ADAPTATION OF PRE-EXISTING ORBIT DETERMINATION LIBRARY FOR INTERPLANETARY MISSIONS

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ABSTRACT

The introduction of new low-cost tiny satellites has encouraged autonomous navigation research and development, benefiting other mission types such as deep-space navigation. Making the spacecraft more autonomous has two major advantages: While the communication delay between Earth and the spacecraft can be quite large, autonomous navigation has proven to be more reliable, allowing the spacecraft's safety to be increased, particularly in deep-space highly perturbed environment. Another advantage is the reduced involvement of ground tracking, which results in a reduction in total mission costs.

BOLERO is a mathematical library developed by CNES, since 2000, for on-board orbit determination in the Earth's vicinity. It is initially composed of a Kalman Filter, measurement functions such as GNSS measurements, and dynamical models. BOLERO contributes to the notion of improving spacecraft autonomy by providing an onboard orbit determination library that may be paired with an onboard navigator and orbit controller. It has already been deployed on Topstar receivers with multiple flying experience since 2000 (HETE2, DEMETER,...), and is currently used on Syrlinks receivers. DIONE is a navigation system that employs the BOLERO library to compute the estimated trajectory as well as dynamical and measurement parameters.

The adaptation of BOLERO and its navigation system DIONE, for interplanetary missions, will be presented in this paper. It consists of implementing the missing interplanetary dynamical environment, as well as new reference frames and time scales. New measurement types, such as Lidar, optical navigation, and Doppler measurements, are also added. The study raised many concerns about measurement management, including the use of DSN measurements on board, clock management, and the generation of optical measurements. Within the framework of this study, the image processing component will be assumed to have been generated by an image processing tool separate from the navigator.

1 INTRODUCTION

This paper describes the project's design phase, "Interplanetary Autonomous Navigation", which was carried out within the context of the BOLERO project.

BOLERO is a navigation library created by CNES, that contains all of the thematic building pieces needed to create an onboard space navigation system. These subject components address dynamic models for Earth orbits from LEO to GEO, time and space reference frames, measurement models (GNSS in particular), and Kalman filtering. This study attempts to fulfill the requirements of certain interplanetary mission initiatives, namely the feasibility of extending the BOLERO library to missions beyond the terrestrial suburbs and gaining new mission analysis tools. As a result, in the following paragraphs, we will outline the keys library components that will be impacted by interplanetary modification. These changes are mostly related to new functionalities:

- New reference frames
- Time scales
- Improved satellite attitude definition
- New forces and perturbation models
- New measurement types

2 MATERIAL AND METHODS

This section will cover the high-level architecture of BOLERO, its relationship with the DIONE navigation system, and the new functions included for the interplanetary version in contrast to the initial architecture.

2.1 BOLERO library and DIONE

BOLERO means “Bibliothèque d’Objets Logiciels Embarqués de Restitution d’Orbite”, that is “On board orbit determination objects library ” . It has been developed since 2000 in C language, and is compliant with embedded code constraints such as memory management, computation time, software quality, unitary tests. The first version was limited to mono constellation GPS measurements and was integrated on several receivers such as Thales Alenia Space (TAS) Topstar 300 then Topstar 3000) receiver. It was used on board different missions: HETE2 (2000), Demeter (2004) with an Autonomous Orbit Control (AOC) module and Proba-2 (2009). In 2019, it was decided, due to emergence of multi-constellation GNSS receivers, to adapt the library to the possibility to handle any GNSS constellation measurements together. More recently, since 2020, multi-satellite and relative navigation functionalities have been developed.
The state vector represents the parameters that can be estimated by the navigation filter: they are divided into the dynamical parameters, used to compute the movement of the spacecraft and the measurements parameters, such as the receiver clock bias model, the carrier phase ambiguity and inter constellation bias. A typical configuration of the state vector is: 6 orbital parameters, drag, solar radiation pressure coefficient, maneuver (3 axes possible), earth orientation parameters (pole, 2 parameters), and for measurements, receiver clock bias, drift and drift rate, carrier phase ambiguities, inter constellation biases.
For performance studies and on ground validation purpose, we used a generic navigator called DIONE, based on BOLERO library. DIONE provides all necessary interfaces to configure and control BOLERO navigation functions : The configuration includes in particular the definition of satellite(s) geometry, of the extrapolation model, the Kalman filter tuning parameters (initial values, initial and model covariances). The control of the navigator is done through “ directives ”, which enables to provides measurements from a GNSS receiver, to command the orbit propagation, or to request position and velocity or any estimated parameter at a given date. Some directives allows to change the parameters of the navigator during operation : filter tuning, dynamic model, etc. Some requests can be sent

through Telecommand (TC), to be taken into account at a given date. A typical one is the TC to order a maneuver, providing its description to the navigator.

