data available, we can use the related dynamic models to constrain the physical parameters of the studied objects at the highest level, while more and more challenging technological experiences can be invoked (flyby of moons at very close distances, orbital maneuver, mission scenarios, etc.). In view of the already accomplished steps in space exploration field, the synergy between space agencies and ephemeris institutes at a much higher level will be a key point to fulfil the challenges of the upcoming decade.

Regarding the observational data applicable to the dynamics modeling, we must emphasize the increasing impact of the radio science. Radio range and Doppler measurements of the Viking landers were made between 1976 and 1983. Unfortunately most of the Viking lander Doppler data have since been lost, since it was in the extended mission and not considered a primary science data type. Viking also pre-dated the current Planetary Data System (PDS). Two years of the Viking Doppler data were recovered from navigation team tapes, and archived along with the Mars Pathfinder radio tracking data set. Though used for construction of ephemerides, the precision of these data was the precision of the S-band with significant perturbation from the plasma effect. The situation changed significantly with the Mars Pathfinder lander in 1997.

While radio tracking was conducted over 90 days only, the Pathfinder radio system allowed much more accurate measurements, since the radio signal at frequency used (X-band, ~8 GHz) was much less affected by propagation effects in the solar plasma than the S-band (2 GHz) signal used by Viking. Accurate radio tracking of Mars orbiters has been performed nearly continuously since Mars Global Surveyor arrived to Mars in 1997, followed by Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter. This rich data set has been used continuously since then to improve the Martian ephemerides.

The use of the Very Long Baseline Interferometry (VLBI) for support of planetary missions was developed more than thirty years ago and has been used in missions requiring ultimate accuracy of a posteriori trajectory determination . In particular, VLBI was used for measurements of the lunar rotation dynamics and winds on Venus . JIVE led the world-wide effort in VLBI tracking of the Huygens Probe during its descent in the atmosphere of Titan and several hours after the touch-down . Additional input from VLBI tracking of the Huygens probe to one of the Huygens experiments, the Doppler Wind Experiment (DWE) has been provided. The outcome of Huygens VLBI tracking exceeded expectations . The VLBI tracking experiment resulted in the descent trajectory reconstruction with the accuracy of the order of 1 km. A detailed description of the Huygens VLBI Tracking Experiment is presented in several articles . The Huygens VLBI tracking experiment triggered developments of software tools incorporating the so-called VLBI Theoretical Delay (VTD) models based on the ultimately accurate astrometric and dynamic models of the Solar System in the General Relativity approximation. This tool has been widely used for the studies proposed here.

All the former works are benefiting from observations of several types which cover today a large time span and involve huge file sizes. Hence, it necessitates the realization and maintenance of important databases. In principle such databases should be fed by a permanent flux of data coming from spacecraft missions and ground-based observation surveys. Unfortunately, high priority is most of the time given to the original purpose the instruments or surveys were intended for. It entails that many important scientific data are not present in the proper databases, simply because the extraction of the data has not been done or published.

The objectives of the ESPaCE project are the following :

- to improve the efficiency of the spacecraft-satellites expertise,
- to revive the value of old data,
- to enhance the radio science for precise planetary positioning,
- to develop reference systems on some natural satellites for improving the exploitation of the space imaging for astrometry,
- to enhance the application of the VLBI technique and the Laser Ranging technique for the planetary and spacecraft positioning,
- to give access to astrometric data, spacecraft orbit kernels, moons orbit kernels,
- to provide new ephemerides of the main natural satellites.

Project Results:
Our consortium deals with the extraction and analysis of astrometric data related to natural satellites and to spacecraft and with their use for providing ephemerides.

We have proceeded with digitization of a very large set of photographic plates of satellite systems of Mars, Jupiter, Saturn, thanks to the accurate machine, DAMIAN digitizer, installed at the Royal Observatory of Belgium. Numerous plates of Martian satellites, Phobos and Deimos, and of the Saturnian satellites from US naval Observatory, and partly from the South Africa Yale station have been digitized. These data led to accurate astrometric measurements. Other types of ground-based observation, the mutual events (eclipses and occultations of satellites one by each other) of the Jovian, Saturnian, and Uranian systems of satellites, have been collected and studied. On the other hand, spacecraft-based images usable for astrometry of Martian satellites, not yet applied to dynamic solutions, have been studied. While not in the original proposal, astrometric reduction of thousands of ISS-Cassini images, involving the eight main moons of Saturn, have been considered, as well. On the basis of these digitized photographic plates and space imaging, a wide astrometric data base, NSDB, has been set up. Its interface uses standard format and is operating through the ESPaCE web site. These data, together with radio science data, have been used for providing new ephemerides of the Martian, Saturnian, and Uranian satellites in the SPICE kernel format which are now under implementation in the on-line IMCCE ephemerides.

The use of space data can be improved by a better knowledge of the spacecraft orbits and a work package of the ESPaCE project was dedicated to the Radio science. It allowed us to study spacecraft orbits and to provide in particular Mars Express orbit kernels from 2004 to 2011. Such space data are combined with ground-based astrometry in order to improve constraints on the dynamics and the physics of the objects. Viking-1 and MEX tracking data have been used for a new estimation of the mass of Phobos.

Besides, the consortium also investigated new implementation of VLBI (PRIDE) and Laser Ranging (LR) techniques for precise positioning of spacecraft. Through four reports, the performances of the interplanetary Laser ranging method have been estimated. Software developments have been completed. The application to the Lunar Reconnaissance Orbiter has been performed and the progress done makes us now capable of estimating orbits comparable in quality to those from Goddard Space Flight Center (GSFC) from Doppler and altimetry data. Three research subprojects have been set up: analysis of atmospheric turbulence on the accuracy and precision of the laser ranging measurements; comparison of one- and two-way interplanetary ranging systems; coupling between proper time rate uncertainty and space segment state uncertainty.

The VLBI/PRIDE (Planetary Radio Interferometry and Doppler Experiment) tracking method intends to provide the residuals of spacecraft tracking data with respect to an a priori given state vectors of the spacecraft. Reports on VLBI algorithms and VLBI-SPC state vectors have been provided. Applications to operational space science missions, such as RadioAstron, Gaia (tests only), Venus Express (VEX) and Mars Express (MEX) have been done. The PRIDE approach was successfully applied by using a huge follow-up network of the MEX spacecraft including 31 worldwide radio astronomy stations during the Phobos flyby on 2013 December 29th, with the goal to improve the Phobos ephemerides and to determine its gravity field.

