Reviewed plan of the ALR, the laser rangefinder for the ASTER deep space mission to the triple asteroid 2001-SN263

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Abstract: The Brazilian deep space mission ASTER plans to send a small spacecraft to investigate the triple asteroid 2001-SN263. The launch is expected to occur in June, 2020. The main motivation of the mission is the development of technology and expertise to leverage the national space sector. The main scientific goal is the investigation of the triple asteroid 2001-SN263. To aggregate the widest possible Brazilian involvement in all mission sectors, some instruments for the mission are planned to be developed in partnership among Brazilian institutions. In this effort, a preliminary design of a laser altimeter to meet the mission needs was created and presented in 2010-2011. Since then, many studies were conducted and new information on the target asteroid was gathered. To take this into account, a review of that plan was conducted and the current results for the instrument design parameters are presented.

1. Introduction
The Brazilian deep space mission ASTER plans to send a small spacecraft to encounter and investigate the triple asteroid system 2001-SN263. There is a launch opportunity in June, 2020, with insertion in heliocentric orbit in Feb, 2021, arrival in April, 2022, time of flight: 1.85 years, exploration phase: 4 months, and estimated budget of 60 Million USD. The use of the low-cost Finnish-Russian platform MetNet is planned.

The main motivation of this mission is the development of technology and expertise to leverage the national space sector. In terms of scientific goals, the investigation should bring some indications on the formation of this triple system and each of its main three asteroids will be separately investigated as to dynamic and orbital properties, shape, size, volume, mass distribution, mineral composition, topography and surface texture, gravitational field and rotation speed.

In order to fulfill these goals, different scientific instruments are planned including one laser altimeter. The scientific data will be sent to Earth via telemetry. References [1, 2, 8, 9, 11] provide more details on the ASTER mission and the target system.

A preliminary design of a laser altimeter to meet the mission needs, named ALR (ASTER Laser Rangefinder), was created and presented [6]. Since then, many studies were conducted, including the creation of simulation software for the better understanding of the instrument operation (ALR_Sim®) [4, 5], new decisions were made and new information on the target asteroid was gathered. To take this into consideration, a review of that plan was conducted and the current results for the instrument design parameters are presented.

2. ALR – The Laser altimeter for space mission ASTER
Concept - The instrument measures the time of flight (T.O.F.) of the laser pulse, i. e., the time the laser pulse takes to leave the instrument, reflect on the target asteroid surface and return to the instrument. Thus, the distance and relative velocity between the spacecraft and the asteroid system can be precisely measured. A topographic profile of the target, corresponding to the course of the beam over the surface, can be produced and, by interpolation, a global model of the asteroid shape can be obtained.
Functions - The ALR will contribute with the geodesic and geophysical characterization of the asteroids that are part of the triple system. The data acquired with the equipment will be combined with data from the imaging cameras to gather up topographic features of the targets.

The instrument will also be useful in the probe navigation in the approximation stage – distance of 30 to 40 km from the center of gravity (CG) of the system – and proximity stages (to each of the asteroids; decision of reaching distances <30 km), providing precise information concerning the distance spacecraft-target, and the relative velocity between them. Also, the ALR will be used to calibrate the infrared spectrometer on board.

ALR Scientific Objectives
- A model of the shape of the main asteroids in the system should be obtained with ≤10m precision, in terms of spatial resolution (surface) and height (topography), in relation with the CG of the asteroid, in illuminated regions or those with no illumination.
- The mass of the asteroids should be defined (level of precision to be determined).
- Gravitational terms J1 and J2, which describe how the mass of the asteroid is distributed, should be determined (level of precision to be determined).

Use of the data obtained by the ALR
- Construction of topographic profiles of the asteroids;
- Creation of a model of the global shape of the asteroids;
- Support for the study of geodesic parameters of the asteroids (coordinate system, rotation, etc.);
- Support for the definition of the orbit and the modelling of gravitational data;
- Support for spacecraft maneuvers;
- Measuring surface roughness and albedo (at laser frequency);
- Support for autonomous navigation (as a sensor) at the approximation stage.

3. Design General Directions
- Design aiming to minimize instrument size and weight.
- Minimize telemetry commands and functions; simple commands: on, off, start of operation, end of operation, gain adjustments, etc. Table 1 summarizes the wanted features for the instrument.
- Use of simple and independent optics: transmitter and receptor.
  The classic Cassegrain telescope, with optical deposition and a light material mirror, but also hard and resistant (silicon carbide or aluminum).
- Low-power Electronics.

4. About the instrument operation
From initialization, the equipment should operate continuously throughout the whole investigation period of the mission (T≤6 months). The initialization should occur at a distance of less than 50 km from the target. Initially, it may be useful for navigation providing precise information concerning distance and relative velocity. Following the preliminary investigations results, the signal to start the maneuvers and obtain a closer position to the system will be given. In this case, a new spacecraft-target distance (CG of the triple system) will be defined by the mission management. References [2, 3] show more information on the physical data of the triple asteroid system.

