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Research Article

ALR_Sim_tracks — Trajectory Simulator Software to Assist the Search for Favourable Trajectories for the Exploration of the Triple Asteroid 2001-SN263 from the Laser Altimeter Point of View

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This paper presents a simulator tool, named *ALR_Sim_tracks*, dedicated to the preliminary analysis of trajectories planned for a space mission to explore the surface of celestial bodies using optical sensors, such as a laser altimeter. The software offers a prediction of the coverage results obtainable in a simulated exploration campaign carried out along a selected/simulated trajectory, for the set of target and instrument parameters used (in qualitative and quantitative terms, including 2D/3D visualizations). The software was created to perform an analysis that would allow the identification of favourable trajectories for conducting the intended exploration of the triple asteroid 2001-SN263 during Brazil's first deep space mission (ASTER mission) from the point of view of the Laser Altimeter being designed to fly on this mission, which was named ALR. Because there are few tools described and available for this type of analysis in the literature, and these are generally complex, proprietary, and of restricted use, this work aims to help broaden the understanding of the process involved and the access to this type of tool. The paper contains the description of the *ALR_Sim_tracks* software and everything involved in its operation. The illustrative examples presented in this text involve the exploration of an asteroid from the point of view of a laser altimeter, because this was the initial motivation for creating the simulator. However, other optical instruments with similar operation, used to explore other types of targets (e.g., planets or moons), are also considered when suitable modelling is available.

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1. Introduction

ALR_Sim_tracks is a trajectory simulator/analyzer software for space missions involving the exploration of the surface of celestial bodies using optical instrumentation. It was created to help with the preliminary analysis of the ASTER mission, Brazil's first deep space mission, which aims to explore the triple asteroid 2001-SN263, from the point of view of the Laser Altimeter designed for this mission, named ALR (to know more about the ASTER mission, please refer to references [1][2], and about the ALR, see [3][4]). The program simulates the point of view of the modelled optical instrument; it allows one to predict how the instrument will see the modelled Target. Its use makes it possible to foresee, qualitatively and quantitatively, the type of surface coverage that the instrument will be able to obtain using the parameters employed in the simulation.

There are few mission analysis tools that serve this purpose, and they are generally huge, complex, proprietary (in which case they are expensive), and/or restricted in use. Perhaps the most famous of these is the Systems Tool Kit[1] (STK) from the software development company ANSYS. Described as a "software for digital mission engineering and systems analysis," this is a proprietary, huge (multi-purpose), robust, and expensive software package dedicated to assisting in the conduction of the space mission since its design. This system is currently an important tool used by many space agencies. Another renowned system, the SPICE tool kit[2], was created by the Jet Propulsion Laboratory of the US National Aeronautics and Space Administration (JPL/NASA) to help design NASA missions and/or those in co-operation with other countries. The package is described as "an observation geometry system for space science missions." This system is large and complex (multi-purpose), requires training and programming skills to apply, and, although it is available for downloading and training on the internet, it may have restrictions on use depending on the user's location (ITAR[3] restrictions may apply).

ALR_Sim_tracks simulator is a dedicated tool created to focus attention on the design of the optical instrument. Its use allows the simulation of trajectories of interest (in both ways, geometrically and traditionally), and a preliminary visualization of the results of the exploration to be carried out by the instrument. For this reason, the software is small and relatively simple to use. It can be applied in the mission design phase with regard to test trajectories, but it can also be useful in the design and improvement of the optical instrument. Since there are only a few tools described and available for this type of analysis in the literature, this work also aims to help broaden the understanding of the process involved and the access to this type of tool.

In more specific terms, the simulator *ALR_Sim_tracks* was created to: **i)** generate 3D trajectories for the spacecraft based on geometric considerations of the target-spacecraft movement within the period considered, and analyze their effectiveness in exploring the surface of the celestial body targeted by the mission; **ii)** receive as input 3D trajectories of the spacecraft generated externally to the program and then analyze their effectiveness in exploring the surface of the celestial body targeted by the mission. In this case, the input trajectories are generally generated taking into account the dynamics relevant to the spacecraft's movement within the considered system during the period of interest.

The process of generating trajectories based on purely geometric considerations (target ephemerides only) is described. The details of the analysis carried out to evaluate the test trajectories in terms of their efficiency in exploring the surface of the celestial body targeted by the mission are also presented and explained in the text. Compared to the traditional approach, which uses trajectories generated by integrating the relevant dynamics involved, this simplified approach offers less expressive results. However, its main advantages are its simplicity and the speed with which preliminary results can be obtained for the exploration campaign being planned, which is why it is recommended for use in the early stages of mission planning. For validation purposes, a comparison of the results obtained using the approach described here with the traditional one was carried out and is discussed in reference [5].

Because it was created to simulate the ALR point of view within the period considered for mission ASTER (an asteroid exploration mission), the examples given in this article are related to this mission. The program has been used twice to analyze trajectories favorable to the ASTER mission from the point of view of the Laser Altimeter. In the first [5], it was used to generate and analyze encounter trajectory arcs that would allow the main target of the mission to be explored; in the second [6], it was used to help analyze specific orbits around the main target, called 'terminator orbits', with the aim of complementing the exploration carried out in the first part of the exploration. The modular nature of the software, however, allows other optical equipment to be modelled in order to have their specific viewpoints simulated and analysed over any period of interest. The same goes for different targets, such as planets, moons, etc.

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2. What the software does and how it works

The ALR_Sim_Tracks is software created using the MATLAB platform. The main program works as a script, where the sequence of activities carried out in the simulation is called. Designed to be modular, each task performed in the simulation is carried out using specific functions called within the main program, but which are programs outside of it. The same applies to data input, which is read from specific 'txt' files produced for this purpose. Figure 1 shows the sequence of operations carried out by the simulator in its first use, dedicated to the simulation and analysis of encounter trajectories for mission ASTER [5]. In the second use of the program, described in [6], terminator orbits were simulated and analyzed to check the level of coverage of the poles of the main asteroid that would be achieved using this type of orbit which, in addition and at the same time, would make it possible to observe and evaluate the interior of the triple system. Figure 2 shows the sequence of operations carried out by the program in this second case.

Obs.: In Figures 1 and 2, *DEEVE* means 'dynamically equivalent, equal volume ellipsoid', *PRF* is the pulse repetition frequency of the laser source, and DIV is the divergence angle (half cone) of the laser emitter, 'max range' is the maximum range of the instrument, *dt* relates to the time subdivisions within a simulated trajectory; *ti* are the time instants within a trajectory; ***R***ast and ***V***ast are the position and velocity vectors of the main asteroid (Alpha), ***R***sc and ***V***sc are the position and velocity vectors of the ASTER spacecraft (simulated internally or generated externally; in this case, 'SPICE' is a reference to the software used in [6] for that purpose); 'Solve nonlinear System' means that a solver is applied to find the solution to the system of equations containing the (3D) equation of the line in the direction of the instrument's line of sight (l.o.s.), with the 3D equation of the asteroid's surface (modelled as a scalene ellipsoid); *Pfp* and *ti2* are, respectively, the solutions found by the solver, i.e., the crossing points that were identified (when they exist), and the instants at which these intersections occur; Along Track Distance (ATD) and Cross Track Distance (CTD) are distance parameters that characterize the spacing of the exploration carried out on the surface. They were created to make it possible to preview the quality of the surface exploration that would be carried out using some inserted set of parameters (they are better explained below); *Dfp* is the diameter of the footprint, i.e., of each circular area illuminated by the laser pulse during its operation.