The ESPaCE project succeeded also to deliver data related to coordinates and reference systems. In this domain, three reports on a Phobos control point network and gravity model, on Lunar control point network and map, on control point network of icy satellites of Jupiter and Saturn, have been provided.

The consortium management and the dissemination of data have required them to provide specific actions and tools. For this goal we have set up and maintained a web site, including education pages, at http://espace.oma.be/ from which the main outcomes of ESPaCE are accessible.

Further information upon the process and the results is given hereafter.

4.1.3.1 Digitized data

A specific work package of the ESPaCE project concerns the Digitized data (digitized images of photographic plates and their metadata). It benefits from the ROB digitization facility DAMIAN (Digital Access to Metric Images Archives Network).
Main objectives
In most observatories, large numbers of photographic plates are available, which have not been analyzed by modern computer techniques. Data Digitization aims at identifying and obtaining appropriate plates, digitizing these plates, and encoding the required meta-data.
ROB with the help of the Belgian Federal Science Policy Office has created a digitization facility for providing digital access to the historic-scientific information contained in photographic archives (see Figure 1). This project was performed in close collaboration with the experts in digitizing astronomical plates at the US Naval Observatory in Washington DC, USA (USNO). ROB had also foreseen in the frame of the ESPaCE project to convert the associated metadata into a digital form and making the results usable for scientific research through the modern techniques of the information society. This applies in particular to the historic collections of photographic plates of the natural satellites of mainly Mars, Jupiter and Saturn, and some of the other planets,

Figure 1: The ROB Digitizer machine.
Digitization
・ A selected glass plate is put in an aluminum plate-holder tray with a central opening and surrounding niche corresponding to the plate sizes. The plate trays are automatically loaded one after the other from the magazine by the plate exchanger/rotator robot into the air-bearing XY-table. The emulsion side of the glass plate is clamped-up against a counter-pressure plate with same central opening as the plate tray. The photographic image is automatically focused at the mean focal distance (Z position) of the plate center and four surrounding positions on the plate. If these individual focal distances differ too much from each other, an error message is generated. The plate is then digitized in a automated step (5mm) and stare (at rest) mode with the appropriate intensity pre-setting of the LED transmission illumination. The raw format 2.5MB full size footprint images (9mm x 7mm; 1280 x 1024 - 7µm x7µm pixels) are archived on a pre-configured HD under a unique plate identifier name and the digitization meta-data are encoded in the raw footprint file header. The footprint filenames and associated meta-data are also stored in a database.
・ The plate pre-scans are made available in tiff format under a file name corresponding to the plate

identifier name.
・ The scanned envelopes and observing logs are made available in pdf format under a file name corresponding to the plate identifier name.
・ The meta-data related to a specific plate are grouped together with their corresponding plate identifier name in the form of a spreadsheet and/or a database.
・ The footprint images are converted to fits format, with the needed meta-data information in their fits header, under a file name containing the plate identifier name, a sequence number and an orientation identification (0 or 1) if digitized in two different orientations at 0° and 180° rotated.
・ The averaged Dark and Flat images in fits format and the parameter values of the correction model for the optical distortion of the objective/detector unit of the digitizer in an ascii file.
・ A full plate digital copy of the negative photographic image in fits file format is also constructed as a mosaic image from the 5mm x 5mm (704 x 704 pixels, ~1MB) non-overlapping Flat and Dark corrected central parts of the individual footprint images under a file name containing the plate identifier name and an orientation identification (0 or 1) if digitized in two different orientations at 0° and 180° rotated.
・ If available, also the calibration plates for the telescope distortion (Pleiades plates or so) are digitized and delivered in fits format under a file name corresponding to the plate identifier name.
・ These digital images and meta-data are delivered on HD drives and/or on a private ftp server. The individual footprint fits files are not flat- and dark-corrected, but are a raw digital copy of the densities of the negative photographic image. If the plates contain sensitometer spots these are also digitized and allow to also create a calibrated positive intensity image if needed.

Main science and technical results
DAMIAN, the ROB 2D-digitiser facility of high geometric and radiometric accuracy and repeatability was used to digitize 2323 old photographic plates of the natural satellites of Mars (521 plates), Jupiter (714 plates of the Galilean moons (Io, Europa, Ganymede and Callisto) of which also 18 of Amalthea the fifth Jupiter moon) and Saturn (1048 plates) and a few plates of the moons of Uranus (24 plates) and Neptune (12 plates) and some of Pluto (4 plates).
These are available as fits files (both footprints and mosaics). The scanned metadata sources are available as pdf or tiff files; the meta-data have been encoded in Excel spreadsheets.

4.1.3.2 Radio science data

Goals
The aim of the radio science work package is to gather radio-tracking data of spacecraft having performed or performing astrometric measurements of the moons targeted in the ESPaCE project (i.e. moons of Mars, Jupiter, Saturn and Uranus). In addition to radio-tracking data, ancillary data are required in order to determine precise orbit of those spacecraft. These ancillary data are: (i) the attitude of each steerable part of the spacecraft, bus, solar arrays, or antenna (as quaternion datasets), (ii) the surface area of each plate of the spacecraft as well as their optical properties (reflectivity and absorptivity coefficients), (iii) the shift between the centre of phase of the spacecraft antenna and the centre of mass of the spacecraft, (iv) the mass history, (v) the range delay of the radio-transponder on-board the spacecraft, (vi) the epoch and the a priori amplitude of the acceleration generated by each uncoupled attitude maneuver (i.e. Angular Momentum Desaturation or Wheel Off Loading of the spacecraft inertial wheels).
For old missions (i.e. before 1997) the radio-tracking data, when available, are in a data format that is

poorly documented and the ancillary data are sparse. This is the case of the Mariner-9, Viking 1 & 2, and the Phobos-2 Martian spacecraft, as well as of the Galileo Jovian spacecraft and of the Voyager-2 Uranian spacecraft.
A fundamental tool for the exploitation of the radio science data is the GINS software for orbit computing. This software is developed by CNES and further adapted at ROB for planetary geodesy applications.

