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PÔDET: A CENTRE FOR EARTH DYNAMICAL ENVIRONMENT

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Abstract. The monitoring of the Earth space environment has gained some importance these last decades, in particular at the European level, partly because the phenomenon which origin come from space can have socio-economic consequences; and also because our understanding of those phenomenon – their associated prediction and risks – is still limited. For instance, the Space Situational Awareness programme (SSA) at ESA has set up in 2013 a centre and network for aspects connected to space debris (SST), to space weather (SW), and to near-Earth objects (NEO). At IMCCE, the *Pôle sur la dynamique de l'environnement terrestre* (PODET, `podet.imcce.fr`) for the Earth dynamical environment is studying effects and prediction for natural and artificial objects gravitating in the Earth vicinity. These studies englobe near-Earth objects, asteroids, comets, meteoroids, meteorite streams, and space debris. For all object types that are concerned, a general scheme of a functional analysis has been developed. It encompasses data acquisition with dedicated observations—essentially astrometric—or database queries, orbit determination or adjustment, prediction and ephemerides, and eventually impact probability computation and data dissemination. We develop here the general context of this action, the PôDET project, its scientific objectives, interaction with other disciplines, and the development in progress for dedicated tools.

Keywords: NEA near-Earth asteroid, meteoroid, space debris, ephemerides, impact probability, Space Situational Awareness - SSA

1 Introduction & Context

Our planet Earth is not a unique or completely isolated body in space; it is the place of direct interactions with its space environment. Its magnetic field and atmosphere are protecting the Earth against radiation sources and external impacts, and hence ensuring some of the fundamental conditions that allowed life to develop. However, this protection is only partial; several events can still affect the Earth locally with frequencies events that can be of the order of a human generation or a year. Thus we remain dependent of solar activity bursts, reentry of space vehicle or ground impact of natural celestial bodies (meteoroids, asteroids), as well as of artificial body (space debris) and meteoritic streams that affect all space activities. These astronomical phenomena present human and socio-economic risks that have to be addressed carefully.

The PôDET hub* at IMCCE, Paris observatory, France, is carrying out studies and proposing services for topics connected to the Earth space environment. The bodies covered by the activities are the space debris (PôDET-DEB), the meteoroids and meteorite streams (PôDET-MET) and the near-Earth objects (PôDET-NEO), see Fig 1. PôDET has been retained at the 2009 CNES prospective exercise as a data centre. Its activities enter, at the European level, in the general domain of ESA Space Situational Awareness (ESA-SSA), as well as the EC FP7 or Horizon2020 programmes. At the international level, UNO, IAU working group WG/NEO are concerned, as well as the IADC (Inter-Agency Space Debris Coordination Committee). The recommendations and rules on space utilization have been declined as the French Space Operation Act at the French level. The activities developed in the hub are part of other projects, especially *NEOShield* - mitigation of threatening asteroid, *AsteRisk* - decision chain for atmospheric (re)entrance, *FRIPON*, *Cabernet* - surveyance and research of meteorites, *NEOPROP* - orbit propagation of NEO, *MEO parking* - Disposal strategies analysis for MEO orbits.

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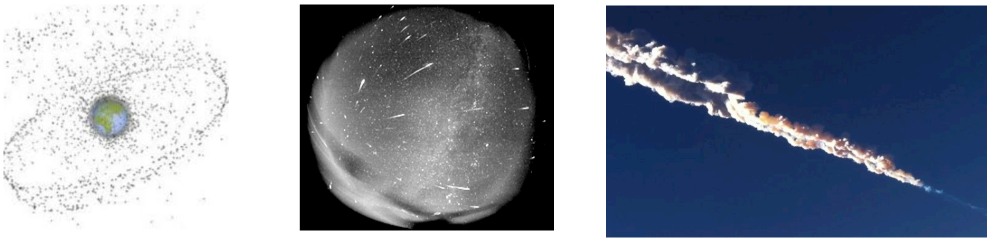

