The ESPaCE consortium as a European producer of spacecraft and natural moon ephemerides

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The consortium ESPaCE (European Satellite Partnership for Computing Ephemerides) is composed of seven European institutes: IMCCE (Institut de Mécanique Céleste et de Calcul des Ephémérides, Paris Obs.), ROB (Royal Observatory of Belgium), TUB (Technical University of Berlin), ERIC (European Research Infrastructure Consortium formerly known as JIVE : Joint Institute for VLBI in Europe), TUD (Delft University of Technology), French space agency (CNES) in France and German Aerospace Center (DLR) in Germany. The objective of the consortium, initiated under an FP7-European project is to provide new accurate ephemerides of natural satellites and spacecraft. For this goal astrometric data issued from ground-based observations as well as from space observations are being analyzed and reduced. On the other hand emerging technologies, specifically VLBI and interplanetary laser ranging, applied to the positioning of spacecraft are also studied.

The ESPaCE project addresses also data related to gravity and shape modeling, control point network and rotational parameters of natural satellites. The accuracy improvement of these ephemerides makes them a powerful tool for the analysis of space missions, the preparation of future missions, or for the determination of planetary physical parameters. Among relevant sub-products for space missions, we note the delivery of updated ephemerides of the Mars moons Phobos and Deimos derived from data by the Mars Express mission. In addition, the ESPaCE ephemerides of the Galilean moons are regularly updated in the context of the upcoming JUICE mission.

The ESPaCE network
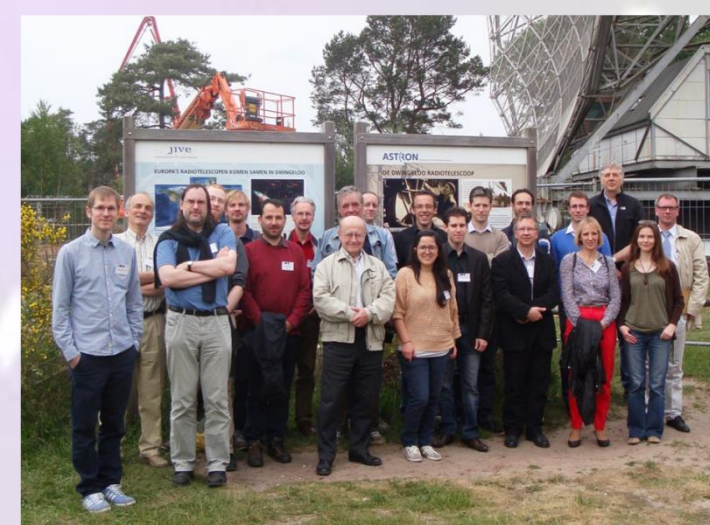
The concept and objectives

The ESPaCE consortium has carried out a study of the natural satellites and spacecraft orbits by combining expertise of seven main institutions. The central part of the activity is focused on the extraction and analysis of astrometric data from spacecraft measurements that have not yet been used in the orbit dynamic reconstruction and on the combination of these data with ground-based astrometric data digitized from old plates. The project intends also to advance the European expertise in ultra-precise tracking of planetary probes and other deep space science missions. By these means, we have provided new dynamical models for several natural satellites, and a characterization of their rotation properties.

This 4 year project (2011-2015) was organized in 12 work-packages including Radio-science, laser ranging, VLBI tracking, digitized data handling, astrometry, definition of coordinates reference frames and improvement of planetary coordinate knowledge, methods for determination of spacecraft and satellites ephemerides. It allowed us to deliver to the scientific communities and communities at large the best scientific products adequate to the present day cutting edge space science and technology.