Main science and technical results

Collaboration with Mars Express teams and with the Jet Propulsion Laboratory (JPL) has been established.
Exploiting data from old missions may be difficult due in particular to the ancient data format which can be impossible to interpret without specific information; it was the case for the Galileo and the Voyager missions. From the JPL we have obtained the Galileo and the Voyager tracking data in a usable data format. This data format, called Tracking Data Message (TDM), is well documented and will be the new standard for the future archiving of any tracking dataset. A new interface for the GINS input data has been written and the Galileo TDM dataset is just being validated using orbit computation with GINS. Preliminary results show long periodic signal in the Doppler post-fit residual, which is under investigation and implies continuing interaction with JPL.

Orbits of Mars Express have been computed for several years 2004 to 2011. SPICE kernels have been computed and made publicly available on the NASA Navigation and Ancillary Information Facility (NAIF) and on the ESPaCE website.

Besides, a specific event occurring on 2013 December 29, the close flyby of the Martian moon Phobos by Mars Express, at 40 km above the surface, has been observed with different techniques with the goal to determine gravitational characteristics of this moon: space imagery before and after the event, radio science positioning during the event, VLBI measurements from a ground-based network during the event. SPICE kernels of MEX orbits for space imagery have been added.

The deep station tracking data have been collected through the Mars express Radio-science experiment (MaRS) group in Cologne. It consists of about 32 hours of quasi-continuous usual Doppler and ranging tracking of MEX in X (8.4 GHz) and S (2.3 GHz) bands performed by the ESA Tracking stations (ESTRACK) and the NASA Tracking stations belonging to the Deep Space Network (DSN). In parallel, the Planetary Radio-Interferometry and Doppler Experiment (PRIDE) data have been collected through the Joint Institute for Very Large Base Interferometry in Europe (JIVE). It consists of 31 antennas belonging either or to the VLBI network or to some arrays of radio-astronomy antennas like the Very Large Base Antennas (VLBA) in the USA. All these antennas have received the signal sent by the deep space stations and sent back to Earth by MEX through its radio-transponder, when visible in the sky of the station. The Doppler, or phase variations of the carrier frequency over 1 second count time, has been recorded at these 31 stations. These stations have also recorded differences in arrival times between the radio-signal coming from Mars Express and the ones coming from sky reference sources (i.e. quasars) previously identified. The cross-correlation of these radio-signals is on-going and will provide corrections of the position of the spacecraft in the celestial sphere w.r.t. position derived from the navigation orbit provided by the European Space Operations Center (ESOC) of ESA. These corrections of MEX position will then be used in GINS in order to improve the orbit determination of MEX around the flyby event.

The Radio science work package has been able to provide contributions to the ephemerides work package of the ESPaCE project in the following fields:
• Improvement of the Phobos mass from older Viking and MEX flyby data,
• Estimate of the gravitational parameters of Phobos from the 2013 Mars Express flyby.

4.1.3.3 Laser ranging

As a demonstration for the potential added value of laser ranging on planetary missions, an analysis was performed of the performance of a Phobos Laser Ranging mission for estimating geophysical parameters of Mars and Phobos. Our results show that a strong potential improvement could be obtained in the uncertainties of Martian tidal Love number and quality factor estimation, as well as Phobos moments of inertia and deformation. Covariance analysis was employed to determine the influence of both random and systematic errors. Systematic range measurement errors were shown to be of much stronger influence than random noise. Since systematic errors in laser ranging will, in general, be relatively more influential than for Doppler tracking, such errors must be taken into account in simulation studies and should be developed to greater detail. Also, it is shown that a combination with complementary data types from different mission architectures will be required to make full use of the highly accurate laser range measurements. Specifically, we find for the Phobos lander mission the uncertainties in Phobos' shape model limit the physical interpretation of the estimated Martian libration and gravity field coefficients. The work on the Phobos lander simulations has been published in Planetary and Space Science .
We performed an analysis of the influence of atmospheric turbulence on the accuracy and precision of the laser ranging measurements. Up to until now, the only turbulence-induced contribution that was typically included in laser ranging error budgets was the stochastic time-of-flight variations. In the context of optical communications, however, the signal strength variations at the space segment due to near-field turbulence at the ground station have been investigated in detail. We have applied these models to an interplanetary laser link, mapping the turbulence-induced signal strength variations to accuracy and precision variations of the observations. We find that measurement quality degradations (in both precision and accuracy) at the several (1-5) mm level can occur for a representative interplanetary laser ranging mission. This influence can be nearly fully mitigated by the use of a single-photon signal strength detection system, although at the expense of reduced normal point precision. The article in which this work is described was accepted for publication by Advances in Space Research .
Furthermore, we compared the performance of one- and two-way interplanetary laser ranging systems. This was done by means of numerical simulations where the influence of clock noise on both the one- and two-way range measurements was included by generating realizations from the clock error Allan variance descriptions. We subsequently included the estimation of clock parameters in the estimation from simulated one-way data. We performed estimations from simulated one- and two-way data for both a lunar orbiter and a Phobos lander. Our simulations, which represent the first detailed comparison of one- and two-way laser ranging systems, indicate that although a two-way system will be clearly superior in terms of potential science return, limitations in associated models for data analysis may (largely) mitigate this advantage, as measurement accuracy is no longer necessarily the dominant source of error in the final products. Specifically, we found that the uncertainties in the space segment dynamical model limit the quality of the estimated orbit of the lunar orbiter. For the Phobos lander, we again found the uncertainty in

Phobos' shape to be a limiting factor in interpreting the Phobos geodetic parameter interpretation. Our results have been published in Planetary and Space Science .

Additionally, we investigated in detail a very specific aspect of the data analysis of laser ranging data that may become relevant in future missions. Specifically, we analyzed the coupling between proper time rate uncertainty and estimated space segment state uncertainty. Since clock calibration is typically performed in an a priori manner, errors in the a priori parameter estimates will spill over into this clock calibration and consequently in the reduction of time transfer or one-way range data. This effect was shown to be small for time transfer to Low Earth Orbit (LEO) by previous research (not performed by ESPaCE partners), but has not been investigated in a general sense. We have developed a general analysis framework for this issue, allowing its influence to be clearly assessed for arbitrary mission configurations. In our approach, we have developed a manner in which to treat the initial proper time of an observer on equal footing with its initial translational state, extending the variational equations used in orbit determination to include an estimation of this initial proper time. We have applied this model to the analysis of planetary (Mars and Mercury) lander missions. Our results show that although the coupled estimation may not be required for a reasonable assessment of the estimated parameter error budget, the situation will likely be different for orbiters, for which the orbital dynamics reconstruction is less stable due to large non-conservative forces. Nevertheless, we find that the clock calibration should be recomputed after each iteration of the least squares estimation to prevent large errors in the analysis of one-way data. Our work has been documented in a manuscript that is presently under review by Classical and Quantum Gravity. The applicability of our work is not limited to laser ranging systems, but may be extended for a consistent relativistic treatment of the analyses of other data types, such as radio Doppler.