Fig. 1. *PODET covers research activities on three different celestial bodies type: space debris, meteoroids and streams, and near-Earth asteroids. Left: portrait of catalogued debris with different orbital classes (GEO, MEO, HEO,). Middle: image of a meteorite stream monitored with a fish-eye camera. Right: The Chelyabinsk (Tcheliabinsk) event of 2013, Feb. 15 from resulting from an asteroid blast in the atmosphere. (Credits, ESA, IMCCE, N. Plekhanov)*

Research activities encompass different topics including observation analysis, models for propagation and predictions, uncertainties and probabilities for associated risk estimation. The PôDET data center is hence able to provide necessary information to space operators and stakeholders - on different time scales - on the risks inherent in the Earth's space environment. All this in an independent manner, providing also higher robustness to similar predictions obtained by other centers (NEO at JPL/NASA, NEODys at Pisa univ.). Economic or societal benefits expected are far from being negligible.

This paper presents the structure of the data and analysis center PôDET—hosted at IMCCE—which strengthen research capability and development of new services in France dedicated to the dynamic evolution of near-Earth objects, meteoroid streams and space debris.

2 General objectives

Detecting potentially hazardous near-Earth asteroids (PHAs) such as (99942) Apophis in 2004, or more recently 2011 AG_5, for the most known; experimenting the extremely close approach to the Earth of 2012 DA_{14} (in February 2013, less than 28000 km from the surface of the Earth); observing the atmospheric penetration followed by disintegrating airburst of asteroid 2008 TC_3, or even their fall to the ground as that of the object Carancas in 2007, and last the Chelyabinsk event in February 2013; all highlight the interest of research activities for a maximum orbit-determination precision on short notice. The same is true for the identification and tracking of space debris: the importance of this type of orbit determination has increased further after the collision that occurred in 2009 between an Iridium and a Cosmos artificial satellites, or the unpredicted reentry of a piece of Ariane IV tank in Brazil in February 2012 near the village of Anapurus. The knowledge of asteroidal and cometary grains population in the solar system is of importance for the identification of their origin (asteroid or comet and association with a specific body) and of the physical processes that generate them. It is also of importance for the daily management of space missions, since meteor showers may pose a risk to any operational satellite or to habited space vehicles.

The scientific objectives of PôDET aims at a better knowledge of our space environment, and more specifically to develop new methods for the dynamical modeling of the objects under study. Our approach is hence to develop, in an original way, common areas of research and services related to orbital characterization and dissemination of data for the three types of objects that are: near-Earth asteroids and comets, meteoroids and meteor streams, and space debris. The scientific objectives, which are applied for operational services can be summarized as follows.

2.1 Space debris - DEB

Waste of launchers components, fragments from artificial satellites or subsequent collisions; they pose risks to space operations and spaceflight — broad size range is [cm - m].

On the very short term (order of one or two days), the collision-risk assessment with an operating satellite must be done quickly and with sufficient accuracy to plan avoidance maneuvers. In the longer term, it is necessary to have orbital models including a full error budget and precise enough to estimate the lifetime of a satellite before its entry into the atmosphere, or otherwise guarantee its long-term orbital stability. In all cases, a new methodology is required to insure greater precision and stability compared to the models currently in use in operational centers. This concerns *(i)* the model itself (accuracy, timeliness for simultaneous application to several tens or even hundreds of objects) *(ii)* and the data assimilation (real time or delayed time, with maximum or reduced accuracy, models reset, etc.), and *(iii)* the error budget itself, accounting for parameters that can not be modeled in advance (solar activity for instance). Let's recall that according to the current models, the minimum distance required between the Iridium and Cosmos satellites was supposed to be about 400 meters, before their actual collision.