Further information on the ESPaCE web server at http://espace.oma.be

Work Packages

No	WP	Work performed	Tasks list and results	Deliveries list
WP 2	Radio-science	Tracking data of probes which flew by natural satellites are collected and analyzed thanks to a priori ephemerides of the objects. Several considerations upon the acting forces, gravitational and non gravitational forces, are made in order to get the best results. These forces are estimated and precise orbit of the probes can be computed. Other parameters such as mass of the natural satellite are determined.	1. Collection of the Radio-science tracking data 2. A priori ephemerides 3. Strategy development for the analysis 4. Analysis of the tracking data **Results:** X-band Doppler and range tracking data from MarsExpress, Mariner-9, Viking 1 and 2, and Phobos-2, are used in order to compute the ephemeris of Phobos and Deimos.	• Ephemerides biases • Spacecraft orbit SPICE kernels
WP 3	Laser data	The performance of planetary laser ranging concepts is analyzed and compared to existing tracking types. Range observation error budgets are derived from hardware and environmental models. One-way laser ranging data from LRO are processed for precise orbit determination as a case study in planetary orbit determination..	1. Information collection on laser tracking, VLBI and DSN (Deep Space Network). 2. Inventory of existing and required tools 3. Selection and modification of preferred tools 4. Performance studies 5. Demonstration project **Results:** Significant improvement in geodetic parameter estimation quality of Phobos and Mars from a simulated laser-equipped Phobos lander. One-way laser-only orbits of LRO show difference of ~10 m with operational SPICE kernels. Quantitative comparison of one- and two-way laser ranging has been performed; new methods of coupled space-time dynamics in data analysis have been developed.	• Report on performance parameter of laser tracking, VLBI, DSN • Report on software packages for solutions of satellite trajectories • Report on selected software tool and modification. And fine-tuning for trajectory determination • Report on performance study incl. quality estimation of simulated and actual results • Report on LRO Laser Tracking results
WP 4	VLBI	Applications of VLBI technologies to spacecraft tracking are studied. VLBI tracking data are analyzed in view of their use for various planetary science objectives. A special software is developed and applied to planetary science spacecraft VLBI observations.	1. Installation, verification and tests of the VLBI near-field theoretical delay 2. Verification and tests of the on-purpose developed ultra-high spectral resolution correlate software for SPC VLBI correlation 3. Scheduling and performing test VLBI observation of several existing SPC 4. Post-correlation analysis of the broad-band far-field phase referencing radio sources (from ICRF and other catalogues) data and near-field narrow band SPC data. 5. Analysis of the results 6. Optimization of the observational, processing and analysis techniques, recommendation. For further development. **Results:** VLBI campaigns observing radioscience signal from different spacecraft have been performed and first results are analysed.	• Report and algorithms of ultra high spectral resolution SPC signal correlation • Measured state vectors of the SPC together with a priori state vectors used
WP 5	Digitized data	This WP is dedicated to the scan of many photographic plates of planetary systems of satellites. We have identified in particular plates of Martian, Jovian and Saturnian satellites to be scanned. But we know that other relevant plates can be available in archives of several observatories; we have find and scanned some of them. This work is made possible thanks to the recent setting up of a new digitizing machine in ROB.	1. Digitization of Mars plates 2. Digitization of Saturn plates 3. Identification of new plates 4. Digitization of relevant plates **Results:** The ROB digitizer was used to digitize 2364 old photographic plates of the natural satellites of Mars (483 plates), Jupiter (732 plates of the Galilean moons (Io, Europa, Ganymede and Callisto) of which also 36 of Amalthea the fifth Jupiter moon) and Saturn (1106 plates) and a few plates of the moons of Uranus (24 plates) and Neptune (12 plates) and some of Pluto (4 plates). The digitization was done in step and stare mode. The individual overlapping footprint images and the reconstructed full plate (mosaic) images were delivered in FITS format for data extraction and astrometric reduction, together with pre-scans of the plates before cleaning in TIFF format and the scans of the envelopes and logbook together the meta data in PDF format. All available meta data were encoded in Excel files.	• Digitized form of the plates of Mars • Digitized form of the plates of Saturn • Digitized form of new plates identified