The only operational implementation of interplanetary laser ranging has been in a one-way system on the lunar orbiter LRO. To gain experience with the analysis of such data and demonstrate its potential in planetary missions, this one-way data has been processed and analyzed, culminating in laser-only orbit determination of the spacecraft. A preliminary orbit determination of LRO performed by us was achieved at the end of the second reporting period, but a variety of effects and limitations prevented our estimated orbits from converging to similar quality of the orbits produced by Goddard Space Flight Center (GSFC) from Doppler and altimetry data. It was concluded that when using only single station passes, clock parameters can only be decoupled from state parameters for long clock parameter arcs, resulting in orbit residuals that are inferior to those obtained by Doppler tracking. We have largely mitigated these issues in the third reporting period by modifying the settings of the estimation, most notably by estimating clock parameters over a period of about 1 day, and we are now capable of estimating orbits comparable in quality to those from GSFC. We have quantified in much detail the influence of the length of the state and clock arcs of the estimation, as well as added the estimation of empirical acceleration parameters and the use of a priori information. We have assessed the quality of our orbits in two manners. Firstly, we have quantified the arc overlap error during two subsequent orbit estimation arcs. Secondly, we have compared our orbits in the absolute sense to those produced at GSFC. Both analyses result in rms differences at the 10-20 meters, when selecting suitable settings on clock and state arc length, empirical acceleration settings, etc. Our results on the orbit determination of LRO have been documented in ESPaCE deliverable 3.4. Manuscripts for journal publication are currently in preparation detailing both the data analysis and orbit determination work.

One of the primary tasks the Laser Ranging work package during the first segment of the ESPaCE project concerned the development of software to both simulate and process laser ranging measurements for analyzing the performance of existing (LRO) and future missions using laser ranging at planetary distances. The software development required for this work package was successfully completed and documented in project deliverables. Software development has been performed in the Tudat software suite, an open source software developed in-house at TUD. The development focused on the development and implementation of highly modular environment, dynamics and observation models in the context of orbit determination from real and simulated data. Due to the highly precise nature of laser ranging measurements, the software now supports variable precision (i.e. single, double, extended precision). An estimation procedure using simulated data from data of a two-way Earth-Mars laser link has shown convergence to the sub-micron accuracy level when using equal truth and estimation models. This shows the internal consistency and numerical applicability of the software at levels beyond what is expected from laser ranging. Furthermore, the software comes with ~200 unit tests, each of which test the functionality of a specific piece of the code and may be run in series upon code modifications to verify that no existing functionality has been compromised.

4.1.3.4 VLBI data
Goal

The objective of this work package is to provide the residuals of spacecraft tracking data with respect to an a priori given state vectors of the spacecraft using the European and Global VLBI network observations, data processing and analysis.

Main science and technical results

As the entire ESPaCE project, originally (by the time of the contract signing in March 2011), this work was supposed to be conducted primarily with the Russia-led Phobos-Soil mission, specifically, during its “near-Phobos” phase that was to start in the middle of 2012. Accordingly, the time-table of this work package implementation has been designed to provide optimal support to the Phobos-Soil mission.
The results of its activities would then provide direct feed-in into the major deliverable of the entire project related to the determination of satellite (Phobos in this case) ephemerides. In turn, the improved ephemerides would be used for estimating geodynamical parameters of the Martian system. The work package is to produce two deliverables:
• VLBI algorithms
• VLBI-SPC state vectors
After the failure of the Phobos-Soil mission immediately after its launch in November 2011, the implementation of this work package has been re-oriented toward ESPaCE-compatible applications on other planetary and other space science missions. The emphasis was made on developing generalized VLBI tools (not specific for Phobos-Soil only). In particular, ahead of schedule, a significant fraction of the deliverable VLBI algorithms on near-field VLBI tracking has been presented in a publication . Throughout the remaining part of the ESPaCE project, the algorithms described in that paper have been applied to operational space science missions, such as RadioAstron, Gaia (tests only), Venus Express (VEX) and Mars Express (MEX). These four missions have very different science objectives and differ significantly in their technical parameters (trajectories, characteristics of the radio signal) relevant for VLBI tracking. Only the MEX mission is suitable to address in a rather limited way the original science and methodology tasks of ESPaCE VLBI work package. Nevertheless, during the 3rd ESPaCE reporting period, a number of developments insured fulfilment of the original tasks. The following works have been performed:

➢ Installation, verification and tests of the VLBI near-field theoretical delay calculation software (VTD-NF) based on the models developed for the Huygens VLBI tracking experiment has been amended and verified on more than a hundred of observations of the ESA's VEX spacecraft, as well as on other targets (Herschel, RadioAstron, Gaia and MEX). The algorithms, developed and verified in the framework of this activity have been described and their further development presented in a recent article , including specific implementations for the closest VLBI tracking target, RadioAstron, and in another article including the implementation on the VLBI Correlator SFXC at JIVE

➢ Verification and tests of the on-purpose developed ultra-high spectral resolution correlator software for VLBI correlation have been implemented on the SFXC correlator at JIVE. This task has been completed in full in the beginning of the last ESPaCE reporting period, ahead of the ESPaCE schedule and published . This part of the VLBI work package has enabled a scientifically valuable by-product, a new diagnostics tool for the turbulence of the interplanetary plasma.

