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Preliminary development plan of the ALR, the laser rangefinder for the ASTER deep space mission to the 2001 SN263 asteroid

Abstract: *The Brazilian deep space mission ASTER, as temporarily named, plans to send a small spacecraft to encounter and investigate the triple asteroid 2001-SN263. The launch is scheduled (initially) to occur in 2015, arriving in 2018. The main motivation of the mission is the development of technology and expertise to leverage the national space sector. Within the scientific goals, the investigation of the still unknown asteroid 2001-SN263. The main project guideline is to aggregate the widest possible Brazilian involvement in the platform, the development and operation of subsystems, integration, payload, as well as in the tracking, navigation, guidance and control of the probe. To meet this guideline, among others, the decision for the development of a laser altimeter in Brazil to fly in the mission was taken. This effort is currently coordinated by a group of researchers from the aerospace engineering personnel of UFABC. This article presents the preliminary development plan for the design of this instrument, which was called ALR (ASTER Laser Rangefinder).*
Keywords: *Deep space mission, Laser altimeter, Laser rangefinder, ASTER, ALR.*

THE FIRST BRAZILIAN MISSION TO DEEP SPACE: ASTER

The Brazilian space mission ASTER, as it was temporarily named, plans to send a small spacecraft to find, orbit and investigate the still unknown triple asteroid system 2001-SN263 for approximately six months. Launch is initially scheduled for 2015 (first launch window), arriving in 2018.

The mission will be conducted from the low-cost Finnish-Russian platform MetNet, with initial liquid mass of 152 kg and total mass directed to a 30 kg payload and nominal power of 2.0-2.1 kW. Such restrictions demand reduced dimensions, masses and consumption in the project of scientific instruments.

The main motivation of this mission is the development of technology and expertise in order to leverage the national space sector. Thus, the main guideline is to aggregate the widest Brazilian involvement in the platform, the development and operation of subsystems, integration, payload, as well as in tracking, navigation, guidance and control of the probe.

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.

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In order to fulfill these goals, different scientific instruments are planned to compose the payload of the mission. Among them, there are a multispectral camera (wide and narrow-band), a laser altimeter, and an infrared spectrometer. The scientific data will be sent to Earth via telemetry. The references Sukhanov *et al*. (2010), Araujo *et al*. (2010) e Winter *et al*. (2010) provide more details on the ASTER mission and the target system.

To meet the project guidelines, the laser altimeter was developed in Brazil, and the engineering coordination of this initiative was a responsibility of the research group of Navigation, Instrumentation and Aerospace Systems (NISA, in Portuguese), comprised of professors of the Aerospace Engineering course at *Universidade Federal do ABC*. This article presents the preliminary plan to develop this equipment, which is called ALR (ASTER Laser Rangefinder).

ALR – THE LASER ALTIMETER FOR THE ASTER MISSION

Concept

The instrument will measure the length of time for a laser pulse to leave the instrument, reflect on the surface of the target asteroid 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 will be produced. By interpolation, a model of the global shape of the asteroid will be obtained. From measurements of amplitude and shape of the returning pulse, the reflectivity of the surface, its inclinations and roughness (within the area illuminated by the laser pulse = footprint) will be modeled. The characteristics of the equipment are defined and presented this study, in order to enable the described investigation.

Functions

The ALR will contribute with the geodesic and geophysical characterization of the asteroids that are part of the triple system. The data in 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 for the navigation in the approximation stages – distance of about 30 km from the center of gravity (CG) of the system – and closest to each of the asteroids (decision of reaching distances <30 km), thus providing precise information concerning the distance of the spacecraft to the target, and the relative velocity between them. Also, ALR will be used to calibrate the infrared spectrometer.

Due to the high number of functions and the importance of each of them, the laser altimeter is essential for the mission.

Scientific Objectives of ALR

- A model of the shape of the main asteroids in the system should be obtained with ≤10 m 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).