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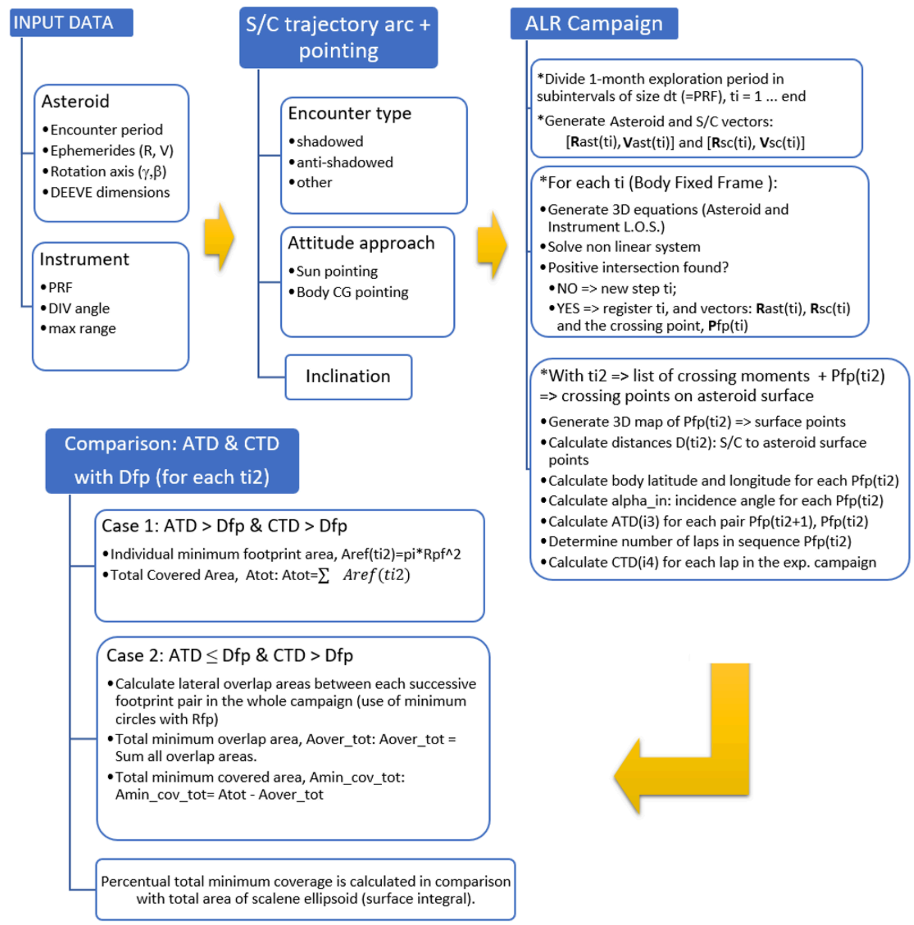

Fig. 1. Flow diagram of the sequence of operations carried out to simulate encounter trajectories favorable to the exploration intended by the ASTER mission in the view of the laser altimeter. **SOURCE:**[5]

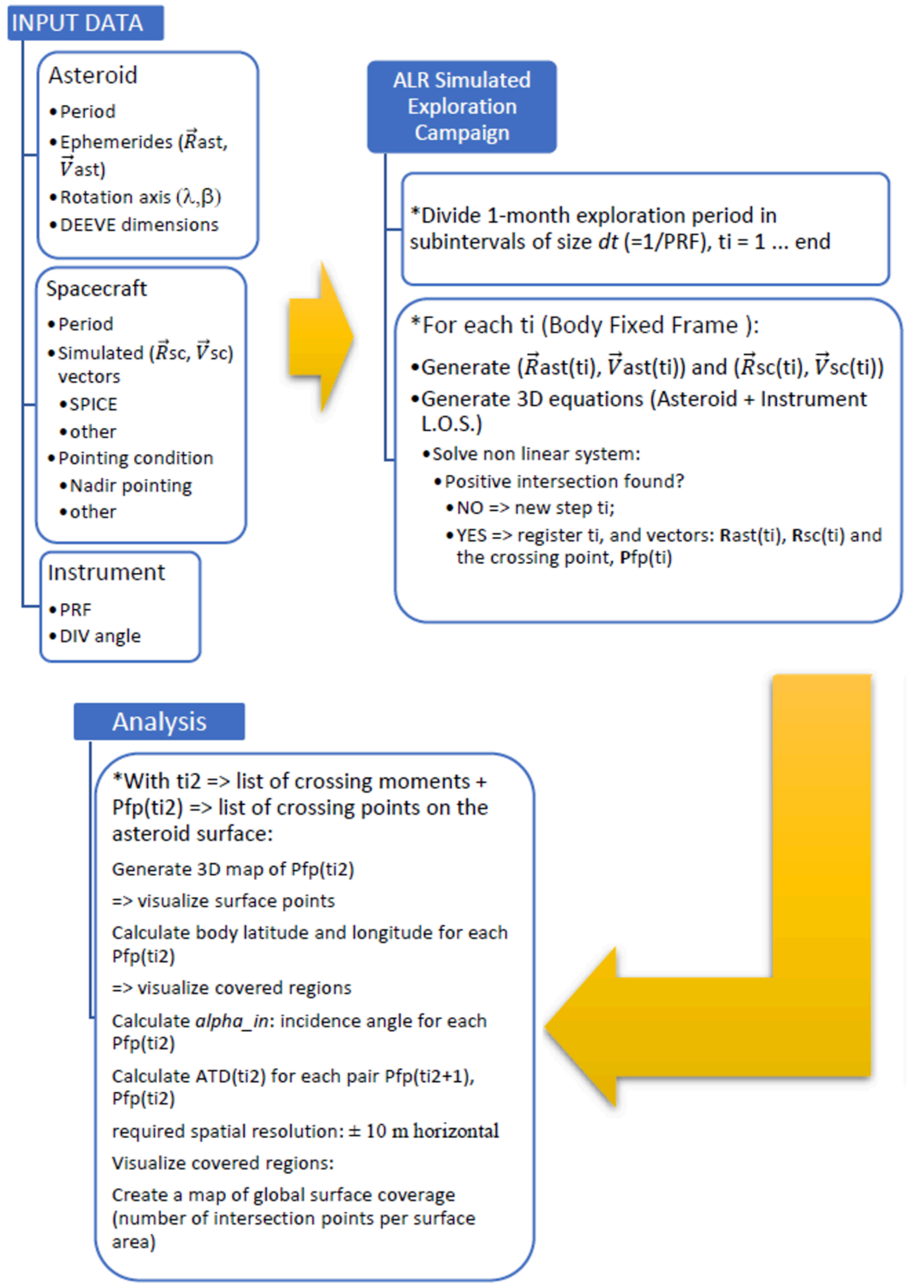

Fig. 2. Flow diagram with the steps followed in the 2nd simulation process with use of the simulator *ALR Sim Tracks*. **SOURCE:**[6].

A more detailed explanation of the program's operation is given below, starting with a description of the input parameters used (section 2.1), simulations carried out, and analysis parameters created (section 2.2), visualizations offered (graphs), and results displayed by the program (section 2.3).

2.1. Input parameters

The input parameters for the simulator are described. Each different target and/or optical instrument should have its own module, usually a specific function, where the respective characterizing parameters are listed and described, along with the values assigned to

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them, which will be accessed by the program at the start of each simulation. The parameters that model a target or instrument are usually more or less accurate models of them. The simulator can even be used to test different models and parameters in order to refine them.

2.1.1. Target parameters

i. Position and velocity: composed of vectors generated externally to the simulator, within the desired period and in the desired frame. For example, in the case of the ASTER mission, where the target is the triple asteroid 2001-SN263, the period of investigation simulated and analysed was between Dec/2024 and Feb/2025. Cartesian coordinates and velocities of the target in the heliocentric ecliptic inertial frame were generated with the help of the HORIZONS[4] tool, at time intervals of hours to 1 day. Smaller intervals are obtained by interpolation.
ii. Shape, dimensions, and rotation: a solid that models the target and its rotational parameters (axis and rotation speed) are required. Because the model of the target directly impacts the simulation results, the most updated information available should be used here. For example, in the case of mission ASTER, Asteroid Alpha was modelled, according to the most updated reference available then [7], as a 3D scalene ellipsoid with diameter dimensions equal to the minimum values of its DEEVE (dynamically equivalent, equal volume ellipsoid; radii: (rx, ry, rz) = (2. 5, 2.4, 2.1)/2 km), with a rotation period of 3.4 hours, and pole direction (ecliptic longitude and latitude): $(\gamma, \beta) = (309^{o}, -80^{o}) + 15^{o}$. It is important to note that the uncertainty in these parameters also constitutes an important input data for the analysis enabled by the simulations.

2.1.2. Instrument parameters[5]

Here, the parameters that describe the instrument under analysis, with greater or lesser specificity, are entered. These parameters can be tested to refine their design values. In the case of the Laser Altimeter for the ASTER mission, the laser divergence angle (DIV; equivalent to the Field of View of an optical instrument), the pulse repetition frequency (PRF), and the maximum range of the instrument were used. Other characteristics of the instrument, which are important for analysing the expected return signal and include features of the signal generated and/or received (inserted here are the features of the terrain, studies related to its reflectivity, albedo, etc.), and return signal processing and analysis, have been the subject of previous studies aimed at defining the instrument's design parameters [8][9].