➢ Scheduling and performing VLBI observations of several operational spacecraft. This task was the main focus of the VLBI work package implementation during the third reporting period. More than 115 observing sessions on VEX, Herschel, MEX, Gaia and RadioAstron have been conducted during the second and third reporting periods. In the absence of Phobos-Soil and following the recommendation of the second ESPaCE Review Report, the work package activity has been re-oriented toward providing direct contribution of VLBI measurements to the main ESPaCE study goal (determination of satellite ephemerides). The work has culminated in December 2013 by VLBI observations of the MEX-Phobos flyby (global VLBI experiment GR035, PI P. Rosenblatt, ROB, Belgium). The experiment involved 36 radio telescopes worldwide. Data processing of the GR035 observations have been conducted in accordance with the basic approach of the Planetary Radio Interferometry and Doppler Experiment. The Doppler data extraction from GR035 has been completed, the results passed on to the analysis using the GINS software. Cross-correlation of the GR035 data has been conducted for selected baselines and scans.

➢ Also, in the framework of the former item, a continued VLBI tracking campaign of the ESA's Venus Express (VEX) mission enabled the ESPaCE collaboration to evaluate PRIDE data for orbit determination of planetary orbiters. The result of this work is published in one refereed article . The paper contains methodology of evaluation of phase instabilities due to a propagation of spacecraft radio signal through the inhomogeneous interplanetary plasma. Another paper is in preparation and will address the evaluation of the VEX orbit determination efforts during the VEX atmosphere drag campaign of April-May 2013. Materials of both papers will serve as feed-in into the future PRIDE experiments with planetary orbiters.

4.1.3.5 Astrometry

Goal

The goal of the astrometry work package is to make accurate positional measurements of satellites, generally by analyzing images obtained from ground or space and by referring to positions of catalogued the stars in the field of view. But in a specific case, astrometric measurements can also be issued from the timing of events, the mutual events, photometrically observed.

Main science and technical results

In this project, we could perform a large number of astrometric measurements using the method of the stellar astrometry. We got astrometric measurements from a large number of digitized photographic plates:

Observatory Objects Images number References

USNO Washington DC Martian satellites 893 images A&A 2014 vol.572,A104
USNO Washington DC Jovian satellites 1417 images MNRAS 2011 vol.415 p.701
USNO Washington DC Saturnian satellites 1289 images D6.2
USNO Flagstaff Martian satellites 893 images A&A 2014 vol.572,A104

Some early CCD observations could also be analysed:

Observatory Objects Images number References
USNO Flagstaff Saturnian inner satellites 40 images A&A in preparation
ESO VLT Uranian inner satellites 18 images A&A in preparation

The observation of mutual events (occultation or eclipse of a satellite by another) has also provided a large number of astrometric positions.

Occurrence Planetary system Event number References
Uranus 2007 Uranian satellites 34 events A&A 2013 vol.557 A4
Saturn 2009 Saturnian satellites 26 events A&A 2012 vol.544 A29
Jupiter 2009 Jovian satellites 457 events A&A 2014 vol.572,A120

Space imagery allowed also us to get many accurate satellite positions. In particular, From April 2008 to August 2011 MEX performed 74 flybys of Phobos. Altogether, 155 images were used to determine the positions of the satellite’s center of figure (COF). This time, COF measurements were carried out based on the shape model and control network of Phobos . The estimated uncertainties of our observations are ranging between 0.2 to 3.4 km. Mean astrometric residuals of our observations relating to the orbit models from the Royal Observatory of Belgium (MarsSatV1_0) and the Jet Propulsion Laboratory (MAR085) reach up to 335m.

We also performed astrometry of the Saturnian satellites observed during the Cassini mission. We provided 5463 astrometric positions in right ascension and declination of the satellites: Tethys, Dione, Rhea, Iapetus, and Phoebe, using images that were taken by Cassini NAC between 2004 and 2012. The mean residuals compared to the JPL ephemeris SAT365 are of the order of hundreds of meters with standard deviations of the order of a few kilometers. The frequency analysis of the residuals shows the remaining non-modelled effects of satellites on the dynamics of other satellites.

4.1.3.6 Coordinates and reference systems
Goal
A work package was dedicated to the determination of the shape and the gravity model of the Martian moon Phobos, of reference systems of the Moon and icy satellites, and to the development of rotation models of some satellites.

Main science and technical results

Shape model of Phobos

A new reference shape model of Phobos was finalized and made available in various formats. A global digital terrain model (DTM) was derived applying photogrammetric techniques and using images of the High Resolution Stereo Camera (HRSC) flying on board the European Mars Express Mission (MEX). Significant improvement was made due to additional data available from close MEX approaches past a first publication . Especially the southern hemisphere is now much better constrained due to these additional data than in previous shape models. Several thousand points of this analysis were extracted and used to derive a spherical harmonic function model to degree and order 45. This model shows enough detail to even apply it during ortho-rectification and mapping purposes. The resulting shape models were also used to compute working models of the dynamic environment of Phobos. These working models are already applied e.g. for landing site analysis or studies of surface features like landslides of craters .

Realization of the Phobos coordinate system

A new global control point network was derived for Phobos, based on SRC (Mars Express), Phobos-2, and Viking Orbiter image data. We derived 3-D Cartesian coordinates for 813 control points as well as improved pointing data for 202 SRC and Viking images in the Phobos-fixed coordinate system. The point accuracies vary from 4.5 m on the Phobos nearside, to up to 67.0 m on the farside, where we relied on Viking images (average point accuracy: 13.7 m). Histograms of the data points hint at the shape of Phobos. From tracking of the control points we detect a librational motion synchronous to the Phobos orbital period and measure a libration amplitude of 1.09°, in agreement with predictions from shape information assuming a uniform interior. This suggests that the interior of Phobos is homogeneous – but small local mass anomalies, e.g. associated with crater Stickney, cannot be ruled out. Our new control point network has a higher number of data points and a higher point accuracy than previous data products, represents an critical realization of the Phobos coordinate system and will be an important basis for accurate shape models and maps .

Realization of the Lunar coordinates

Digital terrain models (DTM) are derived for most of the Apollo landing sites. To achieve this goal TUB has developed additional software producing detailed local terrain models and the associated ortho-rectified image data as well as a co-registration tool to bring these data into correct reference to the currently accepted global lunar reference frame. The latter is realized by the Lunar Orbiter Laser Altimeter (LOLA) data set. A LOLA DTM, corrected by co-registration techniques has been accomplished for the Lunar South Polar regions, which has been used for studies of illumination conditions .