2.2 BOLERO's high level architecture

This section will go through the architecture of BOLERO's terrestrial version as well as the additional functionalities included for the interplanetary version.

2.2.1 Reference frames

The selection of an appropriate reference frame is essential when transitioning from requirements for geocentric missions to interplanetary missions. The difficulty of solving the equations might actually increase if the reference frame is chosen incorrectly. In the terrestrial version of BOLERO, three types of reference frames are represented:

- ITRF: The ITRF (International Terrestrial Reference System) is a non-inertial space frame that rotates with the Earth. The IERS manages the specification of the system's orientation and changes the triad's orientation on a regular basis. The International Terrestrial Reference Frames is one of numerous ITRS realisations (ITRFs).
- VEIS: A pseudo-inertial reference frame where the geographic pole and the instantaneous pole of terrestrial rotation coincide. This decision, in keeping with the accuracy of orbit determination, makes it very easy to calculate the reference frame transformation matrix, from terrestrial to pseudo-inertial.
- Local reference frames: the TNW (tangential, radial, out of plane) and the QSW (radial, tangential, out of plane). They are mostly used for establishing the satellite's attitude. It's interesting to note that BOLERO also employs intermediate frames in this context, including the Platform (PF) frame and the TRL (Pitch, Roll, Yaw), with a fixed rotation with respect to the QSW.

It is essential to take into account developing reference frames for solutions that are tailored to new applications while transitioning from terrestrial to interplanetary environments. Two key requirements are chosen for such applications: the necessity for an inertial reference frame and the ability to adjust the origin of the reference frame based on mission needs. As a result, the following new reference frames are added to the library:

- ICRF: Based on 608 extragalactic radio emitters whose coordinates are obtained by long-distance interferometry. It is frequently centred in the solar system's barycenter. It represents a minor improvement over the J2000 since it neglects the definition of the vernal equinox (which moves in time). This reference frame is used to define the most recent stellar catalogues.
- Body centered fixed (BCF) : Because we already have reference frames centred on Earth, we may think of adding ones that are centered on other planets in the solar system as well as asteroids, planetary satellites, and so on, and are fixed with them. As a result, we're talking about non-inertial systems that revolve around the planet of interest. We employ the IAU conventions for defining the parameters of the planet's rotation to establish the direction of the axes (right ascension, declination, prime meridian).
- Barycentric frame: We also investigated at the possibility and interest of introducing canonical barycentric landmarks, which are centred in the dynamic barycenter of two bodies: the primary and secondary. Indeed, the literature occasionally use this type of reference frame since it

appears to considerably simplify the handling of the problem's dynamics. This is especially true in situations like the three-body problem. If we limit the problem to three bodies (Earth, Moon, and Satellite), we may utilise a system centred on the Earth-Moon barycenter, such as:

- X: Moon-Earth direction
- Z: Vector normal to the Moon's orbital plane
- Y: Z x X

It is important to remember that adding additional reference frames necessitates the addition of transition matrices in order to use them. As a result, new transition matrices are introduced:

- Terrestrial-Celestial Transition: There are various ways that allow the Terrestrial-Celestial reference frame transfer. The IERS provides the essential information on the EOPs (Earth Orientation Parameters), the data that allows this transition[11]. In brief, it is a collection of rotations that take into account the earth's rotation, pole movement, precession, and nutation. Figure 1 depicts various approaches for transitioning from a celestial reference frame to a terrestrial reference frame.

- ICRF to BCF: The IAU conventions are used to define the orientation angles of the body in order to carry out the transition from the inertial to body-fixed frame.