Using the data obtained by ALR

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

The importance to develop ALR in Brazil

The development plan that better meets the technological objectives of the mission and of Brazil, according to the National Plan of Space Activities of the Brazilian Space Agency – PNAE/AEB (PNAE for the decade 2005-2014; www.aeb.org.br) , should prioritize the construction and qualification for the space of scientific equipment and instruments, together with the academy, research institutes and national companies, thus strengthening the national space sector as to the development of new essential technologies and human qualification.

ABOUT THE DEVELOPMENT OF ALR

Team

Team of Science

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Laser/detector development

Flávio C. Cruz – IFGW/UNICAMP e company BR Labs (based in Campinas)

Other partners

Álvaro Alberto Cuccolo – OMNISYS Engineering/ UFABC

Requirements related to the operation

From initialization, the equipment should operate continuously throughout the whole period of the mission investigation (T≤1 year).

The equipment should initialize its operation less than 50 km from the target. In this first moment, it may be useful for the spacecraft navigation providing precise information concerning distance and relative velocity in the maneuvers to establish the encounter with the triple system.

After the encounter is established (*rendezvous*), an initial investigation of the system will take place. In this phase, the equipment can be useful to verify the spacecraft pointing (coarse attitude) and the distance to the asteroids, that should be measured with ±10 m precision.

According to the results of the preliminary investigation, the signal to start the maneuvers and obtain a position that is closer to the system will be given. In this case, the new distance between the spacecraft and the CG of the system will be defined by the mission management after more data on the formation and dynamics of the system are obtained. For now, there are few details about the orbits in this system. Table 1 gathers the available information.

According to Winter *et al*. (2010), the mass of asteroid 1 is much greater than the mass of the other asteroids (M_1=1.149x10^{13} kg; M_2=8.0%M_1; M_3=.6%M_1), the mean orbital radius of asteroid 2 around asteroid 1 is ±17 km, which shows that the encounter to a distance much shorter than 30 km cannot occur, unless the satellite asteroids have coplanar orbits. The maximum approximation of the spacecraft in this safer perspective should remain, however, from 20 to 30 km. In this position, 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 with <10 m error.

After this investigation, a new approximation can be conducted. The type of approximation will depend on the decision of the mission management. Both the establishment of a closer position, within the *rendezvous* with the system, and the one obtained from the establishment of an orbit around one of the asteroids are considered at the moment.

The first asteroid to be investigated at a higher resolution will possibly be the biggest one (asteroid 1). Studies conducted by Araujo *et al*. (2010) point to the possibility to establish an orbit around this asteroid with radius between 10 and 13 km. Orbits around asteroid 2 (intermediate mass) with radius of approximately 5 km are also under analysis. In these cases, ALR will be used to map the topographic characteristics of these asteroids with 1 m resolution. Also, at the end of the

Table 1. Orbital and Physical Data.

Asteroid	Orbit	a[1]	e[1]	I[1]	Period[1]	Radius[1]	Mass[2]
A_1	Sun	1.99 AU	0.478	6.69°	~2.8 years	1.4 km	$M_1 = 1.15x10^{13}$ kg
A_2	A_1	17 km	*	*	~147 hours	0.5 km	$M_2 \cong 7.9x10^{-2} M_1$
A_3	A_1	4 km	*	*	~46 hours	0.2 km	$M_3 \cong 5.7x10^{-3} M_1$

*Still not determined; [1]Nolan *et al*. (2008); [2]calculations for density = 1.0 g/cm^3, estimated density: 1.3 ± 0.6 g/cm^3 (Becker *et al*., 2008); Orbital data a, e, I refer to values of semi-major axis, eccentricity and inclination of the elliptical orbit, respectively. 1 AU (astronomical unit) = mean distance Earth-Sun ≅ 150 x 10^6 km.
SOURCE: Winter *et al*. (2010).

mission, a closer approximation and possible contact with one of the asteroids may occur. Since the mission will not have other devices available to measure the distance to the surface of the target, it is recommended that the operational range of the ALR be expanded to the maximum possible proximity (<50 m). In order to meet these objectives, the equipment should be able to operate at a range that varies from 50 km to less than 50 m, with 10 m and 1 m precision, respectively.