Co-registration of the data was validated by comparing known Lunar Ranging Retro-Reflector (LRRR) positions with the observed coordinates in the derived data. Agreement in the order of +/- 2m between known LRRR position and observations was achieved. Several instruments in the near vicinity of the Apollo landing points can be recognized in the derived co-registered orbital image maps and thus provide additional accurate control points for the lunar control point network. The analysis of EVA station has extensively advanced for the Apollo 17 landing site. Here the majority of the astronauts traverse tracks could be reconstructed based on the LRO LRO observations in combination with the astronauts photographs . This is seen as example also for other landing sites due to the labor intensity needed to complete the work. Astronaut photographs have to be identified by means of visual control such that analysis of Apollo 15 landing side has only begun but is not finished yet. The derived image mosaics can be used to extend the DTM coverage around the landing site areas – depending on availability of image data in this region.

Reference shape of icy satellites
Based on theoretical work following the theory of Zharkov we have calculated the expected shapes of the satellites of Saturn and Jupiter for tidal and rotational equilibrium. These calculations were used as a reference for an independent data-analysis, in particular by deriving control-point networks from spacecraft imaging data. In some cases (e.g. Ganymede we also used theoretical predictions to constrain the inversion of the imaging data. In a few cases only theoretical studies could be done due to the lack of sufficient data to improve current models (e.g. Callisto) or due to the lack of improvement of trajectories. Originally we had planned to use updated spacecraft trajectories for the analysis of imaging data. However, improved trajectories were not available for this work-package in the given time-frame and therefore the standard trajectories implemented by JPL SPICE kernels had to be used.
Due to the selection of the JUICE mission (Jupiter Icy Moons Explorer) by ESA we have done a detailed analysis for Ganymede the main target of the JUICE mission. We have also derived new control-point networks for Saturn's satellites Mimas and Enceladus and for Jupiter's moon Io. In case of Europa no significant improvement as compared to a former analysis could be achieved due to the lack of new data and updated trajectories. In case of Callisto the expected deviations from the spherical shape were too small to be detectable with the given data. For these satellites we have obtained only theoretical predictions.

Figure 2. Phobos shape and gravity field models

Realization of icy satellite coordinate systems
The determination of control-point networks from imaging data is essential for the realization of coordinate systems and provides a basis for accurate shape determination. The basic technique of bundle block adjustments has been described recently .We have derived new control-point networks for Jupiter's satellites Io and Ganymede and for Saturn's satellites Mimas and Enceladus. In the given time-frame we could not carry out such detailed analyses for the other satellites. One reason is the lack of updated trajectories from Cassini and Galileo. The other reason is a focus on the satellite Ganymede which is the main target of ESA's JUICE mission. For Mimas, Enceladus and for Ganymede we have also carried out a detailed analysis of the rotational states of these bodies. From imaging data we have derived constraints for the libration amplitudes which have not been measured before for these satellites . The control point networks (here derived for Io, Ganymede, Mimas and Enceladus) provide a convenient first-order realization for the reference frame and coordinate definitions on the satellites.
Theory of the rotation of natural satellites
Within this task the determination of the libration amplitudes is essential. Physical librations are small periodic deviations in the mean spin-rate of a satellite caused by tidal torques from the central planet or by perturbations from other satellites and planets. The short period physical librations due to tidal torques from the planet depend on the interior structure of the satellite and are therefore important measurement constraints, e.g. for the existence of liquid layers in icy moons. The amplitude of the long period physical librations are also important because their amplitudes could be large and have to be introduce in the reduction analysis. We have carried out detailed studies for Phobos, Ganymede, Enceladus and Mimas. The rotational models of Ganymede and Enceladus have been realized before the ESPaCE project . For Ganymede we could demonstrate that the control point method is sensitive to such a librational motion in principle, but subject to limitations in the quality of our image data set.
Results for Mimas have been published . The obtained libration amplitude on the diurnal cycle is about 50

arcmin. This amplitude depends mainly on Mimas' internal structure and has an observed value of twice the predicted one, assuming hydrostatic equilibrium. After considering various possible interior models of Mimas, we argue that the satellite has either a non-hydrostatic interior, or a hydrostatic one with an internal ocean beneath a thick icy shell (see also http://ec.europa.eu/programmes/horizon2020/en/news/saturn%E2%80%99s-moon-mimas-could-be-hiding-underground-ocean)
The Enceladus model has been corrected of phases with respect to the 2010 model. Preliminary results for Enceladus indicate that the amplitudes on the frequency of the forcing by the 2:1 resonance with Dione can easily be detected. One interpretation of the amplitudes obtained on the diurnal cycle suggests that only the outer ice shell is undergoing librations, indicating a de-coupling of the outer ice layer from the deep interior. A possible explanation would be a global subsurface ocean on Enceladus.
The librations of Phobos have been studied in details in order to assess if its interior is homogenous or not. The main librations and the librations close to the proper frequencies are the most sensitive to the interior structure. This rotational model given in SPICE kernel format has been used in studies of Phobos .

4.1.3.7 Satellite ephemerides
Goal
The aim of this work package is twofold: (i) gathering astrometric data of natural satellites with a dynamical model of the orbits to provide accurate ephemerides; (ii) gathering normal matrices associated with both spacecraft and to perform a global inversion. Outputs of this WP are ephemerides of the moons with high accuracy as well as improvement of the spacecraft orbits after global inversion.

Main science and technical results

The Saturn system
Several thousands of astrometric images of the visible camera ISS on board of the Cassini spacecraft were astrometrically reduced. Moreover, several hundreds of photographic plates were digitized and reduced. Such new accurate and numerous data sets required to improve the modelling of the Saturnian system gravity field and tidal parameters. This was done. An extensive set of observations covering the end of the XIXth century up to the early XXIth century (ISS data) was considered. Numerous physical parameters were released in the fit including: the initial state vectors of all moons, the masses of all main moons, the orientation of the pole and the precession of the primary, and the tidal parameters within Saturn. Besides the eight main moons, six other moons were considered: Epimetheus, Janus, Telesto, Calypso, Helene and Polydeuces. Ephemerides for all these moons were finally successfully obtained. We succeeded for the first time to separate the tidal Love number of Saturn k2 from the tidal dissipation factor Q. This provides strong constraints for improving the modelling of the interior of Saturn, with consequences for the exoplanetary systems.
The Mars Express (MEX) flyby of Phobos (29th December 2013)
Following an informal Memorandum of Understanding (MOU) signed between ESPaCE and MaRS team, new ephemerides of Phobos and Deimos were developed with special emphasize on the Mars Express flyby in the end of 2013. Astrometric data from SRC delivered by DLR/TUB were introduced in the global fit. These observations were pretty important since there are still the only ones available close to the flyby itself. Several hundreds of plates digitized with DAMIAN machine and reduced were also used. Ephemerides of the Mars moons could be developed after proper modelling of the Mars system. The very

last constants for the gravity field of Mars were considered from JPL's publication. Initial state vectors and tidal ratio k2/Q for Mars were fitted successfully