2.1.3. Spacecraft parameters

i. Selected trajectory: the type of trajectory the spacecraft is to follow is entered here. In the case of mission ASTER, encounter trajectories for the 1st phase of the mission were initially tested; then, with a view to exploring the poles of the main asteroid, terminator orbits were tested. Reference [10] explains what a terminator orbit is and provides useful parameters for its modelling. Other trajectories and orbits can be tested by simply modelling them (internally) or inserting them (from an external source).
ii. Attitude: taking into account the trajectory to be followed, the pointing condition of the spacecraft must be selected so that the scan is carried out accordingly. In the simulations carried out, the attitude chosen is directly associated with the pointing of the device. The attitude conditions modelled and already used are:
   - * *Sun pointing attitude* – This attitude approach was inserted to comply with the encounter test trajectories of the types 'shadowed' and 'anti-shadowed' proposed in [5]. The Sun pointing attitude is not a steady inertial pointing condition, but a special Sun pointing condition, which requires attitude control to keep the

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instrument line of sight (l.o.s.) aligned with the Sun-to-spacecraft (s/c) line (positive or negative) during the exploration period. For the anti-shadowed trajectory (meaning the s/c is positioned in between the Sun-Asteroid line, in front of the Asteroid), the instrument l.o.s. is pointing to the direction from the Sun to the Asteroid C.G. Similarly, the negative Sun-s/c direction was used together with shadowed test trajectories (when the s/c is simulated in a position along the Sun-Asteroid line, behind the Asteroid).

- * *Nadir pointing attitude* – In this condition, the s/c (and also the instrument l.o.s.) is always pointing to the Asteroid C.G. no matter the s/c position. In reference [6], this pointing condition was used together with terminator orbits to allow the exploration of the poles of Asteroid Alpha. An important issue in that paper is that the analysis demonstrated the mission need for 'off axis' capability to assure the coverage of both poles.

2.2. Computations and evaluation parameters created

The parameters for evaluating the scanning carried out by the optical instrument during its operation are created according to the instrument and the specifications of the planned exploration. Their purpose is to make it possible to qualitatively and quantitatively evaluate the type of surface coverage expected for the device's operation during simulations using a set of parameters. In this way, the parameters that characterize the simulated device can be refined. When considering a laser altimeter, the footprint diameter (FTD) is a very important item to consider in the evaluation of instrument results. It influences not only the amount of coverage but also its quality (horizontal resolution). It depends on the laser-surface distance and on the divergence angle of the instrument. In the case of a narrow FOV camera, this parameter would be related to the surface area imaged by each shutter release.

Another important evaluation parameter that has an impact on the quality of the coverage is the angle of incidence (*Alpha_in*), defined between the line connecting the instrument and the normal to the target's surface. This angle must be small enough so that the deformation (elongation) of the area covered by each image taken, in the case of a camera, or illuminated by the laser in each pulse (the footprint shape, in the case of a laser altimeter) is also small. So, favorable incidence angles are important for good surface coverage. As an example, in the evaluation of encounter trajectories favorable to the ASTER mission, the footprint diameter (FTD), Along Track Distance (ATD), and Cross Track Distance (CTD) parameters were created to allow the quality of the coverage provided by the laser altimeter to be assessed in each simulation of the device's continuous operation in an exploration campaign.

These parameters are used to assess: **i)** FTD - the area covered by each laser pulse on the surface and its (geometric) shape, which is a function of the apparatus (optics) and the relative instrument-surface position (*Alpha_in*); **ii)** ATD - the distance between successive pulses and/or images taken along the imaged line, which is a function of the frequency of image-taking or emitted pulses (PRF) and the rotation dynamics of the target body; **iii)** CTD - the distance between successive lines (profiles) in an exploration campaign, which is a function of the instrument-surface distance and of the trajectory under test (inclination between the simulated spacecraft trajectory arc and the target orbit). Figure 3 illustrates ATD and CTD in the case of the instrument ALR, the laser altimeter for mission ASTER. It is important to emphasise that, depending on the selected trajectory type, some of the mentioned parameters may become meaningless, and other parameters or approaches will be used to assess coverage. For example, in the case of the simulation of the complementary part of the exploration to be carried out with the laser altimeter during the ASTER mission, described in [6], which aimed to identify trajectories favourable to exploring the poles of the main asteroid, terminator-type orbits were identified and simulated. In this case, because of the geometry involved and the relative target-spacecraft dynamics, the CTD parameter became less important, and coverage was assessed using the more usual approach of the number of images taken per sector of surface area.

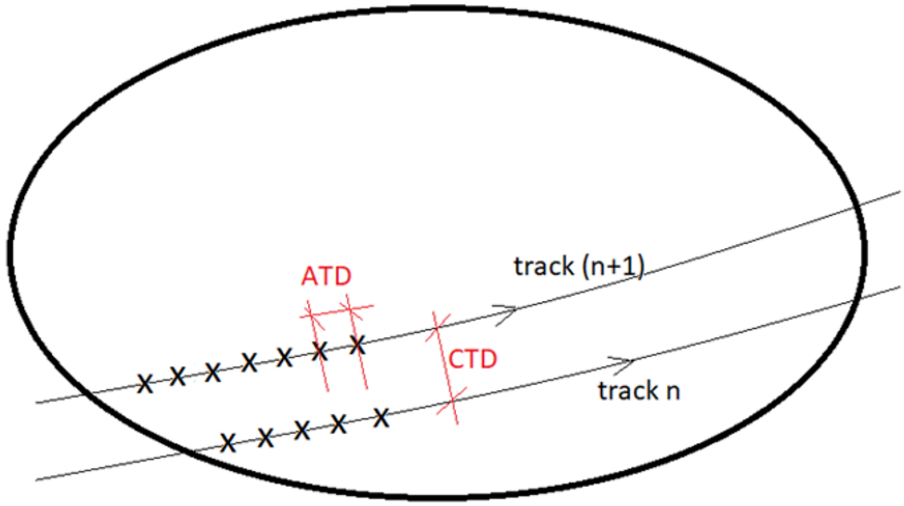

Fig. 3. Definitions of ATD and CTD on the target surface during a simulated exploration campaign. The side-by-side points in a track represent the successive footprint centre points obtained through successive emission of laser pulses and are related to the instrument PRF. CTD is represented by the distance between track *n* and track *(n+1)*. **SOURCE:** [5].

2.3. Main results produced

Once the simulation has been carried out, the simulator offers graphs and tables that allow visualisation of the details of the exploration that would be conducted using the set of parameters entered in the simulation. Although the software also allows the insertion of externally generated trajectories, as is the case with trajectories and orbits generated from the integration of the dynamics relevant to the movement of the spacecraft [6], which is the most common case, special attention is paid here to the results obtained using geometrically simulated trajectories. This possibility makes it simple, easy, and quick to obtain a preliminary view of the results expected for the exploration to be conducted using a set of parameters and is useful in defining and refining them. Some results regarding the use of the simulator to study the intended exploration in the ASTER mission with the laser altimeter have been presented previously and had their validity discussed in [5][6].

2.3.1. Main graphical results

i. **Visualisation of simulated or inserted trajectories or orbits:** in the preferred system, inertial or body, this graph makes it possible to visualise the trajectories in use in the current simulation over an exploration period. Encounter trajectories (side by side with the target) and orbits around the target have been simulated. Other trajectories can also be modelled and inserted. Figure 4 shows 'terminator' orbits around the main asteroid, with a reference distance of 8 km from it. This orbit was identified as promising for mission ASTER [6] (it has been widely studied in the mentioned reference and was called there 'reference orbit'). The analysis carried out in [6] used orbits obtained externally, from the integration of the dynamics relevant to the spacecraft's movement within the triple system. Figure 4(a) shows the orbits travelled by the spacecraft over a period of 30 days (the simulated exploration period), as seen from a coordinate system centred on the asteroid. The visualisation of these orbits therefore shows them to be more compact around the asteroid. Figure

4(b) shows the same orbits, but they are now viewed from an inertial coordinate system centred on the Sun, which explains the orbit-to-orbit spacing/shifting seen in the period. Figures 4(c) and 4(d) show internally generated orbits based on geometric factors relating to this type of orbit (characterisation parameters to generate terminator orbits were obtained in [10]). Figure 4(c) shows these orbits in the asteroid-centred frame (AST2). When compared to Fig. 4(a), the 11 orbits followed in the period of 30 days (see [6]) coincide in this view because of the idealisation applied to generate them. In Figure 4(d), the same orbits are seen in an inertial coordinate system centred on the Sun. Compared to Figure 4(b), the same orbit-to-orbit shifting due to the frame of view is expected here, but the regularity seen here is due to the idealisation applied to generate these orbits. The visualisation offered by Figures 4(c) and 4(d) favours comparison with those obtained by integration, in Figures 4(a) and 4(b). In terms of exploration results (surface area covered, density of surface coverage, preliminary identification of uncovered areas, preliminary assessment of attitude strategy), both orbits produced similar results.