No	WP	Work performed	Tasks list	Deliveries list
WP6	Astrometry	The data scanned in WP5 and other relevant data are analyzed in terms of astrometry in order to obtain orbit model. Among these data, a special work is carried out for rare events, the mutual events of the natural satellites (eclipses and occultations of satellites each other during the planetary equinoxes), which are the most accurate astrometric observations from the ground. In this WP, a special task is devoted to the astrometry of Phobos and Deimos which have been the goal of several space missions.	1. Reduction of Phobos/Deimos images 2. Reduction of mutual events data 3. Reduction of Jovian images 4. Reduction of the Uranian images 5. Reduction of the relevant images 6. Reduction of the DAMIAN images **Results:** The reduction of the Phobos and Deimos images from Mars Express SRC (Super Resolution Camera) images, which incorporates corrections for pointing offsets, center of figure/center of image due to insolation, coordinate transformation, incorporation of astrometric background. Also mutual events have been observed (262 events in 106 stations) and analysed and the corresponding metadata carefully gathered. The positions of the natural satellites, the planet and the reference stars were extracted from the digitized plates and corrected for distortion. Star catalogues were used for the astrometric reduction. With a very good performance at the level of about of 200 mas or 60 km for the new positioning accuracy of Phobos and Deimos.	• Astrometric space data of Mars, Jupiter, and Saturn satellites • Mutual events data for the Uranian, Jovian and Saturn satellites • Astrometric data from DAMIAN images
WP 7	Coordinates and Reference systems	On the basis of space observations, the shape and gravity model of the natural satellites can be obtained. The WP7 is devoted to these tasks for the Martian satellites, Moon, and the icy satellites. A coordinate system for these objects can be defined and a model of rotation can be deduced. These data have been also used for physical ephemerides (precise aspect of the bodies versus the time) of the natural satellites.	1. Reference shape and gravity model for Phobos 2. Realization of the Phobos coordinate system 3. Realization of the Lunar coordinate system 4. Reference shapes of icy satellites 5. Realization of icy satellites coordinate systems 6. Theory of rotation of the natural satellites **Results:** New SRC (Super Resolution Camera) image data from Mars Express have been added to increase the resolution of the current Phobos control point network. While hitherto only few selected SRC images have been used for global shape analysis, HRSC (High-Resolution Stereo Camera) are currently used as a basis to compute a dense topographic network for Phobos. Phobos' rotation has been investigated using these images. Concerning the Moon, landing sites, for which the lunar-fixed coordinates are precisely known, have been analysed together with DTMs (Digital Terrain Models) to improve the lunar coordinate system.	• Report on Phobos control point network, reference shape, and gravity model • Report on Lunar coordinates and selected base maps • Report on icy satellites control point networks, shapes and coordinate systems
WP 8	Spacecraft and Satellite ephemerides	New dynamical models of the natural satellites and improved orbit models of spacecraft are obtained by using the digitized astrometric data as well as spacecraft data. The dynamics models of the Martian satellites Phobos and Deimos can be improved in particular on the basis of the new analysis of the recent MEX data and the past Viking data. Combination between space observations and ground based ones, and processing of data related to the satellites and the probes, allow getting strong constraints for the dynamics of the objects. Other data from the Galileo and Voyager missions permit also to provide new ephemerides of the Galilean and the Uranian satellites and new orbital models of the probes. Spice Kernels are provided.	1. Arc splitting method 2. Merging data method 3. Modeling Mars SPC orbits 4. Modeling Phobos/Deimos orbit 5. Mars global inversion 6. Modeling Galileo orbit 7. Modeling Jovian satellite orbits 8. Jupiter global inversion 9. Modeling Voyager 2 orbit 10. Modeling Uranian satellites orbit 11. Uranus global inversion **Results:** Mars spacecraft orbits have been analysed in detail and a specific method studying splitting the radio-science data has been performed. Using these data as well as astrometric data, Using these data as well as astrometric data, new Phobos and Deimos ephemerides were calculated. VLBI data are presently added to this study.	• Mars SPC, Galileo, Voyager 2 orbit kernels • Ephemerides of Martian, Galilean, Saturnian and Uranian main satellites
WP 9	Databases	Setting up of databases and of the method to access the data and models developed in the other WPs.	1. Astrometric database 2. Rotation database 3. SPC Kernels 4. Satellite kernels 5. Map images 6. Topography **Results:** First setup set-up has been constructed.	• Collecting Topography data in standard format • Collecting Satellite and SPC data in SPICE format • Collecting Rotation data in standard format • Selected image map and topographic data products including documentation
WP 10	Data distribution	Allowing the whole scientific community to access our new data available. Databases is fed step by step, each deliverable is now available. **Astrometric Data base NSDB** is accessible at https://nsdb.imcce.fr/ **SPICE Kernels of the satellites ephemerides** are accessible at: ftp://ftp.imcce.fr/pub/ephem/fp7-espace/	1. Astrometric database 2. Rotation database 3. SPC and satellite kernels 4. Map images 5. Topography 6. Planetary constants 7. Interface with EUROPLANET IDIS **Results:** First set-up has been constructed.	• Implementation of the astrometric database • Implementation of the SPC/Satellite kernels • Distribution of the planetary constants • Interface method with EUROPLANET IDIS
WP 11	Education and Outreach	See http://espace.oma.be/		

New Natural Satellite Ephemerides

New ephemerides of the satellites of Mars and of the main satellites of Jupiter, Saturn, Uranus are provided in SPICE format. Ephemerides of the Lagrangian Saturnian moons are provided, also.

On this figure (left), we give the astrometric residuals of the four Lagrangian satellites from ISS-Cassini. Telesto and Calypso are the two coorbital moons of Tethys. They move around the Lagrangian stable points L4 and L5. Helene and Polydeuces are in equivalent orbital configurations but along the orbit of Dione. The associated ISS-NAC astrometric data are fitted in sample and line coordinates (pixel). Residuals are here converted to kilometres.

All our ephemerides of the orbit of the moons are available here:

ftp://ftp.imcce.fr/pub/ephem/fp7-espace/

Such new ephemerides are a keypoint for the success of specific experiment with space missions like MEX and JUICE.