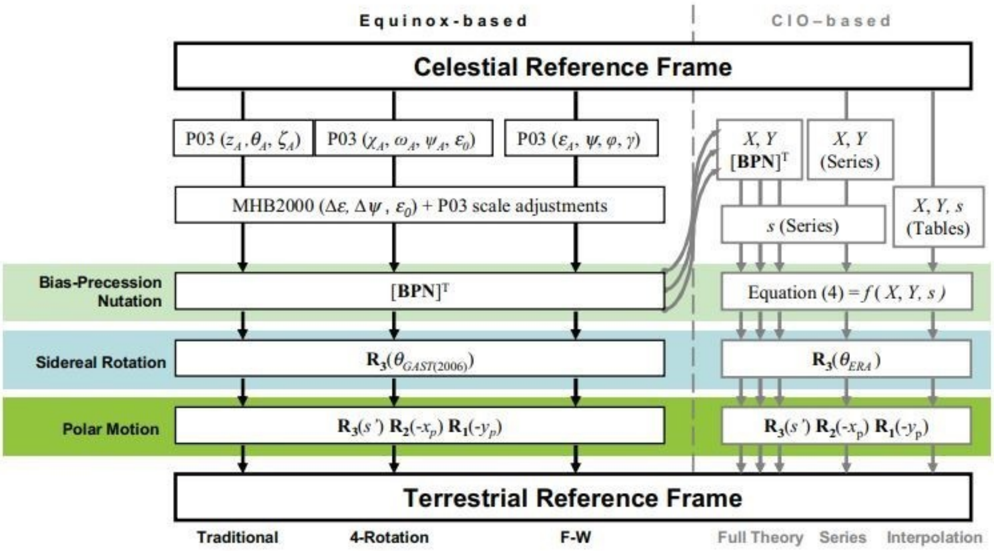

Figure 1: ICRF to ITRF methods [3]

2.2.2 Time scales

BOLERO defines a "system time", which defaults to UTC time. However, the time scale may be adjusted by using the ECART (DIONE) directive, which determines the difference between UTC and system time. For example, by setting this difference to $18s$, the system time will match to the GPS time ($TGPS - UTC = 18s$). The system time will be the TAI ($TAI - UTC = 37s$) if the difference is equal to $37s$. The terrestrial version of BOLERO can handle different types of time scales:

- TAI: International Atomic Time. It is a time scale given by the BIPM that is based on almost 150 atomic clocks located across the world.

- GPS: The Global Positioning System's atomic clocks on its satellites and ground control stations maintain a time scale known as GPS time (GPS).
- TT: Terrestrial time. It is a time scale derived from the TAI and specified by the International Astronomical Union for performing time measurements on Earth-based astronomical observations.

Different functions in BOLERO can be used to convert between these different time scales. For interplanetary applications, it is important to specify new time scales, particularly the Barycentric Dynamical Time (TDB), which is required for specific computations. It will be used to describe the satellite's equations of motion, planet's positions, the defining of reference points in the solar system, and measurement processing.

2.2.3 Attitude

BOLERO models the satellite's attitude as attitude laws that rely on the satellite's position and sometimes on other bodies (Earth, Sun). These principles govern the orientation of the platform's axis as well as the direction of the solar panels. Attitude is employed for two purposes:
- Position the satellite's (and solar panels') faces in a local orbital reference that allows the acceleration of solar radiation pressure to be calculated.
- Precisely set the satellite's GNSS antennas for theoretical measurement modelling.
There are three sorts of attitude laws represented in the terrestrial version of BOLERO:

- Geocentric
- Heliocentric
- Yaw-steering

New attitude management algorithms have been introduced for the interplanetary version of BOLERO.

- Celest-Body pointing: This pointing allows the satellite to change its attitude in order to position itself well in respect to the center of the planet/asteroid of interest: an axis orientated in the satellite-center of the planet direction. Indeed, in the context of interplanetary missions, there is a necessity to adjust the satellite's attitude to point to different planets in the solar system for observation, heat regulation, radiation (albedo), and so on.
- Inertial Provider: The goal is to be able to compute your own attitude in respect to a fixed inertial reference at all times. It's a useful and straightforward feature to implement, and it gets increasingly crucial as you work with a large number of reference frames.
- Quaternions: Quaternions are an alternate method for representing attitude. They are increasingly being used to characterise satellite attitude. They have two significant advantages: an unique representation and no singularities.