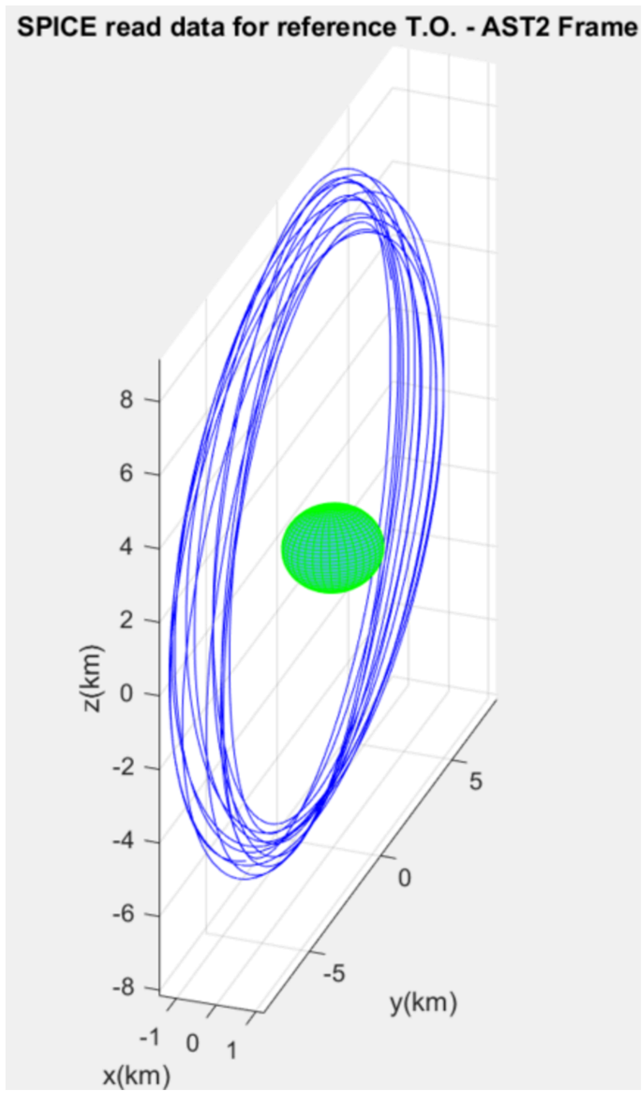

Fig. 4(a). Terminator orbits obtained externally (by integration), inserted into the main program for analysis. Here, views of the AST2 frame (centred on the asteroid with X to Sun, y to the Asteroid's Velocity vector).

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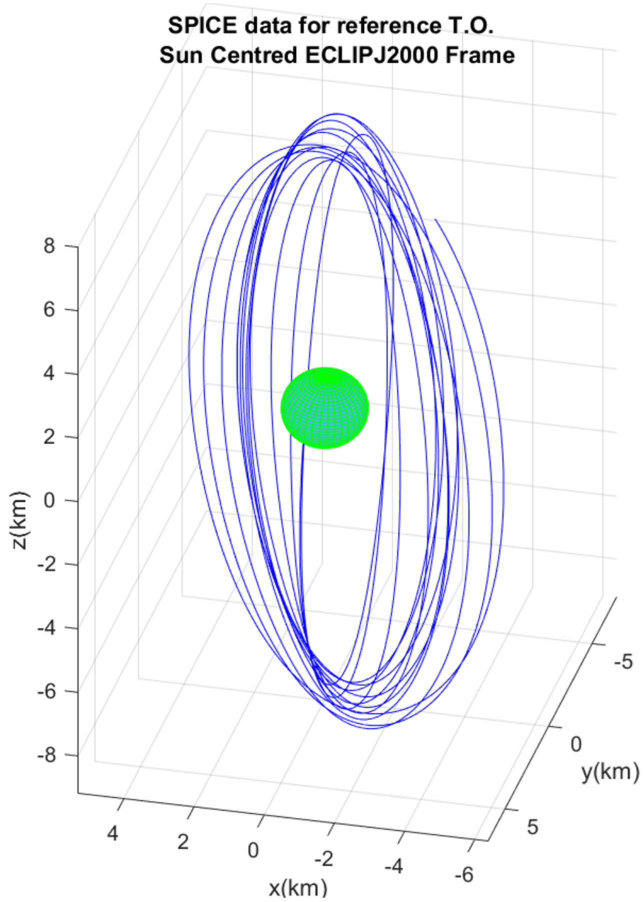

Fig. 4(b). The same Terminator orbits obtained externally are seen here from the ECLIP J2000 frame, which is heliocentric, ecliptic, and inertial. The observed shifting among them is explained by the heliocentric point of view.

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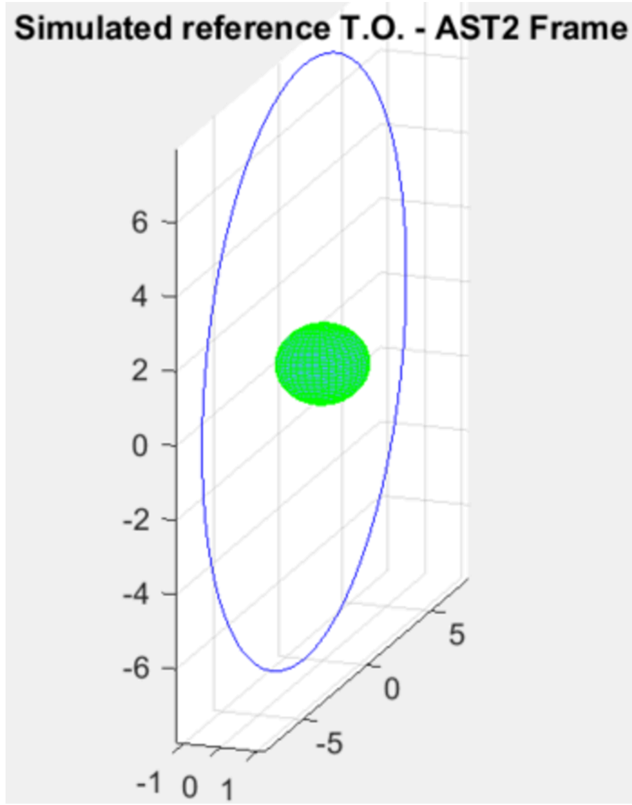

Fig. 4(c): Terminator orbits simulated from the expected geometry within the simulator software are seen here in the asteroid-centred frame (AST2).