The challenges faced here are essentially the implementation of high-precision orbit computation methods in terms of orbit determination and propagation, preparing for the arrival of a substantial flow of new data, and the contribution to the estimation of risks for space systems and civil society. These efforts involve the acquisition of high-precision data and the relevant dynamic modeling. Each object in the Earth's space environment is linked to a number of scientific questions, origin and evolution of objects, physical and orbital properties, evaluation of interactions and driving forces that motivate especially research in astrometry, celestial mechanics and space mechanics. Given this context, the objectives (which are partly common with near-Earth asteroids) set in this area are:

- Development and optimization of methods for orbit determination in the short term and with few observations,very useful for newly discovered objects. These include various types of algorithms and methods, e.g. by genetic, Bayesian, or MCMC algorithms (that do not require any *a priori* knowledge of the trajectory (Deleflie et al. 2013), in opposition to classical least square-based LLS methods);
- Development of methods and tools for orbits propagation as well as error propagation (rapid methods and / or accurate) (Deleflie et al. 2013b);
- Systematic exploitation of all series of images acquired by different telescopes for non-trailing satellites (geostationary) and for streaking ones (Laas-Bourez et al. 2008), this step can be largely automated, but not completely, and 'manual' astrometric validation are sometimes required;
- Establishment of a catalog of dynamical parameters (orbital elements, orbital precision estimators) based on a new analytical and fast extrapolation model, alternative to existing ones;
- Constraints, from the observation of the model parameters, on the long-term evolution of the debris population. Estimation of 'dynamical areas' (i.e. not described in terms of spatial positions) of debris concentrations or less densely populated areas;
- Collision probability between satellites and space debris, prediction of minimum approach distances;
- Implementation of the access and dissemination of data, ephemeris, and observations' alert, all following Virtual Observatory (VO) standards (Le Petit et al. 2012; Deleflie et al. 2013c);
- Development of astronomical-observation strategies needed for critical objects, using in particular robotic or dedicated network telescopes, in close cooperation with CNES, and other partners.

2.2 Meteoritic streams & meteoroids - MET

Dust, fragments of comets (or asteroids) yielding meteor showers; they are responsible for damage to artificial satellites, reduced solar panels lifetime and major power outage — broad size range is [μm - m]

Earth in its orbit around the Sun is regularly crossing meteor streams whose origin is generally associated with passages of comets. If the parent-body association is now relatively well established for the biggest well known events, it is not the same for the quantitative characterization of these streams (ZHR, etc.). Neither is it for the association of other smaller individual stream population. These however are sources of damage to artificial satellites and it is essential to quantify and predict their activity over time and space. Moreover, it becomes increasingly likely that some of these streams are associated with near-Earth asteroids. The analysis of this relationship will help a better understanding of both the dynamic characteristics and physical properties of NEOs. In addition, this type of association provides useful information to the scientific study of the conditions of formation of the solar system and its dynamic evolution. The role of a data center on the dynamics of the Earth's environment in this area is also to collect and disseminate relevant physical and dynamical data, streams prediction, and to provide tools for predicting risk associated to collisions with artificial satellites and manned missions. The service should also provide validated data and online data including interoperability through the 'Virtual Observatory' protocol. Given this context, the goals set in this area are:

- Development and optimization of methods for the orbit determination, especially by triangulation of data from Carbernet and FRIPON networks of cameras (Atreya et al. 2012);

- Physical and dynamical modeling of meteor streams - search and identification of the parent body (Rudawska et al. 2012);

- Treatment of observations from international campaigns (IMO, REFORM, FRIPON networks);

- Predictions of meteor streams crossings, and streams activities (dates, and ZHR rate);

- Implementation of data access and dissemination following OV standards.

2.3 Near-Earth objects - NEO

Asteroids and comets whose orbit crosses or approaches the Earth; impact with the planet can produce, according to the object's size and the energy released, a simple yet surprising light and sonic phenomenon, or a crater and other more catastrophic events — broad size range is [m - km]

The technology used to provide astrometric data necessary to the orbital modeling is in constant progress. The next decade—with ongoing or future survey programs—will see a considerable change in the volume of data available. The present detection rate of newly discovered NEOs is already very high, about 900 new bodies per year (see `http://neo.jpl.nasa.gov/stats/`). The advent of new generation telescopes (PanSTARRS, LSST) equipped with performant cameras and adapted observing strategies, moreover supplemented by space missions (Gaia, NEOSSAT), will result in a huge quantitative leap of data to analyse; and sometimes in a considerable need of follow-up activities to avoid any rapid loss of a discovered object.