2.2.4 Force models

BOLERO takes into account the following forces:

- The force due to the gravitational potential of the Earth
- The direct force (Newton's equation) and tidal force owing to the Moon (Love's model)

- The Sun's direct force (Newton's equation) and tidal force (Love's model)
- The direct solar radiation pressure force (SRP)
- Atmospheric drag force
- Hill's empirical forces

The two key evolutions that will be added to the interplanetary version of BOLERO are the introduction of n-body dynamics in the solar system and the development of relativistic accelerations. Some new functionality were also added to pre-existing force functions, such as eclipse management for the SRP force. The next section will discuss these changes in detail.

2.2.5 Measurement models

Measurements are managed in BOLERO through the MEASURE directive. Currently, five types of measurements are considered, separated into two categories:

- Satellite measurements, using signals coming from satellites (GNSS):
  - Pseudo Range from the satellite
  - Pseudo Range Rate from the satellite
  - Phase measurements
- Stations measurements, using signals coming from ground station :
  - Pseudo Range from the station (Pseudolite)
  - Pseudo Range Rate from the station (i.e. DORIS measurements)

As can be observed, the only measurements considered are inapplicable in an interplanetary environment where new measurement types must be introduced. Typically, two types of measurements are provided in interplanetary missions: absolute and relative.

Absolute measurements with relation to the Earth, such as two-way Doppler measurements. This measurement is typical in such missions; however, as the name implies, the signal goes from the Earth station to the spacecraft and then returns to Earth to be processed. In these circumstances, it is inappropriate to use for autonomous navigation. One way Doppler is another type of measurement that may be employed. We may consider the signal simply travelling in one way and being processed by the satellite. However, this approach has not been employed in the past since it is dependent on the precision of the on-board clock, which evolves with the mission duration. When the conditions are favorable-that is, a precise enough on-board clock-or situations that allow the clock to be updated or the clock parameters to be identified-this measurement may be included in the interplanetary version of BOLERO.

When approaching or orbiting a body, relative measurements are generally more useful. These measures can be performed on board. First, optical data from the navigation camera allow the spacecraft's position to be determined in relation to the centroid of the body or a specific landmark. Laser ranging is another method that can be employed. Using laser methods, this measurement determines the distance (or time of flight) from the spacecraft to the surface of the targeted body. Finally, in the case of multiple satellites, the inter-satellite pseudo-range measurement can be used to improve the estimation of the spacecraft's relative positions. However, the last two methods have not yet been implemented in BOLERO.

2.2.6 Navigation filter

The Navigation filter is the last component that must be addressed. Of course, in order to be an autonomous navigation library, BOLERO must include a navigation filter that processes both the measurements data and the dynamical model. The Extended Kalman filter, which may also be used in the interplanetary version, has been implemented in the terrestrial version of BOLERO. As a result, no changes were required to update this filter.

3 THEORY AND CALCULATION

3.1 Reference frames

The inertial frame is necessary for the integration of calculations related to the dynamics of the satellite. The needs are to define transition functions between the inertial frame and a fixed frame linked to the central body (planets, asteroids, etc.). Two cases were differencied:

- Earth case: When the central body is the Earth, we have access to a very exact model (the orientation and movements of the Earth's pole), which necessitates specific processing. The transformation implemented to compute the transformation between the inertial frame (ICRF) and the Earth frame (ITRF body fixed) is described by Equation 1.

  $$M_{ICRF \to ITRF} = R_{PM}(t) R_3(\theta_{ERA}) R_{NPB} \tag{1}$$

  where, R_{PM} is the polar motion matrix, $R_3(\theta_{ERA})$ is the Earth rotation matrix (ERA is the Earth Rotation Angle) and R_{NPB} is the bias-precession-nutation matrix. The algorithm implemented is based on IERS specifications (SOFA algorithm) [5].