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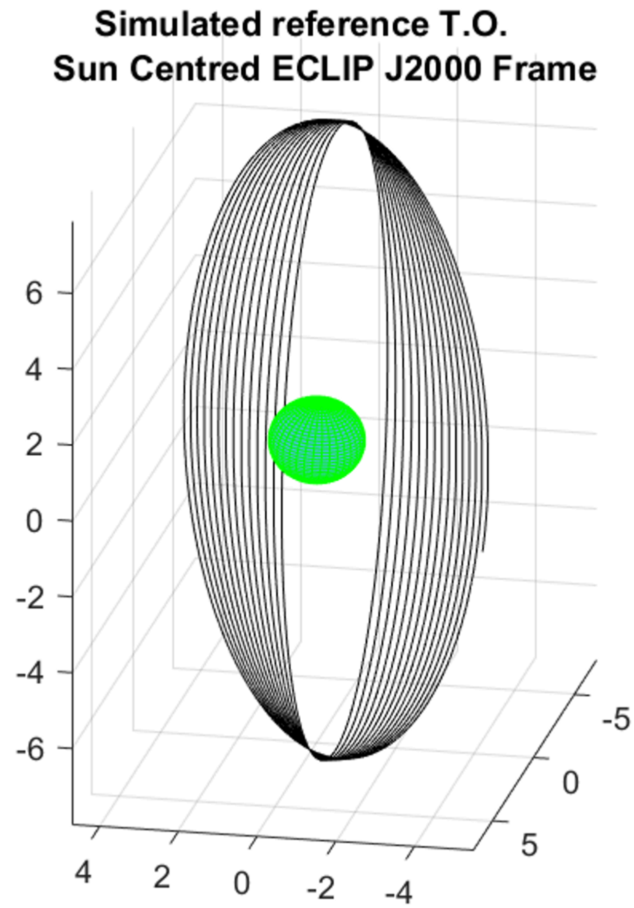

Fig. 4(d). Terminator orbits simulated internally within the simulator software are seen here in the ECLIP J2000 frame, which is heliocentric, ecliptic, and inertial.

ii. **Visualisation of the pattern imprinted by the scan on the target surface:** in the coordinate system fixed on the target (body system), this visualisation shows the centre points of the images taken or areas illuminated by the optical instrument on the target surface, obtained from the intersection of the optical instrument's line-of-sight with the ellipsoid or other solid model representing the target. In the case of laser altimeter pulses, these are the centre points of the areas illuminated by each pulse according to the simulated scan. This graph shows the pattern imprinted on the target's surface by the simulated scan and, together with the accompanying data, makes it possible to assess the surface resolution of the scan that would be achieved (along track and cross track), including the visualisation of regions with greater or lesser coverage. Fig. 5(a) exemplifies a case presented in [5] (related to the simulated exploration of the main asteroid of the system 2001-SN263, named 'Alpha'), and shows this pattern for an exploration carried out on a selected area of this target (latitude range, in this case from -40 to +40 deg). Fig. 5(b), extracted from the same case illustrated by Fig. 5(a), shows a detailed view of the minimum areas (red circles) illuminated by each pulse for a test of a set of simulation parameters.

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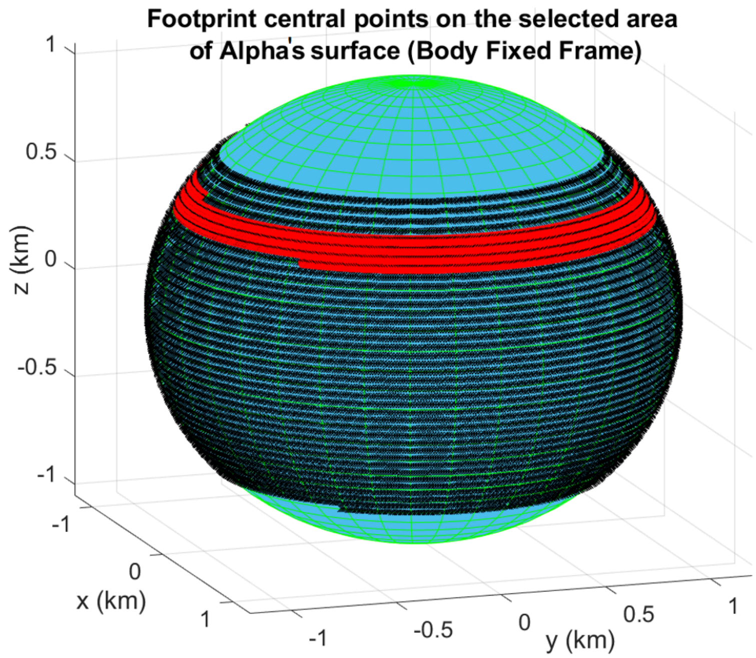

Fig. 5(a). Graph illustrating the points of intersection of the instrument's l.o.s. with the target surface (footprint central points, in black) on the main asteroid surface (2001-SN263). It is possible to zoom in on the figure. In red, the footprint areas are represented.

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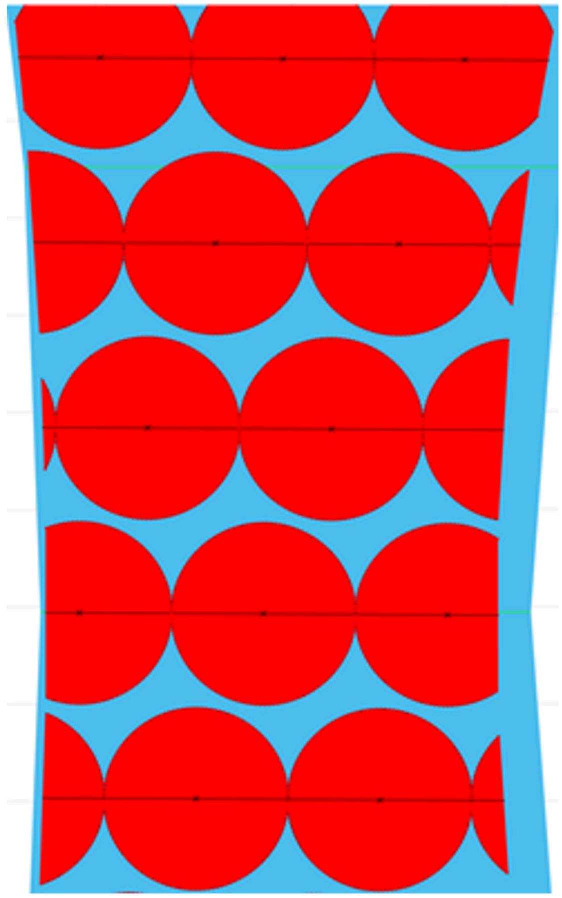

Fig 5(b). Detail (close-up) of a group of footprint minimum coverage areas (red circles). Extracted from Fig. 5(a), here, they are seen in the limit where no overlap areas for CTD exist.

iii. **Incidence angle distribution along the latitudes of the target body:** in the body system and as a function of its latitudes, this graph shows the distribution of the incidence angles of each l.o.s. of the optical instrument (taken with respect to the normal to the target surface). This information is important because the intensity of the light signal that returns to the device after reflection on the surface (to be detected and recorded by the instrument) depends on this angle being small enough. It is common, for example, at high latitudes and also due to the geometry (model) of the target, to have the existence of large angles of incidence. In these cases, the intensity of the light reflected by these regions is reduced, which affects the signal-to-noise ratio and the quality of the information collected. Figure 6(a) illustrates the incidence angles for the exploration simulated in [5] (asteroid 2001-SN263). In this case, the scan extends over the entire surface (latitudes -90 to +90 degrees), which reveals the existence of very high incidence angles in the regions closest to the asteroid's poles.

iv. **Distribution of footprint diameters:** in the body system and as a function of body latitudes, this graph (Fig. 6(b)) shows the variation in the footprint size (total area illuminated by each pulse over the surface) throughout the simulated exploration. In the case of an optical instrument, this information is related to the portion of terrain that will be covered by each image or illuminated by each pulse (in the case of a laser altimeter). It is clear that this parameter affects the resolution of the images or profiles acquired by the instrument and must be kept within values that comply with the mission requirements for the instrument. When considering a laser altimeter, these values must also be controlled because, in this case, the intensity of the signal which returns for detection and recording also depends on it. As an example, in mission ASTER, the requirements for the laser altimeter are ±10m horizontal resolution for a distance of about 40 km [5].