In terms of footprint (area that is illuminated by the laser beam over the surface of the target, and depends on the beam divergence and the distance to the target), at initialization and first trigger of ALR (from 40 to 50 km away from the target), beam divergence should provide a return signal of the pulse that was sent, in order to confirm the spacecraft pointing and the proper functioning of the equipment. Within the limits of operation of the equipment (approximately 40 km), the first values concerning the distance to the asteroids can be determined, thus confirming the relative positioning of the spacecraft. The first scientific use of ALR should be about 20 and 30 km away from the main target, asteroid 1. In this case, the beam divergence, α (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 1, about 10 km far, the ray of the footprint should be from 5 to 10 m, which implies a beam divergence angle between 0.028° and 0.057°, in which α=atan (d/D), with d=footprint radius and D=distance to the target; 0.028°=500 μrad. It is also recommended to observe that subsequent studies on the dynamics of the bodies in the triple system should confirm the values of the cited characteristics, related to the transmitter optics. The footprint should also be 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 target rotation can not exceed a maximum value that would make it impracticable to obtain an improved surface model in terms of horizontal resolution. The distance considered as ideal is the one which results in approximate continuous measurements of the terrain topography.

Design guidelines

1. Reduced configuration (mass, dimensions, power, resource consumption).
2. Modular approach to develop the system.

Thus, the development of modules in Brazil (and their parts) may be conducted as a result of a partnership between the academy and institutions of the national aerospace sector. The initiative is coordinated by the aerospace engineering team of UFABC.

Modular division

There are three modules to be developed: transmitter, receptor and electronics. The design regarding the parts and the whole system aims to simplify all the items related to the instrument operation. Thus, the design of the LIDAR, which flew with the Hayabusa mission, was the basis for the division proposed here and for the ALR design in general (Tsuno *et al*., 2006; Hashimoto, Kubota e Mizuno, 2003).

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 analyze the return signal.

DESIGN GENERAL CHARACTERISTICS

- Integrated design aiming to minimize the size and weight of the instrument.
- Minimizing telemetry, commands and functions.
- Using 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).

  Obs.: The possibility of integrated optics is investigated (receptor and transmitter).
- Electronics of low-power signal processing (development).

Telemetry and simple commands: on, off, operation start, end of operation, gain adjustments, etc.

The desired characteristics for the instrument translated in terms of design parameters are presented in Table 2.

Table 2. Characteristics wanted for ASTER Laser *Rangefinder*.

Mass	Reduced (<5 kg)
Dimensions	Reduced (Max: 37.5 x 23.0 x 35.0) cm^3
Power	≤20 W
Operational Range	50 m≤D≤50 km
Precision	Vertical: 10 m (D<50 km) 1 m away (D≤10 km) Horizontal: <10 m
Wavelength	1.064 µm
Pulse-width	To stablish (ns)
Repetition rate (frequency)	1 Hz = >fixated. Should be sufficient for topographic analysis (can be variable)
Pulse energy	5 to 16 mJ (depending on the distance, reflectivity, divergence and wavelength)
Transmitter's divergence	<500 µrad
Life period	>1 year
Footprint:	<10 m (radius; 10 km away)
Temperature:	±2°C (depending on the detector)
Self-calibration during flight	Yes

Brief description of the parts

A preliminary version of ALR and its most important elements is demonstrated in Fig. 1. The most important parts are the transmitter, the receptor and the control unit. The latter is part of the electronics set of the equipment (which includes power sources, not shown here). In Fig. 1, the electric connections are represented by full lines, and optical paths are represented by dotted lines.

Generally, ALR will use the time gap between transmission and reception of a laser pulse to calculate the distance between the spacecraft and the asteroid. A new aspect related to the existing equipment is the possibility to use integrated optical transmission and reception. In this case, the function of the optics interchange, from transmitter to receptor, by means of an electro-optical key. However, the choice for independent optics is still more likely.