The Uranian system
Ephemerides of the Uranian system were developed and benefitted from the PHEURA mutual event campaign.
New ephemerides of the systems of Mars, Saturn and Uranus
Ephemerides of the Saturn, Mars and Uranus systems were obtained and used for SPICE kernel realization. These ephemerides are now being implemented on the MULTI-SAT IMCCE server at the address http://www.imcce.fr/sat.
4.1.3.9 Databases and data distribution
Goal
The ESPaCE project includes two work packages for the databases set up and data distribution. It aims at collecting data and setting up standard public reservoirs for the data issued from the other work packages.
Main science and technical results
In this context several tasks have been performed:
➢ We have developed an astrometric database with a web interface. The database named NSDB (Natural Satellite Data Base) gives access to more than 17 000 records of astrometric positions of natural satellites. The interface itself involves different codes and accesses the database (MySQL language) through an Apache web server. It allows us to access the data as user (Data access channel), and also to feed the database as provider (Data deposit channel). At this date, only our team can use this facility as provider. The user can filter the data according to a list of parameters and get the data under several formats: HTML, ASCII, VOTable (Virtual Observatory Table). A guideline is provided in order to explain which data are provided in which units. We intend to ingest all the available astrometric data related to the natural satellites in this database but in a first step we put only the ESPaCE astrometric products in this database. This NSDB database is operating and will be public soon at the address http://nsdb.imcce.fr

Figure 3. Home page of the NSDB database

➢ The rotation models of satellites built in SPICE kernel format are accessible through the ESPaCE website (will be soon made public). The data for Phobos and Ganymede are provided as PcK SPICE Kernels files.
➢ Satellite kernels are accessible from the ESPaCE website. They will be publicly accessible soon through a « SPICE » directory for each planetary system (Mars, Uranus, Saturn) on the IMCCE ftp at the address ftp://ftp.imcce.fr
➢ These new satellite ephemerides are progressively being implemented. Ephemerides of the main satellites of Saturn and Uranus are still accessible on-line from the web server maintained by IMCCE at http://www.imcce.fr/sat
➢ Tools and interfaces for accessing to map images and topography have been developed. These data are made accessible through the DLR/TUB repository through the websites:

- http://europlanet.dlr.de/jra1/index.php?id=2
- http://europlanet.dlr.de/node/index.php?id=536

➢ Planetary and satellite constants are diffused. We maintain a web site which is accessible through the ESPaCE web site at the address:
http://www.imcce.fr/hosted_sites/saimirror/paramhe.htm

➢ Interfaces with the FP7-EuroPlanet IDIS system for distribution of data have also been maintained. Actually SA-IDIS is not much active and a new EuroPlanet system will be developed (named VESPA) in a H2020 project. But, the SA-IDIS pages can be a channel for accessing to several ESPaCE data.
- this is the case for the IDIS node hosted at OBSPAR at the address:
http://voparis-europlanet.obspm.fr/index.shtml
- this is also the case for the DLR repository at the address:
http://europlanet.dlr.de/

4.1.3.10 Education and outreach

Website

The ESPaCE website at the address http://espace.oma.be is the main tool for dissemination. It has been designed to be adapted to new technology (fast upload of the site, support-adapted width,…). This website contains the following pages:
• Home
Project and Goals
• ESPaCE management
Concept & Objectives
Members & Contacts
Affiliated Participants
Internal Wiki
Useful Links
• Work Packages
WP1 – Coordination
WP2 – Radio science
WP3 – Laser Ranging
WP4 – VLBI
WP5 – Data Digitization
WP6 – Astrometry
WP7 – Coordinate & Reference Systems
WP8 – Spacecraft & Satellites Ephemerides
WP9 – Databases
WP10 – Data Distribution
WP11 – Education & Outreach
WP12 – Scientific Coordination
• Meetings
2015
2014
2016

2012
• Science
Scientific Results and Deliverables
Papers and Documents
ROB digitization Facilities
Databases
Mutual Events
• Related Space missions
Phobos-Grunt (this website has been taken out due to the failure of the mission)
YingHuo 1 (this website has been taken out due to the failure of the mission)
Mars Express
Gaia
JUICE-Laplace
• Outreach and Education
A Tour in the Solar System
Information on Icy Moons
3D Animations
Flyers & Posters

It is linked (level "Internal Wiki") to a private website of the ESPaCE Consortium (wiki at http://www.imcce.fr/espace/) and to other interesting websites for the readers. The different pages are constantly updated, corrected or implemented. We must note important work on few of them.

Flyer

A flyer has been done for advertising our ESPaCE Consortium and is available on the website (see section above and http://espace.oma.be/outreach/flyers-posters.html).

Posters

A poster has been done for advertising our ESPaCE Consortium and is available on the website (see section above and http://espace.oma.be/outreach/flyers-posters.html).

3D Animations

3D animations have been done for advertising/explaining our ESPaCE Consortium/project and they are available at http://espace.oma.be/outreach/3d-animations.html. They concern:
• An explanation on astrometry of the moons of Jupiter and how the motions of the moons can be retrieved from the observation.
• An explanation on a spacecraft flyby of the moon Europa of Jupiter.
• An explanation on MarsExpress flyby of the moon Phobos of Mars and the influence of the interior of Phobos on the flyby trajectory.

Education activities

Education and Outreach activities are mainly performed through our website (http://espace.oma.be/ part Outreach and Education) and personal communications at congress or public conferences. These activities are related to the websites, the blogs, the 3D animations and the general presentation, all mentioned above, in addition to local activities not mentioned here.