- Other cases: In cases where the central body is not the Earth but another body (such as planets or asteroids), we define a body-fixed frame based on IAU requirements. This frame is defined by three angles: the north pole's direction is given by the value of its right ascension α and declination δ, and the position of the prime meridian is indicated by supplying a value of W. (Eqs. 2, 3, 4).

  $$\alpha = a_\alpha + b_\alpha T_{cent} + \sum_{i=1}^{n} K_\alpha^i \sin(c_\alpha^i + d_\alpha^i T_{JD}) \tag{2}$$

  $$\delta = a_\delta + b_\delta T_{cent} + \sum_{i=1}^{n} K_\delta^i \cos(c_\delta^i + d_\delta^i T_{JD}) \tag{3}$$

  $$W = a_W + b_W T_{JD} + \sum_{i=1}^{n} K_W^i \sin(c_W^i + d_W^i T_{JD}) \tag{4}$$

  The transformation between the inertial (ICRF) and the body fixed frame (BCF) is then computed from Equation 5.

  $$M_{ICRF \to BCF} = R_3(\frac{\pi}{2} + \alpha) R_1(\frac{\pi}{2} - \delta) R_3(W) \tag{5}$$

  The IAU 2009 model is used for the moon and IAU 2015 for others bodies [4] [8].

3.2 Bodies position

In order to compute the forces of a n-body system, the positions of these bodies are required. Because the spacecraft does not have direct access to the positions of the bodies on board, a method to retrieve them must be established. JPL's ephemerides files allows to compute the positions of bodies in the Solar System using Chebyshev coefficients. However, these files are exceedingly large and cannot be kept on board. A program has been created to extract particular sections of these files and then save the Chebyshev coefficients a_i of a certain body across a specified time range. This program use the SPICE toolkit to do this extraction [1].
Bodies position are then computed using the Chebyshev polynomial. Equation 6 shows an example of how to compute the x coordinate. The calculated position is presented in the barycentric inertial Solar System frame (ICRF).

$$x = \sum_{i=0}^{n} a_i T_i(\bar{t}) \tag{6}$$

with recurrence relation,

$$\begin{cases} T_0 = 1 \\ T_1 = \bar{t} \\ T_i(\bar{t}) = 2T_{i-1}(\bar{t}) - T_{i-2}(\bar{t}) \end{cases} \tag{7}$$

and,

$$\bar{t} = \frac{2(t - t_1)}{t_2 - t_1} - 1 \tag{8}$$

3.3 Time scales

The definition of new time scales such as the TDB (*Temps Dynamique Barycentrique*) is required in order to perform various computations such as body position, planetary orientation angle, and so on. This time scale is defined by a number of equations, each of which is more or less accurate. However, we must consider the embarquability requirements, and certain associations with a complicated model and hence excessive CPU use, have been eliminated. As a result, we chose to use a rather basic formulation with a precision on the order of $50\mu s$ [10], which is suitable for interplanetary navigation applications.

$$TDB = TT + 0.001657 \sin g \tag{9}$$

With $g = 6.24 + 0.017202(JD_{TT} - 2451545)$.

3.2.1 Gravitational acceleration

Gravitational potentials are stored on board. They are only used to compute the central body potential and are given in body fixed frame. To compute the potential, transformation matrix from inertial to body fixed frame describe in 3.1 is used, and the implemented formulation is given by Equation 10.

$$U = \frac{\mu}{r} \sum_{l=0}^{n} \sum_{m=0}^{n} \left(\frac{r_0}{r}\right)^n \bar{P}_{lm}(\sin\ \Phi)(\bar{C}_{lm} \cos m\lambda + \bar{S}_{lm} \sin m\lambda) \tag{10}$$

3.2.2 Perturbing bodies

A perturbing body is one that has a gravitational influence on the spacecraft but is not the central body. The acceleration owing to a system of n-perturbing bodies is the total of each individual contribution. The acceleration calculation is divided into two parts: direct acceleration (Equation 11) and tidal acceleration (Equation 12). The ability to adjust the tidal effect's contribution has also been included.

$$\vec{\gamma}_P = \sum_{j=1}^{n} \mu_j \left(\frac{\overrightarrow{SP}_j}{SP_j^3} - \frac{\overrightarrow{CP}_j}{CP_j^3} \right) + \vec{\gamma}_{Tidal_j} \tag{11}$$

and,

$$\vec{\gamma}_{Tidal} = \frac{3}{2} k_2 \frac{GM_p}{r_b^3} \frac{R^5}{r^4} \left[(1 - 5\cos^2(\Psi)) \frac{\vec{r}}{r} + 2\cos(\Psi) \frac{\vec{r_b}}{r_b} \right] \tag{12}$$

with, S, P, C spacecraft, perturbing body and central body positions respectively.
The position of each perturbing bodies is calculated from Chebyshev coefficients (JPL ephemerides) stored on board.