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

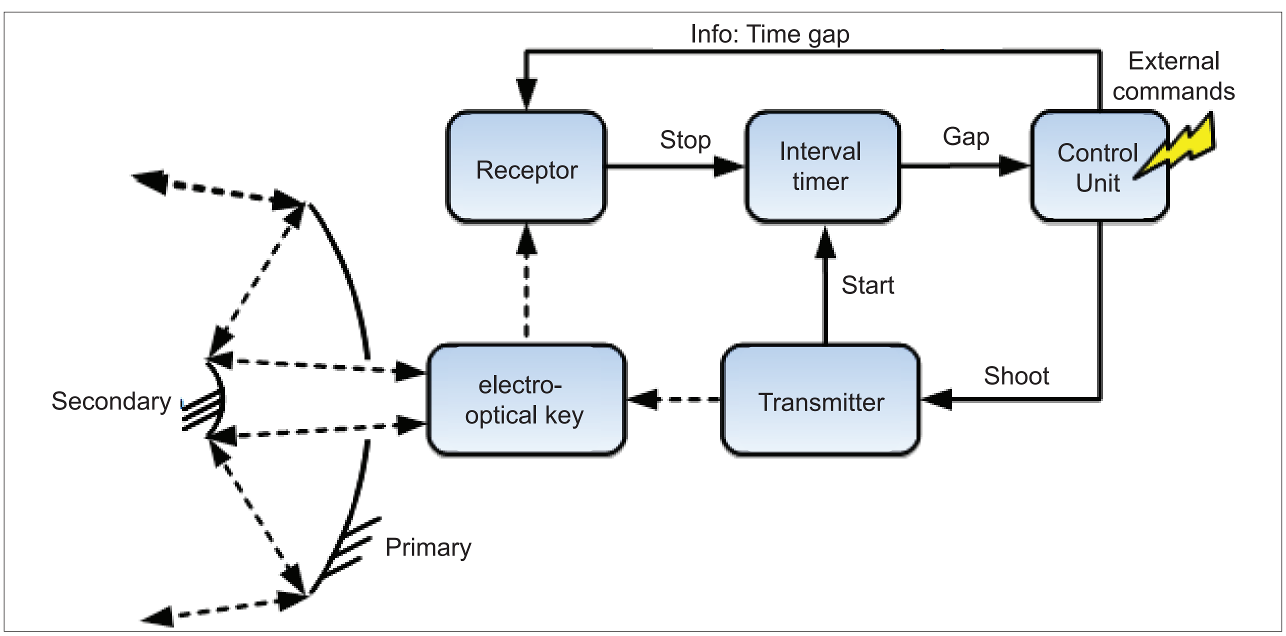

Figure 1. Preliminary block diagram of the ASTER Laser Rangefinder program. Here is the version of the study with unified optics. Independent optics is still the first option.

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, with a Q-switch, operating at 1.064 μm. 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 $LiNbO_3$ electro-optic modulator for the Q-switch. The laser source operating in Q-switching mode should be able to produce minimum energy pulses of 10 mJ to 1.064 μm, 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 Reddy *et al*. (2008), the 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.

The operation of the receptor will be controlled by a temporal gate, which is also internally programmed in the control unit of ALR. 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.

A start signal is sent to the counting clock when the transmitter generates the exit pulse. When the echo or return pulse is received by the receptor, a stop signal is sent to the counting clock. The returning signal is received and sent to the processing unit. The results reveal the distance to the surface, as well as additional data concerning inclination, roughness and albedo, which are stored to be possibly used by AOCS or by other instruments in the spacecraft, and/or to be sent out by telemetry. The registers in the clock are then formatted for the next reading.