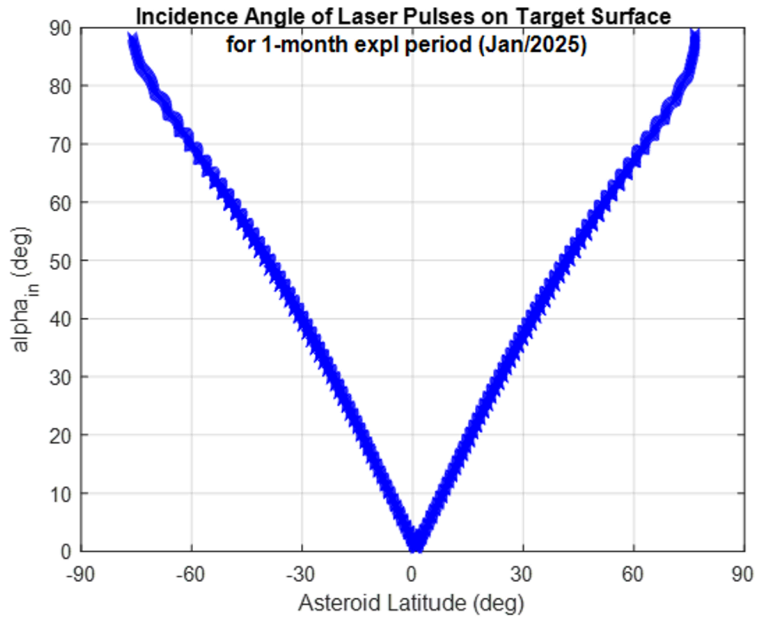

Fig. 6(a). For the main target of the ASTER mission, this graph shows the distribution of incidence angles of each pulse hitting the surface as a function of the latitudes of the target body. Very high incidence angles are expected in the regions close to the poles. Source: [5].

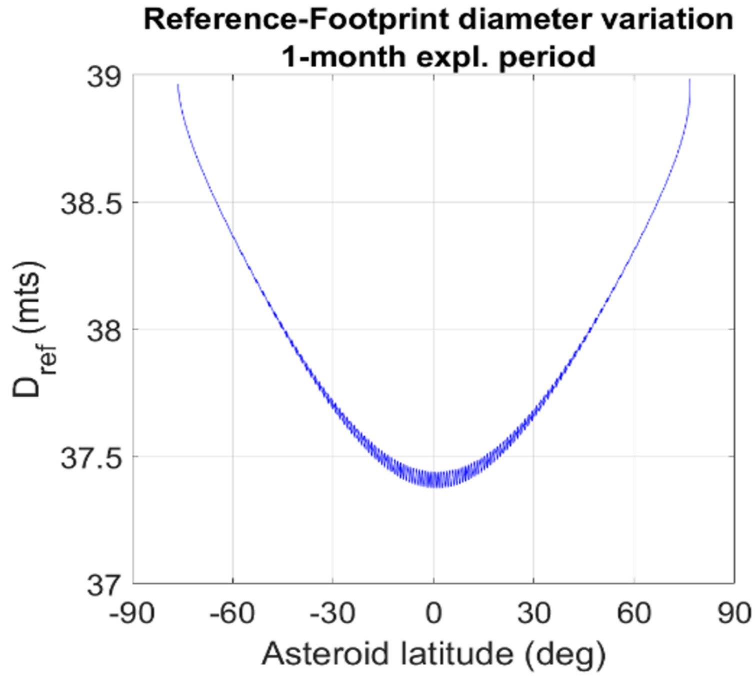

Fig. 6(b). For the study related to the ASTER mission, from the point of view of the laser altimeter, this graph shows how the diameters of each footprint vary within a complete exploration campaign (1 month, in this case). Source: [5].

v. **Along Track Distances (ATD):** in the body system and as a function of body latitudes, this graph shows the variations in the distance parameter between successive images taken (or incident pulses, in the case of the laser altimeter) over the course of a complete simulated exploration. Fig. 3 explains the concept of ATD, and Fig. 7(a) shows an example of the variation of this parameter in the simulated exploration conducted for mission ASTER. Note that only the region of interest is focused on (-40 to + 40 deg latitudes). More specifically, the distances are calculated between the centers of the areas successively illuminated by each pulse or covered by each image (in the case of an imaging camera). Together with D_{ref} (Fig. 6(b)) and CDT (Fig. 7(b)), this parameter is important if the spatial resolution requirement imposed on the instrument for the mission is to be met.

vi. **Cross Track Distances (CTD):** like ATD, this graph shows the variations in the parameter that monitors the distance between successive profiles (lines imaged/scanned) during a complete exploration campaign. This is very useful when the exploration is done with the use of an encounter trajectory, which profits from the rotation of the target to image it systematically and sequentially, like the peeling of an orange, but it loses (or changes) its importance when the simulated trajectory is an orbit around a rotating target. Fig. 3 illustrates the CTD concept, and Fig. 7(b) shows the calculated variation of this parameter during the simulated exploration for the ASTER mission (note the selected region: -40 to + 40 deg of body latitudes). Together with D_{ref} (Fig. 6(b)) and ATD (Fig. 7(a)), this parameter is important for fulfilling the spatial resolution requirement of the mission in relation to the instrument operation.

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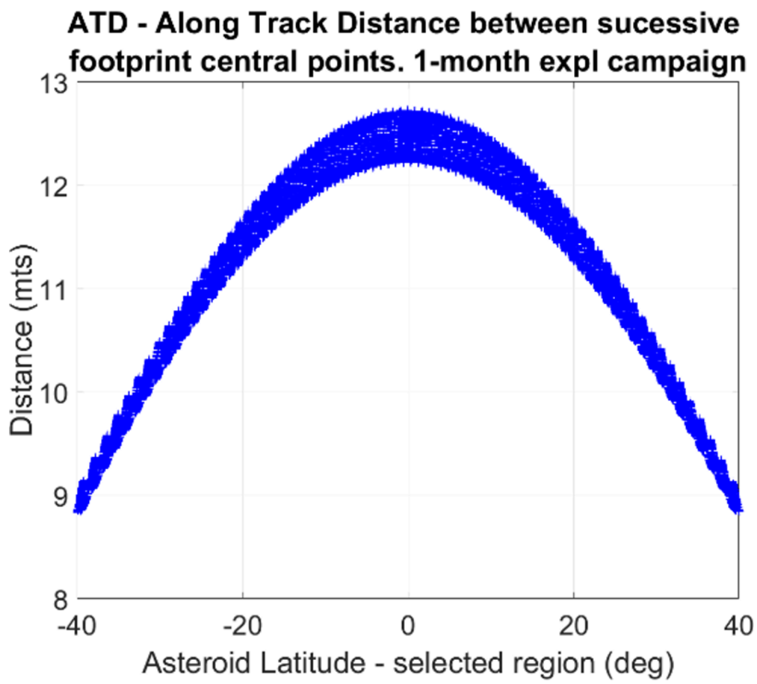

Fig. 7(a). Distribution of distances between successive pulses hitting the surface (Along Track Distances, ATD) for a test case and a selected region (-40º to +40º). Source [5].

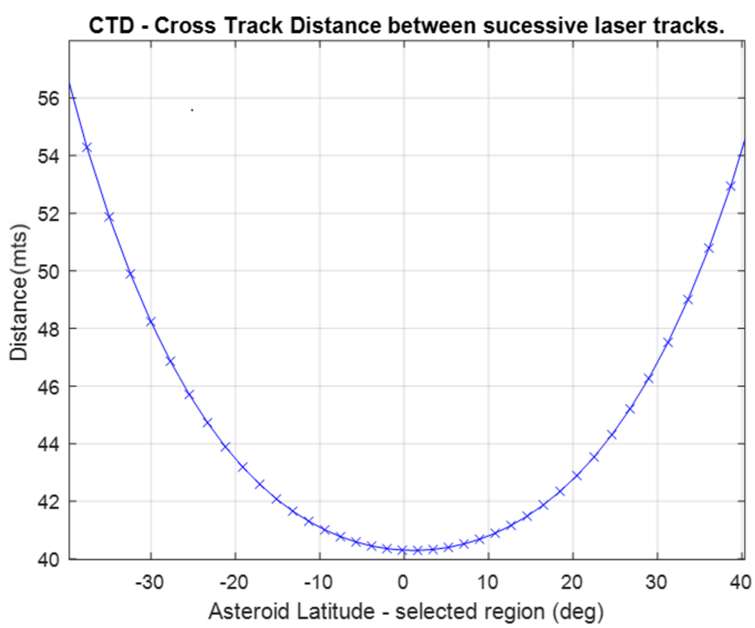

Fig. 7(b). CTD - Distribution of distances between successive lines within a complete exploration simulation for a test case (selected region only).

vii. **Total coverage:** In the body system, this graph allows the visualisation of the surface area of the target that is expected to be covered by the scan when some specific set of parameters is entered. When the details of this graph are observed, the quality of the

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scan can be assessed in terms of the spatial resolution that is expected to be obtained. Fig. 5(a) illustrates the partial coverage of the target's surface on an area of interest (latitudes between +40 and -40 degrees, in this test case). Fig. 5(b) shows the details of a portion of the minimum areas covered by each pulse hitting the surface, identified in Fig. 5(a). Total coverage is calculated from the sum of all partial coverages, excluding the intersections between them, if any. Parameters ATD, CTD, and D_{ref}, presented above, are important in these calculations.

viii. **Coverage in number of hits per surface area:** This is a 'Mercator' or 'world map' type graph, which shows a flat projection of the target's surface (latitude vs longitude), where a count of the number of laser pulses or images that hit each rectangle of the target body's surface area is displayed. The counting takes into account the footprint or F.O.V. centre points calculated and stored during the simulation. The latitude and longitude subdivisions are adjusted as desired, for example, 2^o x 2^o, 1^o x 1^o, etc. Figures 8(a) and 8(b) are examples of this type of graph. In addition to the graphs, the software also calculates the value of the total minimum coverage area, based on the sum of the minimum areas covered by each footprint, excluding the areas where they intersect, within a complete exploration. In the case of the Laser Altimeter for the ASTER mission, these calculations were used to demonstrate that the minimum coverage desired for the main exploration campaign (50%) could be achieved if the conditions raised in the survey were followed (see [5] for details of these calculations).

