A LASER RANGEFINDER FOR THE FIRST BRAZILIAN DEEP-SPACE MISSION: CONCEPT AND BASELINE DESIGN

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Abstract. *The ASTER deep-space mission will be the first Brazilian interplanetary voyage to explore the triple near-Earth asteroid 2001 SN263. A laser rangefinder should be developed for spacecraft navigation around the asteroid and its satellites and surface topography of each. Basically, this onboard instrument measures the time delay between transmission of a laser pulse by the spacecraft and detection of the reflected signal from the asteroid, thereby determining the distance between them. The concept and design of the laser rangefinder are preliminarily addressed herein within the operating restrictions for the spacecraft and the scientific objectives of the mission.*

Keywords: Deep-space mission; Asteroid; Altimeter; Laser; Space engineering

1. INTRODUCTION

In the first decade of the 21th century, a new era in space exploration began with the advent of spacecraft observations of asteroids. In 2000, the NEAR spacecraft went into orbit around the asteroid 433 Eros for a year of scientific investigation of its geology, mineralogy and surface chemistry (Chapman, 1995 and Cole, 1997). In 2005, the Hayabusa spacecraft arrived at Itokawa asteroid for scientific observation of the asteroid's shape, spin, topography, composition and density and subsequent touch-down, sample collection and return to Earth (Yano et at., 2006 and Fuse et al., 2008). Both spacecrafts were equipped with a laser altimeter (or laser rangefinder) for navigation and topographical purposes (Mukai et al., 2008 and Cole, 1998). Basically, such an onboard instrument determines the elevation from the spacecraft to a given location on the surface of the asteroid by simply measuring the time delay between the transmission of a laser pulse and its return as illustrated in Fig. 1.

In Brazil, laser altimetry for spacecrafts is a new branch of research and development for engineers and scientists whose interest in the technique has grown as the country plans its first ever deep-space mission (Sakharov et al., 2010). Based on science and technical advisory reports conducted recently by Brazilian experts at universities, research centers and private companies, Brazil government has now recognized the importance of an ambitious deep-space mission in order to test key national technologies in space, burst the national aerospace industry and train the new generation of space scientists and engineers of the country. The ASTER deep-space mission will be the first Brazilian deep-space mission (with Russia as a partner) to explore the unknown triple near-Earth asteroid 2001 SN263 (see Fig. 1). The ASTER deep-space mission aims to measure the following asteroid properties:

A. Bulk (size, shape, mass, density, three-body dynamics and spin state);
B. Internal (structure and gravity field);
C. Surface (mineralogy, morphology and elemental composition).

In order to make all these measurements the following scientific instruments are being considered to explore the triple near-Earth asteroid 2001 SN263:

I. Imaging camera;
II. Laser rangefinder;
III. Infrared spectrometer;
IV. Synthetic aperture radar;
V. Mass spectrometer;

VI. Libration Experiment;
VII. Camera Aries.

This paper concerns the concept and baseline design of a laser rangefinder for the ASTER deep-space mission to the triple near-Earth asteroid 2001 SN263.

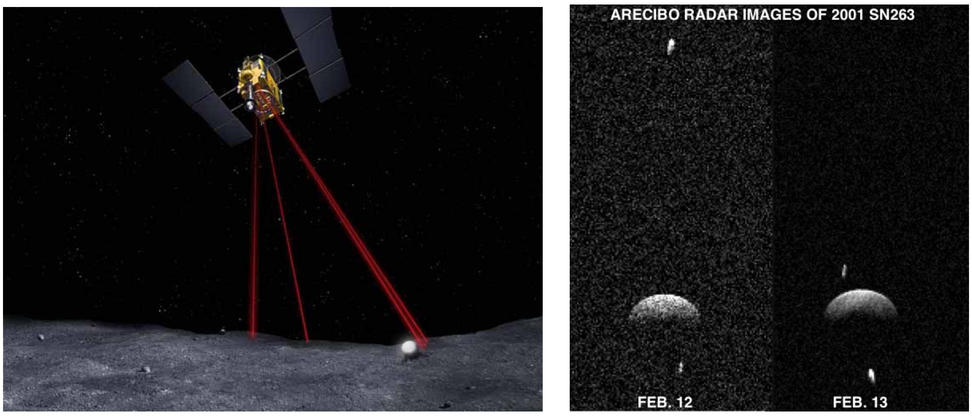

Figure 1. (Left) Artistic concept of a laser altimeter for asteroid research (JAXA, 2007). (Right) Radar images of 2001SN263 asteroid (Arecibo Observatory, 2008).