As to the optics of the instrument, in the version with independent optics, 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. Another possibility that is considered for this moment is unified optics, which consists of coaxial and reflection arrangement with a Schmidt-Cassegrain telescope. A typical diameter for this telescope is around 10 to 12 cm. Both internal mirrors will be made of a hard and resistant material, such as silicon carbide (SiC) or aluminum, the latter being much lighter (however, other properties are not so favorable and need to be investigated, such as high thermal conductivity). The choice for aluminum requires a nonthermal design, like the one used in the laser rangefinder that flew in the NEAR-Shoemaker mission (Cole, 1998). With the coaxial configuration, transmitter and receptor share the same primary optical elements; however, an electro-optical key is necessary, with only one Pockels cell combined with a polarizer. Thus, a selection may be imposed on the state of polarization of the exit and echo pulses. Since the interval between the transmission and reception of the laser pulse can range from 0.3 ms and 66 μs during the phases of the missions, fast commutation will not be required, which makes this technically viable.

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 (sent by the transmitter), treats the signal, obtains the shape of the received pulse wave, processes this signal, storages and sends data (to other equipment on board or to Earth, via telemetry (use of memory), among others).

Internal algorithms

After being implemented in electronic units, they first treat 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 wanted information – calculation of the distance to the target, for example, and other items to be conducted in real time to use on board (other devices/ instruments), or to send to Earth.

Housing

Metal box and fixation of the equipment inside it. The design directions for this element are:

- Reduced dimensions (reference: 37.5 x 23.0 x 35.0 cm^3);
- Fixation with external vibration damping;
- Armoring/isolation (thermal and others);
- Interfaces of internal/external communication (input/ output of energy and data);
- Internal/external power sources (total low consumption: ≤20 W);
- Heat sinks and thermal control (initial temperature: ±2º C).

Integration and tests

The integration and validation of the instrument should be conducted under contract by the aerospace company with proper structure and experience in this type of activity. The participation of the Engineering team of UFABC will be in the contract, since it aims to develop the expertise in the field. For this stage, the company OMNISYS Engenharia (São Bernardo do Campo/SP) was contacted.

CONCLUSIONS AND FINAL COMMENTS

The items to develop ALR for the ASTER mission were defined and presented. The subdivision of this development in parts (modules) and the characteristics of each item and of the whole instrument were previously described, in order to meet the needs and the technological and scientific objectives of the mission.

The schedule for the modular development implies the existence of a specific timeline for each of the parts described. The parallel development of the parts should be inside this scenario, minimizing time and optimizing resources. However, the high level of integration and simplification required by the design can only be achieved with more interchange of information among the developing teams. So, the development is centralized in the Engineering group of UFABC.

Each item has its own costs spreadsheet. The total estimated cost is compounded by the sum of costs of the parts previously listed. The total estimated cost of the mission is initially of US$ 35 million. The development will be performed in stages (A, B, C, D). Stage A consists of the creation of the development plan. In the other stages, the models are created and tested. The creation of a “spider” (the setting of unqualified elements or modules on a plate that is different from the final version; it is used to test the module’s functionality), an engineering model, a qualification model, a prototype and a flight model. If possible, the intention is to use the qualification model as a flight model. In this case, there is one less model to make, causing the costs to reduce. At the moment, the “spider” is being created.

The ASTER Project has been recently included in the activities of the National Institute for Space Research (INPE). At the moment, the management of the mission wants to include the Project as a strategic activity, aligned with *Plano Nacional de Atividades Espaciais* (PNAE), to allocate resources related to developments in the space sector. Also, other financing programs (Research and Projects Financing – FINEP and São Paulo Research Foundation etc.) are considered. The use of regular research scholarships is also included (scientific initiation, internships, masters, doctorate, technical development etc.), since the development of expertise in the sector is one of the purposes of the mission.

The development model used to create ALR, based on the establishment of multiple partnerships, with personal and institutional qualification, should lead the way to projects concerning the development of the national aerospace sector. This approach to the development of aerospace instrumentation has been used successfully abroad. In Brazil, however, it is new and should contribute much to future developments in the sector.

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