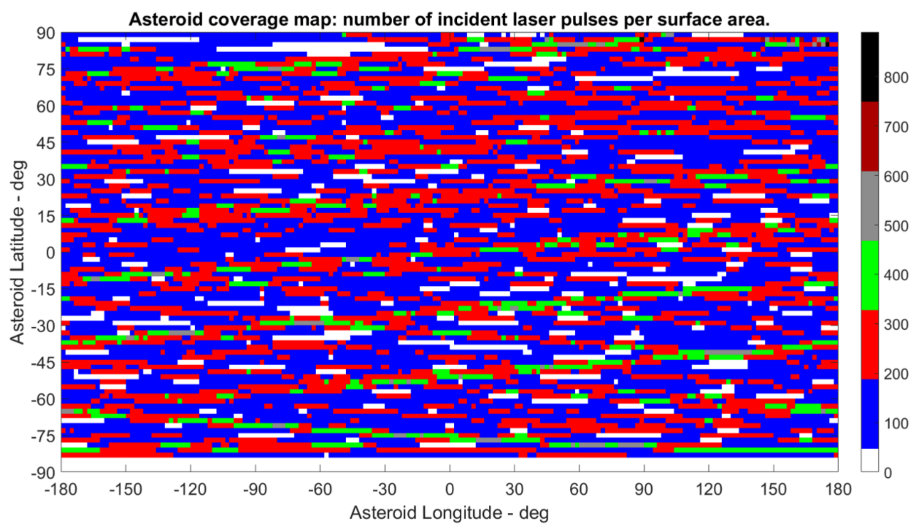

Fig. 8(a). The flat map of points per area indicates the number of times the instrument (identified by its line of sight) hits each sector of the body's surface area, divided into small latitude x longitude elements. The width of the areas is selectable (2^o x 2^o, with pulse repetition frequency, PRF, of 1Hz, in this illustrative example).

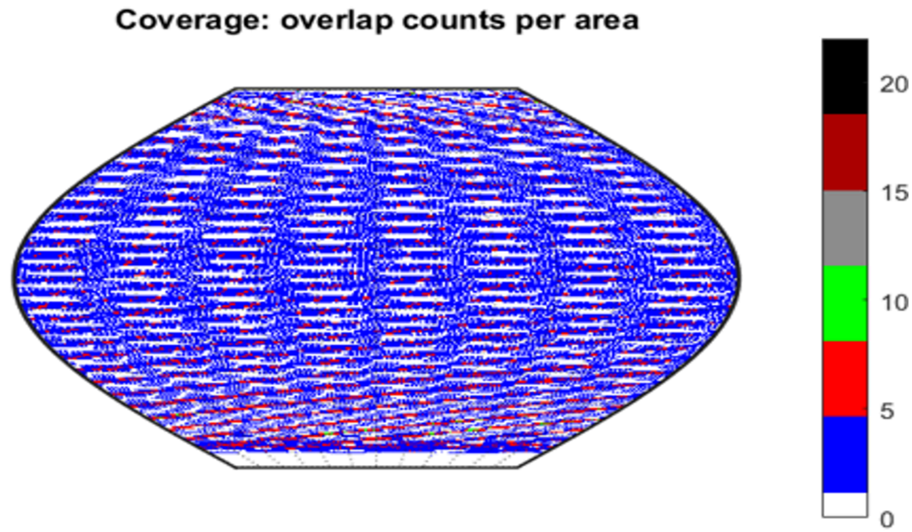

Fig. 8(b). Another presentation of the count of pulses hitting each element of surface area is shown (1^{o} x 1^{o}). In this example, the *Terminator* orbit is used for the simulated 1-month exploration campaign (1 month) studied in [6]. This figure highlights the low coverage of the target's south pole under the simulation conditions.

2.4. Functions that comprise the software

The modules that make up the software are listed below, and the function of each is described. In the MATLAB environment, subroutines are functions called within the main program.

2.4.1. ASTER_ALR_Sim_Tracks_v1.m

This is the main program. It is a script in which the entire flow of calculations involved in the simulation process is inserted. All the functions that make up the package are triggered inside this main program. A brief description of these functions and all the files called inside this main program is given.

i. **importfile_target_ephemeris_data.m** - Initially, the target's orbit data for the desired period, collected or produced externally, is read by the program using this function, which points to the text file with the target's time, position (X, Y, Z), and velocity (Vx, Vy, Vz) coordinates in the coordinate system of interest and for the desired period.

Note: In the case of the study carried out for the ASTER mission, this file was used to read the Cartesian ecliptic heliocentric inertial coordinates (ICRF/J2000) of asteroid 2001-SN263 throughout the month of January 2025, every hour, collected using the HORIZONS platform (JPL/NASA).

The input parameters are then read and/or set:

ii. **read_ target_features.m** - this function loads all the parameters that define and characterise the Target, such as its dimensions (depending on the model used), spin axis pointing direction, and rate.
iii. **read_instrument parameters.m** - this function loads all the parameters that define and characterise the instrument, such as, in the case of the laser altimeter for the ASTER mission, the divergence angle of the emitter (DIV), the pulse emission frequency (PRF), etc.
iv. **read_test_track_ parameters.m** - this function loads all the parameters that define and characterise the spacecraft's test trajectory, such as the desired target-spacecraft

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distance and relative position (in the case of an encounter trajectory), time subdivisions of the trajectory (*dt*: in days, hours, min, or sec), parameters for the relation between the trajectories (such as the slight inclination inserted between the trajectories of the spacecraft and the target, studied in the case of the ASTER mission), and any others.

v. **read_other_ parmeters.m** - This function is used to read additional parameters that are useful and/or necessary for the simulation. For example, here the scan can be focused on the target's region of greatest interest (in the coordinate system fixed to the body of the target). This is useful for concentrating the scan with the instrument in the most favourable region. For example, in the case of the exploration of asteroid 2001-SN263 with the laser altimeter, this region is the central one (equatorial, between -40 and +40 degrees), because the simulations showed large angles of incidence of the laser beam in the regions near the poles, which compromises the detection of the return signal of the laser pulse emitted by the instrument.

vi. **simulate_trajectory.m** - based on the Target's trajectory, the sort of spacecraft trajectory to be tested is selected and generated at previously defined time intervals (*dt*). Initially, in the same coordinate system as the target. There are many possible variations, from various types of encounter trajectories to different types of orbits around the target. In [5], encounter trajectory arcs were simulated geometrically as shadows of the target trajectory (see Fig. 1). In [6], geometrically generated 'terminator' orbits around the target were generated to favour the comparative analysis of them with those generated externally, from traditional integration methods (see Figures 2 and 4).

vii. **Eclip_to_IBC.m** – this function transforms the spacecraft's trajectory coordinates from Inertial Heliocentric Ecliptic to the IBC (inertial body coordinates) system, which is a system centred on the asteroid's body, but is inertial. It has the Z_ibc axis aligned with the z_body axis.

viii. **IBC_to_ast.m** – this function transforms the spacecraft's coordinates from the IBC system to the system fixed on the target's body. It is in this system that most of the computations are carried out.