3.2.3 Solar radiation pressure

The evolution of this force consists in the addition of a solar flux decay factor and a new eclipse management system for a central body other than the Earth. Equation 13 gives the relation to compute acceleration due to solar radiation pressure.

$$\vec{\gamma}_{SRP} = -\nu P_\odot \frac{AU^2}{d^2} C_S \frac{S}{M} \cos(\theta) [k_a \vec{u}_S + 2k_e \cos(\theta) \vec{N} + k_d (\vec{u}_S + \frac{2}{3} \vec{N})] \tag{13}$$

The shadow function ν is calculated from [2]; C_S is the radiation pressure coefficient estimated in the Kalman filter; d the distance to the Sun; $P_\odot = 4.56.10^{-6} Nm^{-2}$ the solar radiation pressure at 1 AU; S the satellite's surface; M the satellite's mass; θ the angle between the sun direction $\vec{u}_S$ and the normal vector of the surface $\vec{N}$; k_a, k_d and k_e coefficients of absorption, diffused and specular refraction respectively.

3.2.4 Relativistic accelerations

Three additional relativistic accelerations have been added to the force models, which are based on the IERS formulation [5].

- Schwarzschild term :

$$\gamma_{\vec{Sch}} = \frac{\mu}{c^2 r^3} \left[\left(2(\beta + \gamma) \frac{\mu}{r} - \gamma v^2 \right) \vec{r} + 2(1 + \gamma)(\vec{v} \cdot \vec{r}) \vec{v} \right] \tag{14}$$

- Coriolis term :

$$\gamma_{\vec{cor}} = 2\vec{\Omega}_{cor} \wedge \vec{v} \tag{15}$$

with,

$$\vec{\gamma}_{cor} = \frac{(1 + 2\gamma)}{2c^2} \sqrt{\frac{\mu_{sun}^3}{r_{body/sun}^5}} \vec{u}_{z\,Ecliptic} \tag{16}$$

- Lense-Thirring term :

$$\vec{\gamma_{Len}} = (1+\gamma)\frac{\mu}{c^2 r^3}\left[\frac{3}{r^2}(\vec{r}\cdot\vec{J})\vec{r}-\vec{J}\right]\wedge\vec{v} \tag{17}$$

3.3 Measurements

Because Lidar has not yet been implemented, the only measurement theory that will be addressed in this subsection is optical measurement. A vision based navigation (VBN) system's purpose is to extract accessible navigation observables from raw images captured by a satellite. The data will be presented in the form of a line of sight (LOS) vector from the spacecraft to the centroid of the targeted body or a landmark, expressed in the camera frame visible in Figure 2 . It is simply assumed that the LOS in the picture has been extracted earlier by an external tool, and hence just the vector is supplied as an entry in BOLERO. The camera model must be provided in order to be used in the navigation filter. In this version of BOLERO, the camera model will be assumed to be the pinhole model, a simplistic model that does not account for perturbing phenomena such as lens aberration, diffraction, etc. The pinhole model considers that "every point on the target emits a single ray and each ray maps to a point on the focal plane" [7], as can be see in Figure 3.