A major challenge for analysing these objects is obviously the amount of data to handle in an automated way. Another problem arrises from the fact that periods of visibility of these bodies are often reduced (for orbits close to the Earth, the body spends long periods of time behind the Sun). Thus PôDET activities have to tackle orbital and dynamical models precision, associated evaluation and assessment of impact probabilities, and risks. These can be computed at two levels, in the short term (immediately after the discovery) or in the longer term (accurate risk estimation, and computation of uncertainties' evolution over decades). Given this context, the goals set in this area are:

- Development and optimization of methods of orbit determination, especially in the short term and with few observations, including various types of algorithms and methods (parametric as well as non parametric algorithms, genetic, Bayesian, or MCMC algorithms, LLS least-squares, etc.);

- Development of methods and tools for orbits propagation and errors propagation (rapid methods and / or accurate) (Bancelin et al. 2012a,b; Desmars et al. 2012);

- Exploitation of astrometric data, including those obtained directly with associated networks (radar, robotic telescopes, ...) (Thuillot 2011);

- Implement datamining tools for identifying objects in selected archives ('precoveries') and orbits linking methods;

- Establishment of a catalog of dynamical parameters (orbital elements, orbital precision estimators);

- Establishment of a sub-catalog of physical parameters necessary to the dynamical modeling, on the basis of available data centers (PDS, PSA, Gaia,), and dedicated ground-based programs;

- Computation of close encounters with the Earth and other planets, estimation of impact probabilities (Harris et al. 2012);

- Implementation of access and dissemination, following OV standards and protocols, for the data and ephemerides; VO-alerts for observing or following critical objects (Erard et al. 2010; Le Petit et al. 2012).

3 Services

The PôDET centre for the Earth's space dynamical environment benefits from research conducted upstream of the operational services. This research focuses on the modeling of non-gravitational forces and studies of their effects on the orbits, on processing observational data, on real-time orbit determination and adjustment, on statistical inversion methods, on orbit propagation, on error propagation, on impact probabilities, etc. Operational services are intended then to provide useful, adapted, and accessible data. One originality of our approach is to consider a common treatment for all objects treated, and compliant with Virtual Observatory standards and protocols. The functional analysis scheme includes the following topics (see Fig.2):

- data: operating astrometric and photometric data as input, including treatment of Gaia stellar catalog and / or ground-based data;

- orbits: refined dynamical modeling, adapted propagators, adapted data inversion and parameter estimation procedures;

- predictions: ephemeris, uncertainty, and impact probabilities, database and visualization tool as output.

The operational part of the centre will—during its nominal phase—use as inputs three main sources of information (see Fig.2):

- The international databases that deliver orbital and physical information about the objects concerned (IAU/MPC, Lowell Observatory, NEODyS, as examples for the NEOs) as well as surveys that perform new detections (Catalina, PanStarrs, etc.). For what concerns space debris, catalogues maintained by services in the USA, and especially by the French CNES teams will be an essential source of information;

- Observatories archive or accessible space missions catalogues, enabling data mining, in order to detect a serendipitous observation in the past. Such pre-discovery observations can yield fundamental astrometric positions to constrain the orbital models based on too few observations (or equivalently on short arcs). This concerns—to varying degrees—the three categories of objects that are near-Earth asteroids, space debris and meteor streams;

- Dedicated observation sites, including some of the telescopes from the Gaia-FUN-SSO network for NEOs (`https://www.imcce.fr/gaia-fun-sso/`), the CABERNET cameras network (`http://www.imcce.fr/langues/en/ephemerides/phenomenes/meteor/CABERNET/index.php`), and the FRIPON network for meteorites (`http://www.imcce.fr/fripon/`), and possible network of robotic telescopes. In all cases, the aim is to densify new observations, and also to put in place a dedicated follow-up strategy for specific newly discovered or critical objects.