ix. **Attitude_select.m** - This function selects the attitude mode to be used in the simulation, which is supposed to coincide with the pointing of the instrument. The attitude modes used so far were Sun pointing and Nadir pointing (target CG pointing). The first is used to test encounter trajectories, where the pointing is given by the line joining the Sun and the spacecraft (direction Sun=>spacecraft or spacecraft =>Sun); the latter was used to test interesting orbits (obtained by other means) around the target body.

x. **bf3d_nonlinear_solver.m** – this function was created for the purpose of calculating intersection points of the laser l.o.s. with the surface of the modelled ellipsoid. In the case of the laser altimeter, the set of points identified represents the center of the areas illuminated by the laser pulses in all shots. This set of points depends on the attitude mode selected.

xi. **Ast_3D_ellipsoid_rotated.m** – this function generates a 3D model ellipsoid already considered the rotation given by its spin axis. This graph is important for the visualizations related to the exploration done on the target surface, for instance, those showing the pattern impressed by the exploration on the surface, grid of points, individual areas (footprints), overlap areas among footprints, coverage, etc.

xii. **ellipsoid_sector_area.m** – this function is dedicated to calculating properly the Target Surface Coverage and the Total Overlap Area.

xiii. **ATD_calcs.m** - In a scanning simulation, successive incident laser beams or images taken in succession have their centre points and areas calculated. This function uses the successive points of intersection of the instrument's l.o.s. with the surface of the target, the centres of the footprints, to calculate the distances between them. In the case of encounter trajectory tests, these distances depend on the latitude of the target body. The graph produced by this function shows the distribution of distances (ATD) in relation to the latitude of the body.

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xiv. **CTD_calcs.m** - this function uses the sequential exploration profiles (lines) demarcated by the centres of the footprints on the target surface to calculate the distance between successive lines, referred to here as cross track distances. These distances also vary with the latitude of the body, and the graph produced with this data is a function of this parameter.

xv. **Incidence_angles.m** – This function is dedicated to the calculation and analysis of the incidence angles of each instrument l.o.s. hitting the target surface. A graph with the distribution of these angles related to the body latitude is produced.

xvi. **Area_calcs.m** – this function is dedicated to the calculations related to the instrument coverage of the target surface. The whole surface area is calculated, the area of the considered sector (lat1 to lat2), the total reference area inside the selected sector, total overlaps area, and the total covered area.

xvii. **Lat_Long_plainMap.m** – This function creates the Asteroid coverage map by dividing the surface area of the target into rectangular subareas of controllable size (latitude vs longitude, in degrees), then it counts the number of incident laser pulses in each area element.

3. Flexibility of the simulator to other optical instruments

The simulator has been created to represent the point of view of a laser altimeter in an asteroid exploration mission. However, it can be adapted to the point of view of other optical instruments used to explore other targets, as long as these instruments operate in a similar way, i.e., by collecting light information from small areas of the target's surface in order to obtain, from the sum of these, the total coverage related to their activity. Instruments like this generally have a Field of View (FOV) with a central line of sight (l.o.s.). In general, they are used for close exploration, as is the case with a laser altimeter or a proximity imaging camera (narrow FOV). Other optical instruments will need to be adapted for use.

4. Future developments

The simulator is in its final stages of development and will be registered soon. Some possible improvements concern the geometric and dynamic models of the target used. As the simulation results depend very much on these models, it is advisable to use the most recent information available to build the most accurate model possible. In the case of the ASTER mission, the main target and its dynamics were modelled by a rotating 3D scalene ellipsoid, built according to the most up-to-date information available at the time [7]. However, as soon as more detailed information on the target's geometry and dynamics is obtained, the model should be improved in order to obtain better predictions of the exploration to be carried out using the modelled instruments. Additionally, with regard to the uncertainties in the models, another improvement suggested by reviewers is to insert them together with the input parameters that define the target, instrument, etc., in order to broaden the spectrum of the simulation carried out, for example, to be able to identify the best and worst possible cases and prepare for them.

5. Conclusions and comments

The *ALR_Sim_tracks* simulator has been created to allow early visualisation of the results that should be expected in a planetary mission when exploring the surface of a specific target (represented by the set of parameters that characterise the target) during a specific period of time, using a modelled optical instrument (represented by the set of parameters that characterise the instrument), in the event that the exploration is carried out when the spacecraft follows the simulated and/or entered trajectory (read as input data). For this reason, a wide variety of trajectories can be tested with its use. More specifically, in the MATLAB environment, the simulator software was created to: i) generate 3D trajectories for the spacecraft based on geometric considerations of the target's movement over the period considered and analyse their effectiveness in exploring the surface of the celestial body targeted by the mission; ii) receive as input 3D trajectories of the spacecraft generated externally to the program and analyse their effectiveness in exploring the surface of the celestial body targeted by the mission. In this case, the input trajectories are generated taking into account the dynamics relevant to the spacecraft's movement within the considered system during the period of interest. The simulator was used twice to analyse trajectories favourable to the ASTER mission from the point of view of the Laser Altimeter. In the first [5], it was used to generate and analyse encounter trajectory arcs that would allow the main target of the mission to be explored as intended; in the second [6], it was used to help analyse specific orbits around the main target, called 'terminators', with the aim of complementing the exploration carried out in the first part of the exploration.

The generation of trajectories geometrically, based on what is known and expected of them, is a novelty and offers an opportunity for quick preliminary analysis to reject conditions and/or first define the set of values inserted and tested in the simulations. This was done previously in the analysis carried out for the ASTER mission [5][6]. For example, the study presented in [5] aimed to verify whether there were favorable encounter trajectories for the exploration intended for the ASTER mission, concerning the laser altimeter. The simulations and analyses conducted then made it possible to positively answer this question by determining which values the exploration parameters (trajectory and instrument) should assume for the exploration to be as successful as intended. Summarizing those results, in terms of trajectory, when the simulation considers target-spacecraft distances of about 30 to 40 km, Sun-pointing attitude, and January 2025 as the period of exploration, then a very slight trajectory inclination is required (on the order of 10^{-6} deg) to achieve the desired surface coverage results (higher than 50%, main asteroid only, already accounting for the resolution requirement of ±10m horizontal). In terms of the instrument, the simulations indicate PRF values (pulse repetition frequency) higher than 1/20 Hz as sufficient (against the preliminary reference value of 1 Hz), together with a laser emitter divergence angle between 500 to 650 μrad (half cone). In addition, a particularly important result is that simulations showed that coverage would concentrate in the equatorial region of the target, which indicated the need for a different approach to reach the poles when this is desired. In reference [6], the aim was to complement the coverage obtained in the main campaign. In this way, the study indicated that some Terminator orbits would be effective in guaranteeing the coverage of the target asteroid poles. In the mentioned work, a terminator orbit about 8 km distant from the main asteroid was successfully tested, and the set of conditions necessary for this complementary coverage to be achieved is outlined.

In this way, this author believes that the simulator *ALR_Sim_tracks* can be successfully used in the analysis of planetary missions with planned explorations to be carried out by optical instruments, such as laser altimeters or even proximity imaging cameras, which have a central line of sight and operate sufficiently close to the target, aiming to cover its entire surface area using sequential individual images or pulse shots. Exploration missions like this are more common today (Bepi-Colombo [11], Messenger [12], the two Hayabusa missions [13], OSIRIS-Rex [14], etc.).

Statements and Declarations

Code Availability

The ALR_Sim_tracks software described in this article is not publicly available at the time of publication but is planned for registration. Further information and requests for access may be directed to the corresponding author.

Data Availability

The datasets generated and/or analysed during the current study primarily consist of simulation outputs derived from the described software and publicly available ephemeris data (e.g., via JPL HORIZONS). Representative results are included in this published article (and its supplementary information files, if applicable). Further inquiries regarding specific simulation outputs can be directed to the corresponding author.

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Footnotes

[1] See https://www.ansys.com/products/missions/ansys-stk

[2] To know more about the SPICE tool kit, see https://naif.jpl.nasa.gov/naif/index.html

[3] International Traffic in Arms Regulations (ITAR) is a U.S. regulatory regime to restrict and control the export of defense and military-related technologies. See http://www.pmddtc.state.gov/index.html

[4] JPL/NASA; http://ssd.jpl.nasa.gov

[5] Many other parameters comprise the design of an optical instrument. Not all of them, however, matter for evaluating the expected coverage of the target's surface from the type of optical scan that is carried out in the simulation.

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Declarations

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