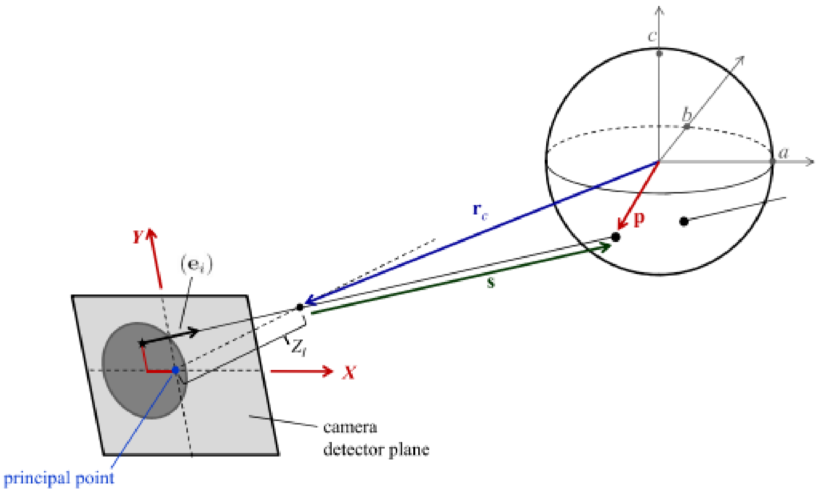

Figure 2: The LOS vector is expressed in the Camera frame [6]

A point $P(X,Y,Z)$ on the body of interest is translated to the pixel coordinates $[u,v]$ in such a model, using the Equation 18.

$$u = \frac{X}{Z}f \qquad v = \frac{Y}{Z}f \tag{18}$$

where f is the focal length of the camera. Hence, the LOS vector, e_i^C can be defined as :

$$e_i^C = \frac{1}{\sqrt{u_i^2+v_i^2+f^2}}\begin{bmatrix}u_i\\ v_i\\ f\end{bmatrix} \tag{19}$$

which can also be expressed in the inertial frame, knowing the transformations matrices from the camera to the targeted body T_C^B, and the one from the body to the inertial frame T_B^I, using the Equation 20:

$$e_i^I = T_B^I T_C^B e_i^C \tag{20}$$

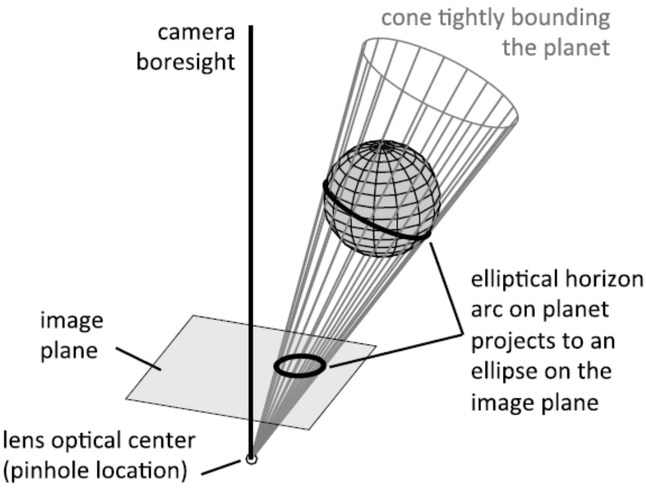

Figure 3: The pinhole camera model [6]

3.4 Validation

The validation was accomplished by selecting a dynamic model and comparing calculated acceleration between BOLERO and Celestlab (mission analysis toolbox from CNES). The idea was to start with a very simple model (keplerian) and gradually enhance it with the various contributions described in the preceding paragraphs.
For each cases, we compare position, velocity and acceleration computed on the spacecraft, resume of cases and added functionalities validated are describe in Table 1.
The results obtained are showing deviations (below $10^{-13} m/s^2$ for each acceleration's term) that are completely consistent to our cross-validation tool. In order to determine the real performances that can be obtained by BOLERO for missions outside Earth orbits, mission analyzes will be carried out using the various added models and measurements.

Table 1: Resume of added functionalities and validation

Added fonctionality	**Validation**
Propagation without Earth as central body	*Test made with Moon as central body*
Consideration of the dynamic model	*Tests made by changing central body, perturbing bodies and force models*
IAU angles computation and consideration of a gravitational potential	*Moon case: verification of angles values and simulation of a trajectory with a 20x20 potential*
Computation of bodies position from Chebyshev coefficients	*Test made by adding perturbing bodies in the simulation, and verification of bodies position by comparing to Horizons.*
Solar radiation pressure model	*Verification of acceleration values and eclipse phases by comparing to CelestLab.*
LOS measurement	*Under validation*