All astrometric data acquired help to improve any preliminary orbits, they also allow orbital models refinement—in particular if they are of high accuracy—by allowing to incorporate all gravitational effects (perturbations by asteroids, relativistic effects, etc.) and non-gravitational forces (Yarkovsky effect, Poynting Robertson, etc.). From the orbital elements one can compute ephemerides and propagate the orbit over the long term; and hence, depending on the object analysed, caracterise close encounters of NEOs with the Earth or other planets, predict meteor streams events strength direction, derive the dynamical stability of artificial satellites when reaching their operational lifetime's end (GNSS or geostationary type). These results are then made available through an interoperable interface to the users concerned. Finally the functional analysis scheme encompass all sequences of data reduction, data analysis, orbit and ephemerides computation, estimation of dedicated parameters and dissemination.

4 Prospective

The centre PôDET at IMCCE/Observatoire de Paris, develops research activities and provides services connected to the near Earth space environment. It aims to encompass – in a common structure – three different kind of celestial objects (natural and artificial): space debris, meteoroids and meteorite streams, near Earth objects (asteroids and comets). In all cases research activities are connected to dedicated observations acquisition and reduction, and orbit computation. A web-site has been made publicly accessible at `http://podet.imcce.fr` since 2013. In the future, operational services will disseminate, as output, dedicated data for a better estimation of the uncertainties, awareness and risks associated to these bodies evolving in the Earth space environment. It

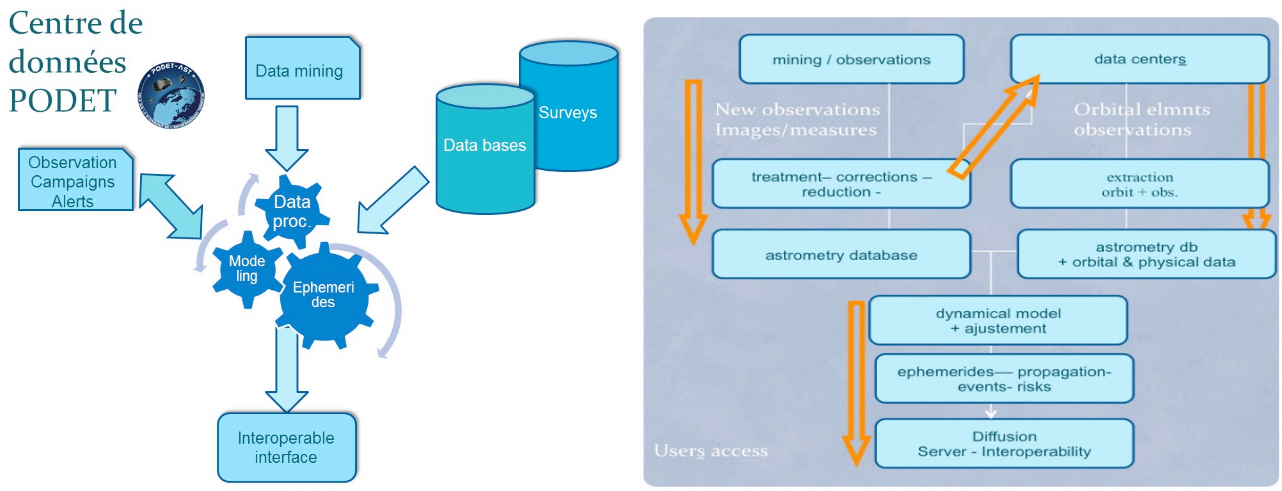

Fig. 2. *General structural scheme for PôDET and functional analysis graph. Observations and data bases are used for orbits adjustments and ephemerides computation, followed by risks estimation, and other adapted data dissemination.*

provides general information and three main sections (Ephemerides, Database, Monitoring) for all three categories of objects (DEB, MET, NEO). Update for the databases, and further developments for orbit propagation will be regularly integrated.

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