Between 20 to 30 km, ALR can be used to investigate the dynamic characteristics of the system, as well as those related to shape, dimension and topography of the asteroids, with distance measurements error <10 m. The first scientific use of ALR should be about this distance from the main target, asteroid Alpha. In this case, the beam divergence, $\alpha$ (half-cone angle), should be small, and the power should be enough to obtain a return signal that is related to a 10 to 20 m footprint (radius of the illuminated area). This is sufficient to conduct the scientific analyses related to this approximation stage. For the stage of closest approximation to asteroid Alpha, about 10 km, the footprint radius should be between 5 and 10 m, which implies a beam divergence angle between 0.028° and 0.057°, in which $\alpha = \text{atan} (d/D)$, with
d=footprint radius and D=distance to the target; 0.028°=500 μrad. The footprint is planned in order to enable the best possible mapping of the target surface. The distance between successive measurements, as a function of the shootings frequency and of the spacecraft-target relative motion (including the rotation of the target), cannot exceed a maximum value that would make it impracticable to obtain an improved surface model in terms of horizontal resolution.

Concept of the joint operation
The laser electronics controls the laser operation and directs pumping diodes inside the laser head, in which the laser beam is generated. The laser beam is collimated and expanded by the beam expander; then, it leaves the instrument through the exit optics of the transmitter, and goes towards the surface of the target asteroid. The signal reflected by the target is received by the reception telescope (receptor) and focused on the detector plan. The rangefinder has algorithms implemented in the receptor electronics to sample, record and transmit the return signal (internally, to the on board computer; externally, to Earth via telemetry).

5. Transmitter and receptor
The transmitter will be operated by shooting commands programmed in the control unit of the equipment. Operation can also be externally commanded, via telemetry. Triggering the transmitter or not will depend on the signal sent by the Attitude and Orbit Control Subsystem (AOCS), which can confirm the correct spacecraft pointing. In operation, ALR will send the collected information to a data processing and storage unit. Such data should be used on board (by AOCS, as information concerning navigation and support to the operation of other scientific instruments) and/or sent to telemetry.

The laser transmitter consists of a Nd: YAG laser, diode-pumped, Q-switched, operating at 1.064 μm wavelength. The technology of this laser is mature and can produce high energy pulses that meet the criteria of low power consumption and reduced size. The operation in the close infrared gives this laser a wide variety of efficient optics and detectors that are commercially available, which positively influences the decision to use it. The optical diode-pumped laser assures the long-life low power consumption of typically 50,000 hours or up to 18 million 10 pps shooting. A unit of laser diode operating at 808 nm will basically consist of its current source and thermoelectric coolers to stabilize the emission wavelength. Pumping geometry will be linear, including the diode laser attached to the Nd: YAG crystal, two infrared mirrors and a LiNbO3 electro-optic modulator for the Q-switch.

The laser source operating in Q-switching mode should be able to produce minimum energy pulses of 5-16 mJ, lasting up to 15 ns with repetition rates varying from 1 to 10 pps, thus producing laser pulses with 1 MW of optic power. The energy of the laser pulse should be high, because, according to [10], 2001-SN263 is a C-type asteroid, which means its albedo should be relatively low at 1.064 μm. Besides, the repetition rate influences the horizontal resolution along the beam path over the asteroid surface. However, the commitment between the horizontal resolution, energy consumption and dissipation of heat was used to establish a value for the repetition rate of the order of 1 pps. Beam divergence and its pattern are mainly determined by the geometry of the optical cavity and have an impact on the size of the footprint over the asteroid terrain.

Receptor operation will be controlled by a temporal gate, which is also internally programmed in the control unit. Generally, the gate only triggers the receptor within the time gap in which the return pulse is expected. Thus, the time to gather random noise decreases, and the relation signal/noise is maximized. This time gap defines de maximum detectable altitude gap in a single shot. In its simplest operation mode, the transmitter is commanded to generate an exit pulse, while a start signal is sent to the counting clock. When the echo or return pulse is received by the receptor, a stop signal is sent to the counting clock to allow range calculation. However, when the record of the return pulse waveform is also demanded, then the return pulse is received, first pre-processed (to extract range), then sampled (at 5ns sampling frequency). The sampled return wave is then recorded and stored for further submission. The entire sampling is commanded by the receptor oscillator. Preliminary results, related to the distance to the surface, are made available for on board use (navigation). The recorded and stored waveforms are
sent to Earth to be post processed in order to extract additional information like inclinations, topography details, and albedo. The registers in the clock are then formatted for the next reading.

Figure 1 – Simplified block diagram of the ALR. The LIDAR, on board Hayabusa mission [12], is the main source of inspiration for the design of the ALR.

As to the instrument optics, selected the independent approach, the transmitter optics is simplified and has functions such as collimation and expansion of the exit beam according to the specification of the mission (divergence <500 μrad). A Galilean telescope with proper filters and lens can be used for this purpose. A Cassegrain type telescope is devised for the receptor, with both internal mirrors made of a hard and resistant material, such as silicon carbide (SiC) or aluminum, the latter being much lighter. The choice for aluminum requires a nonthermal design, like the one used in the laser rangefinder that flew in the NEAR-Shoemaker mission [7].