We would like to underline a special mention to the "Tour in the Solar System" at the address:
http://www.imcce.fr/langues/en/grandpublic/systeme/promenade-en/pages5/51.html
which gives, to a wide public, a lot of fundamental information about all the Solar System objects and the observatories. This web site contains about 1000 pages dedicated either for the general public, for the students and pupils and also for the teachers to go further in the discovery of
the solar system and the planetary satellites.

News in the domain of ESPaCE are also put on the web.
Three blogs have been created:
• On the Phobos Soil mission launch: http://phobos.oma.be/
• On the MSL mission launch: http://msl.oma.be/
• On the Phobos flyby: http://phobosflyby2013.oma.be/

Potential Impact:
At the end of this project, we have delivered all the useful data sets, reports and papers concerning: performances of the Laser Tracking and VLBI technology, digitized images of planetary photographic plates and astrometric analysis for Mars, Jupiter, Saturn, Uranus satellites, accurate ephemerides of these satellites and orbits of the space probes which gave space images of these satellites, rotation data of Phobos, report on icy satellite control point networks, shapes and coordinate systems. An important part of the project will consist soon of merging (for the first time in Europe) natural satellite astrometry data and spacecraft data in a global inversion.

One of the main scientific results of the ESPaCE project is the providing of new orbits of spacecraft and new dynamical models of several natural satellites derived from the natural satellite ground based and space borne observation analysis. Several natural satellite systems are concerned (Mars, Saturn, Uranus) and, as a main impact, we can expect that this work will allow us to improve our knowledge of the interior of the celestial bodies.

We must also note that, providing new accurate natural satellite positioning, may have a consequence for planetary dynamical models which could use the satellites as reference points for the planet itself. More generally, the ESPaCE network will allow Europe (for the first time) to consider and use spacecraft and natural satellite data in a simultaneous process.

Such an expertise is very valuable for prospective planetary missions such as BepiColombo, ExoMars, JUICE and others. Therefore another potential impact can be providing support in preparing, guiding and analyzing space missions to planetary systems in a practical domain, and providing the possibility to get new knowledge of the dynamics and interiors of celestial bodies in the scientific domain.

Furthermore, the work done in ESPaCE for enhancing the application of the new techniques such as VLBI and Laser Ranging for future missions paves the way for new applications and new science in the areas of activity of the ESPaCE project:

➢ For the Laser ranging, in particular, the science case for future missions to employ laser ranging technology is especially strong for the determination of physical effects that manifest themselves as long-periodic variations in the range measurements. Key examples are planetary ephemerides, planetary rotational parameters and relativistic parameters. The several-mm level of range accuracy and precision will allow revolutionary advances to be made in these fields. However, for optimal use of this data, a combined analysis of laser ranging data with other data types, both tracking data and astrometric data, will be crucial. For instance, tracking for planetary orbiters will continue to require Doppler tracking to observe and separate short-periodic spacecraft accelerations. Similarly, determination of solar system ephemerides will continue to require astrometric observations to constrain the solution over long time periods. For the interpretation of the parameters estimated from the laser ranging data, data from e.g. seismometers, magnetometers and altimeters will be crucial, depending on the body under consideration.

➢ For the VLBI note that, in 2012, PRIDE has been selected by ESA as one of the 11 Jupiter Icy Satellites Explorer (JUICE) mission scheduled for launch in 2022 and a three-year science tour of the Jovian system beginning in 2029. The Planetary Radio Interferometry and Doppler Experiment (PRIDE) is designed as a multidisciplinary experiment addressing those areas of JUICE mission science objectives which require precise determination of lateral position of spacecraft on the celestial sphere. PRIDE-JUICE will provide measurements of the spacecraft position directly in the International Celestial Reference Frame (ICRF) thus enabling an improvement of the ephemerides of the Solar System bodies, in particular, the Jovian satellites. This task is naturally absolutely consistent with the main theme of the ESPaCE project. The scientific applications of PRIDE are based on two observable quantities: the radial range rate (Doppler shift of the service communication system carrier signal) and the lateral (transverse) celestial position of the spacecraft. The former is an “inevitable” ad hoc product of near-field VLBI tracking of the spacecraft while the latter is the main outcome of VLBI tracking as such. The PRIDE contribution will be in the following scientific areas:

- Improvement of the ephemerides of the Galilean satellites;
- Accurate input into definition of the Solar System reference frame;
- Characterization of the Ganymede shape;
- Statistical determination of surface slopes, near surface dielectric constant and surface density;
- Vertical structure of the Jovian atmosphere.

In addressing the two first scientific objectives, PRIDE will provide measurements of the spacecraft differential lateral position relative to the ICRF2 background extragalactic radio sources with the accuracy of 100-10 μas (1 sigma RMS) over integration time 60-1000 s. Being large and massive bodies, the Galilean moons will strongly influence the JUICE orbit at different phases of the Jovian tour. This is especially the case during Galilean satellites’ flybys and the Ganymede's orbital phase. PRIDE will monitor the JUICE spacecraft and thus will contribute to the characterization of gravitational perturbations by the moons, allowing in turn accurate determination of their positions. In particular, PRIDE will be very useful to improve the inclination determination.

It must be noted that, in a proposal for the ExoMars 2018 platform, members of the ESPaCE Consortium have proposed a radioscience experiment both tracked from the Earth ESTRACK and DSN ground stations as well as from the JIVE VLBI PRIDE network.

All along the different periods of this project, our consortium has been very attentive to publish and disseminate its results and information on the progress of its work. We attended many meetings and workshops where communications and posters have been done as it is shown the tables below (a longer list of articles, communications and poster is also available on the ESPaCE website at http://espace.oma.be/science/papers-and-documents.html)

Finally, it is important to note that in 2015 the ESPaCE consortium has decided to slightly modify its composition and to extend its activities on a long term, in particular in the context of a new project in the H2020 context, for preparing the exploration of the Jovian system by the JUICE mission. This proposed project is entitled SAGE (Satellites Geodesy and Ephemerides).

List of Websites:

- The project public website is available at the address: http://espace.oma.be

- The names of the consortium members are given on the web site the address: http://espace.oma.be/espace/members.html

- The list of the beneficiaries, addresses and contact names is:

➢ OBSPAR-IMCCE
OBSERVATOIRE DE PARIS (999623122)
Paris Observatory – Institut de Mécanique Céleste et de Calcul des Éphémérides
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Last update: 15 January 2016

Permalink: https://cordis.europa.eu/project/id/263466/reporting