2. ASTER DEEP-SPACE MISSION OVERVIEW

The main scientific goal of this mission is to explore the near Earth triple asteroid 2001 SN263 whose characteristics known so far are listed in Table 1 and illustrated in Fig. 2.

Table 1. Orbital and bulk characteristics of the 2001 SN263 asteroid.

Asteroid	Orbit	*a*	*e*	*i*	*T*	Radius	Mass
Body 1 (B1)	Around Sun	1,9 UA	0,47	6,6°	2,8 years	1,4 km	1,14E13 kg
Body 2 (B2)	Around body 1	17 km	*	*	147 hours	0,6 km	7,9E-2 of B1
Body 3 (B3)	Around body 2	4 km	*	*	46 hours	0,25 km	5,7E-3 of B1

*: Unknown yet

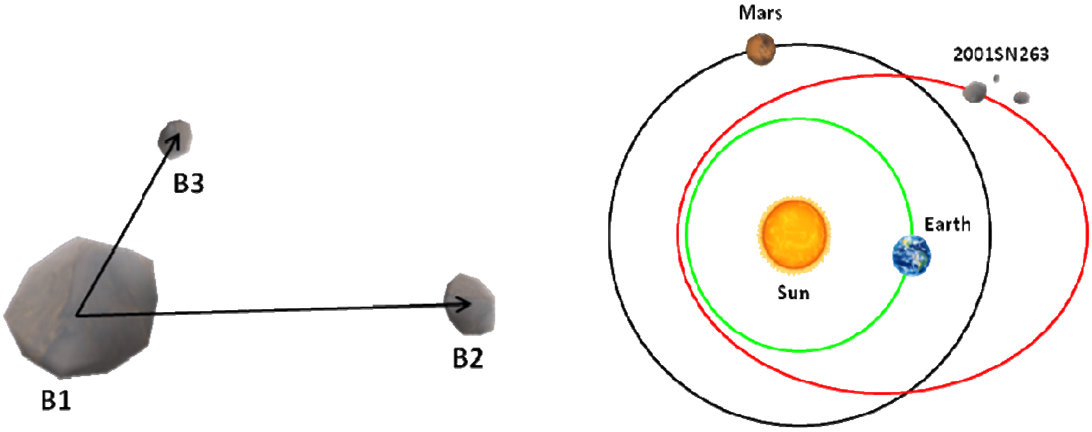

Figure 2. (Left) Scheme of a triple-asteroid system. (Right) Orbits of Earth and Mars showing the 2001 SN263 path.

The launch is will occur in 2015 and the total cost allocated to this mission will be around 35 million of US dollars. The ASTER spacecraft will be an adaptation of the spacecraft platform for the Mars MetNet mission (Cole, 1998) and will be launched by one of the Russian submarine-launched ballistic missiles of R-29 family into a low-earth orbit for subsequent insertion into a heliocentric orbit toward the target as illustrated in Fig. 3. The one-way journey to 2001SN263 will take almost three Earth years with ion engines as primary propulsion system. Three mission phases are currently envisaged during flyby of 2001 SN263 asteroid:

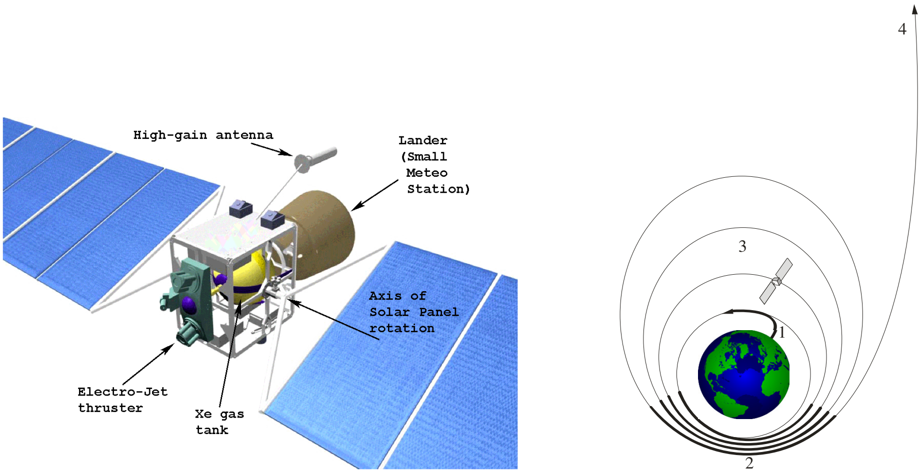

Figure 3. (Left) Mars Metnet spacecraft platform. (Rigth) Spacecraft launch design (Sukhanov et al., 2010).

Phase 1 – Rendezvous with the asteroid system at about 50 km
I. Observation of the triple asteroid dynamics;
II. Search for other small bodies in orbit or in the vicinity of the asteroid system;
III. Determination of the approaching strategy to establish a home position;
IV. Calibration of the scientific instruments.

Phase 2 – Flyby or orbit of about 25 km (closer position)
I. Characterization of the morphology of each asteroid;
II. Determination of the size, density and albedo;
III. Scientific investigation of the asteroids.

Phase 3 – Proximity and possible touch down
I. Possible orbit of about 10 km around the main asteroid;
II. Accurate investigation of the asteroids.

3. ASTER LASER RANGEFINDER (ALR)

Design criteria for the development of ALR should inevitably meet the scientific objectives of the ASTER deep-space mission and spacecraft constrains as shown in Tables 2. The ALR is one of the seven instruments onboard ASTER spacecraft and will make direct investigations of the shape and topography of each asteroid of the triple system and help with the spacecraft navigation around them in synergy with the imaging camera. The instrument will also help in the spacecraft navigation around the asteroids in synergy with the imaging camera. A team of engineers from UFABC, UNICAMP, BR Labs Ltda and Omnisys Co. will take responsibility for developing the ALR while a team of scientists from UFRJ and UNESP will be in charge of setting the ALR scientific objectives and analyzing the data obtained. Both teams will have also international consulting from Russia and Japan.

Table 2. Design criteria for the ALR based on scientific objectives and spacecraft constrains.

Scientific objective and spacecraft constrains	ALR design
Detection of return pulse	Laser energy of 10 mJ per pulse, receiver telescope and high S/N
Elevation resolution	Laser pulse width of 10 ns and high speed detection
Resolution along track	Repetition rate within 1 and 10 pps*
Payload mass	Up to 5 kg
Power available	Up to 200 W of electrical consumption
Platform dimension	Up to 100-mm length × 100-mm width ×100-mm thickness

*: Pulses per second

A preliminary version of the ALR is illustrated in Fig. 4, showing important elements of it with electrical connections drawn in solid lines and the optical paths drawn as dashed lines. Basically, the ALR will use the time interval between transmission and reception of a short duration laser pulse to compute the range between the spacecraft