6. Electronics
According to the guidelines of the mission, it is necessary to optimize resources. In order to meet this objective, the same electronic unit should control both the transmitter and the receptor (integrated electronics). The transmitter electronics includes feeding, triggering and shooting of the laser source, besides the electronics that is dedicated to controlling the operation. The receptor electronics is in charge of its operation, which includes the photo detector element (PD) and the preamplifier, besides the control of the receptor (integrated with the transmitter). This item also detects the pulse reflected by the target, pre-processes it, obtains the shape of the received pulse wave, processes this signal, stores and sends data to other equipment on board or to Earth, via telemetry (use of memory), among others. Internal algorithms are needed here to do this processing.

7. Software
Internal algorithms - After being implemented in the electronic unit, they are used to first pre-process the signal, obtain the shape of the wave, analyze the pulse, detect the border, calculate the distance, etc. Algorithms are implemented in the electronic control unit and conduct the processing of the received signal/pulse, providing the desired information – calculation of the distance to the target, for example, and other items to be conducted in real time for use on board (other devices/instruments), or to send to Earth.
Operation modes - The device shall remain in standby mode. An auto-checking and calibration mode, integrated or not with a desirable FDIR mode (fault detection, isolation and recovery) is required.

Mode 1: navigation - In this mode, at the encounter phase (D ≤ 50 km), the ALR shall be triggered. Its use will solely help navigation, offering AOCS with range measurements to control proximity and relative velocity (at 1Hz frequency).

Mode 2: surface explorer – to be activated only at the stage of greater proximity with the target asteroid (within the operating range of the unit), the ALR system will be used in continuous operation, to survey of topographic features of each area to explore. Here, in addition to the measured distance, the returning pulse waveform is sampled (5 samples, 5ns intervals, 8 levels of signal intensity). Each of these campaigns can last from weeks to months.

A group of algorithms to be used in the processing and control unit of the instrument have already been the subject of study. References [4, 5] describe these algorithms along with the software created to simulate the instrument operation. The simulator software package is called ALR_Sim® and it constitutes an integral part of the instrument design. It was created with the overall objective to serve as a laboratory for the understanding, implementation and testing of all the concepts involved in distance detection using a pulsed laser rangefinder equipment based on the time of flight of the light emitted. The modeling and simulations made it possible to understand the details of the operation of an instrument similar to the ALR. Such understanding allows the identification and definition of design parameters essential to the operation, as well as the refinement of previously established values for some parameters. The Simulator provides the appropriate environment for the implementation and testing of the routines that integrate the control and signal processing software of the instrument. Additionally, the results of the simulations offered important information for the definition of specific components suitable for the composition of the unit, bearing in mind the objectives of the unit within the mission.

Table 1. Summary of predetermined features for the ASTER Laser Rangefinder.

| Feature                              | Specification                                      |
|--------------------------------------|----------------------------------------------------|
| Mass                                 | Reduced (< 5 kg)                                  |
| Dimensions                           | Reduced (Max: 37.5 x 23.0 x 35.0) cm³              |
| Power                                | ≤ 20 W                                            |
| Operational Range                    | 30 m ≤ D ≤ 50 km                                  |
| Precision                            | Vertical: 10 m (D < 50 km) to 1 m (D ≤ 10 km)      |
|                                      | Horizontal: < 10 m                                |
| Wavelength                           | 1.064 µm                                          |
| Pulse-width                          | 10 ns                                             |
| Repetition rate (frequency)          | 1 Hz = > fixed. Should suffice for topographic analysis |
| Pulse energy                         | 5 a 16 mJ                                         |
| Transmitter’s divergence             | <500 µrad                                         |
| Life period                          | < 6 months (after initialization)                 |
| Footprint                            | < 10 m (radius; 10 km away)                       |
| Temperature                          | ±2°C (depending on the detector)                  |
| Self-calibration during flight        | Yes                                               |
| Sampling of return waveforms         | Yes                                               |
| Acquisition data rate                | > 12 bytes/sec                                    |

Data acquisition rate when in operation (mode 2) - As the vertical resolution of the detector has been set at 5ns, this is the returning pulse waveform sampling frequency. Therefore, a data acquisition rate of about 12 bytes/sec (1 for shooting, 2 for arrival, 5 of the waveform, other identification data) is provided for.

8. Conclusions and comments
In general terms, the most important item for the ALR design were defined and presented. This development is centralized in the Aerospace Engineering group of UFABC.
The development will be performed in stages (A, B, C, D). Stage A is at its end and it consists of the creation of a detailed development plan. At other stages, the models are created and tested. The first model, to test the functionality of the core instrument (the setting of unqualified elements or modules on a plate that is different from the final version), is in progress.

The ASTER Project has been recently inserted in the regular activities of the National Institute for Space Research (INPE).

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