4 CONCLUSION AND DISCUSSION

The advancements described in this paper have enabled the navigator to be adapted for use beyond the Earth orbit. In order to be applied in such conditions, new dynamical models, time scales, and

reference frames have been developed. Furthermore, additional types of measurements have been introduced in order to perform relative autonomous navigation around various bodies. As previously stated, only relative measurements have been implemented, while other types of measurements, such as one-way radiometric measurements (from Earth to the spacecraft), are being investigated. This measurement type may be implemented, but it will need improving the qualities of the on-board clock by employing the next generation of atomic clocks, such as the DSAC (Deep-Space atomic clocks), for example. Combination of one-way and optical measurements could yield to a robust and accurate trajectory, performed onboard [9].
Furthermore, the ability to have GNSS and station measurements outside of Earth orbit has been introduced, and validation is underway; GNSS measurements might be used for orbits around the Moon or near-Earth asteroids, and could considerably increase navigation performance. Relative navigation via inter-satellite link is also being developed; it might be used for missions involving a group of spacecraft, increasing the number of missions for which BOLERO could be used, both around and beyond Earth's orbit.

REFERENCES

[1] C. H. Acton, "Ancillary data services of nasa's navigation and ancillary information facility," *Planetary and Space Science*, vol. 44, no. 1, pp. 65–70, 1996, Planetary data system, ISSN: 0032-0633. DOI: `https://doi.org/10.1016/0032-0633(95)00107-7`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/0032063395001077`.

[2] O. Montenbruck and E. Gill, *Satellite Orbits: Models, Methods, and Applications*, ser. Physics and astronomy online library. Springer Berlin Heidelberg, 2000, ISBN: 9783540672807. [Online]. Available: `https://books.google.fr/books?id=hABRnDlDkyQC`.

[3] V. Coppola, J. Seago, and D. Vallado, "The iau 2000a and iau 2006 precession-nutation theories and their implementation," *Advances in the Astronautical Sciences*, vol. 134, pp. 919–938, Jan. 2009.

[4] B. Archinal, M. A'Hearn, E. Bowell, A. Conrad, G. Consolmagno, R. Courtin, T. Fukushima, D. Hestroffer, J. Hilton, G. Krasinsky, G. Neumann, J. Oberst, P. Seidelmann, P. Stooke, D. Tholen, P. Thomas, and I. Williams, "Report of the iau working group on cartographic coordinates and rotational elements: 2009," *Celestial Mechanics and Dynamical Astronomy*, vol. 109, Dec. 2010. DOI: `10.1007/s10569-010-9320-4`.

[5] G. Petit and B. Luzum, "Iers conventions (2010)," *Tech. Rep. DTIC Document*, vol. 36, p. 180, Jan. 2010.

[6] J. Christian and G. Lightsey, "An on-board image processing algorithm for a spacecraft optical navigation sensor system," *Journal of Spacecraft and Rockets*, vol. 49, pp. 337–352, Mar. 2012. DOI: `10.2514/1.A32065`.

[7] S. Li, R. Lu, L. Zhang, and Y. Peng, "Image processing algorithms for deep-space autonomous optical navigation," *Journal of Navigation*, vol. 66, Jul. 2013. DOI: `10.1017/S0373463313000131`.

[8] B. Archinal, C. Acton, M. A'hearn, A. Conrad, G. Consolmagno, T. Duxbury, D. Hestroffer, J. Hilton, R. Kirk, S. Klioner, D. Mccarthy, K. Meech, J. Oberst, J. Ping, P. Seidelmann, D. Tholen, P. Thomas, and I. Williams, "Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2015," *Celestial Mechanics and Dynamical Astronomy*, vol. 130, no. 3, Mar. 2018. DOI: `10.1007/s10569-017-9805-5`. [Online]. Available: `https://hal.science/hal-03373773`.

[9] T. Ely, J. Seubert, N. Bradley, T. Drain, and S. Bhaskaran, “Radiometric autonomous navigation fused with optical for deep space exploration,” Aug. 2019.

[10] I. S. Board, *Iau sofa software collection*. [Online]. Available: `http://www.iausofa.org`.

[11] P. Seidelmann, *Iers: The earth orientation parameters (eops)*. [Online]. Available: `https://www.iers.org/IERS/EN/Science/EarthRotation/EOP.html`.