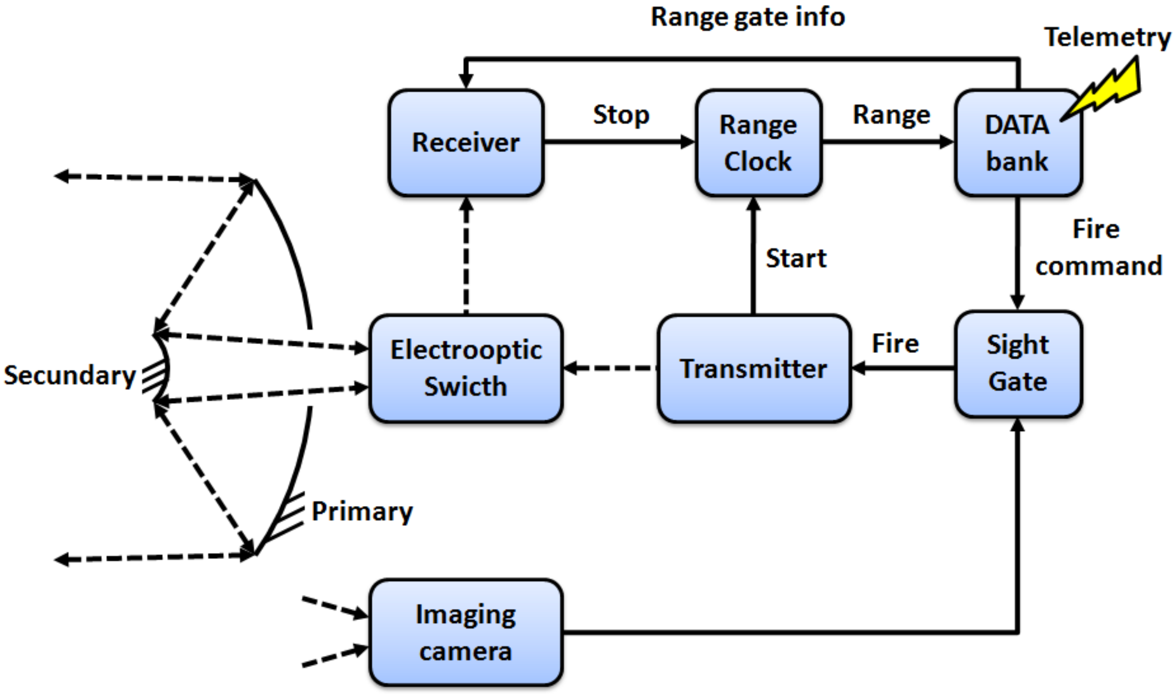

Figure 4. Preliminary block diagram of the ALR.

and the asteroid. In fact, the ALR will be variation of the successful LIDAR which flew on board of Hayabusa spacecraft (Hashimoto et al., 2003), where this time both transmitter and receiver will share the same optics. The function of the optics will be changed from a transmit to a receive optics by the use of an electrooptic switch. The transmitter will be operated under fire commands which are stored in the data bank via uplink channels. Also, the imaging camera will be used in combination with the ALR in order to prevent the transmitter from firing if the imaging camera indicates that the ALR is not along the line of sight to the asteroids. The operation of the receiver will be controlled by the range gate which is also programmed in the data bank. Basically, such a gate opens the receiver only during the time that the return pulse is expected in a manner that the S/N ratio can be maximized because the amount of random noise that can be accumulated during the time interval between is decreased. A start signal is transmitted to the range clock when the transmitter generates the output pulse. When the echo or return pulse is received by the receiver, a stop signal is sent to the range clock, stopping the range count. The information contained in the range clock is then transferred to the data storage bank for posterior telemetry to the ground station network clearing the clock register for the next reading.

3.1 Transmitter design

A preliminary block diagram of the ALR transmitter is given in Fig. 5. From the data storage bank, a command is given in order to initiate the charging of the laser energy storage bank. After the charging is completed a fire command is then given via the sight gate to fire the diode laser. The sight gate will be closed to prevent the optical pumping of the laser source if the imaging camera indicates that the asteroids are not along of its line of sight. If the sight gate is open, the diode laser will be powered and a pulse is sent to the electrooptic modulator for Q-switching. At the end of the optical pumping cycle, the Q-switch will be opened and a laser pulse will be generated. A Si avalanche photodectector (APD) placed behind the laser source is used to detect this output pulse and the electrical circuitry following this detector determines the centroid of the output pulse. The concept of this circuit is identical to the one that will be used with the receiver and is described later. Upon location of the output pulse centroid, a clock start pulse is generated starting the range clock. The transmitter will be cooled by a coolant pump through a spacecraft heat exchanger. From the heat exchanger the heat is dissipated by the spacecraft heat dump. Next, the laser source and the transmit optics are discussed in detail.

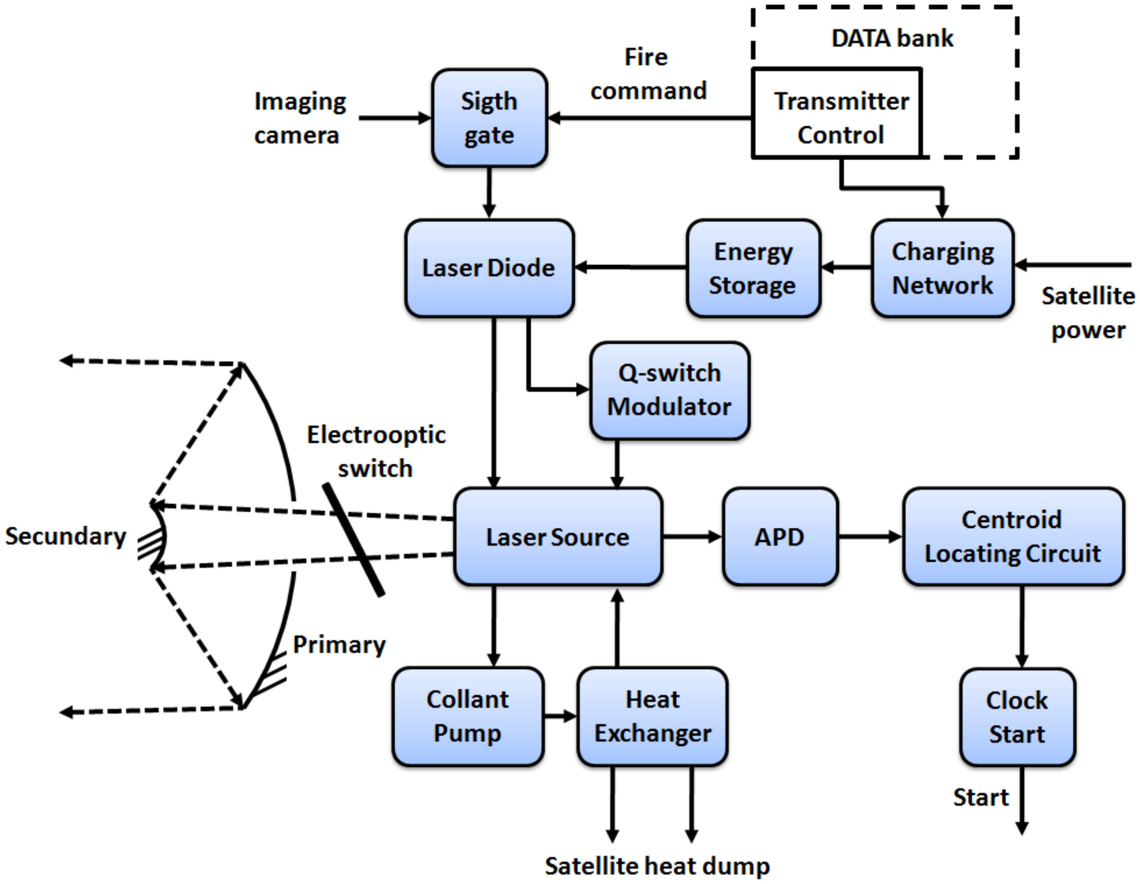

Figure 5. Preliminary block diagram of the ALR transmitter.

3.1.1 Laser source

The laser source of the transmitter will consist of a diode-pumped Q-switched Nd: YAG laser operating at 1064 nm. This laser source whose technology today is mature and robust can produce high energy pulses and fulfill the criteria of low power consumption and small size. Working with wavelengths in the near infrared there is also a large commercial availability of efficient detectors and optics which accounts positively to the use of such a laser source. Optical pumping by diode lasers will assure low power consumption and long life-times of typically 50.000 hours or up to 18 millions of laser-shots at 10 pps. A diode laser unit operating at 808 nm will consist basically of its driver electrical current being cooled by thermoelectric coolers for stabilizing its emission wavelength. The pumping geometry will be linear including the laser diode coupled to the Nd: YAG crystal rod, two infrared mirrors and a $LiNbO_3$ electrooptic modulator for Q-switching (Siegman, 1986). The optical cavity should be cooled in order to prevent degradation of the crystal rod. The laser source operating at Q-switching mode should be capable of producing pulses with minimum energy of 10 mJ at 1064 nm and duration up to 15 ns at repetition rates ranging within 1 and 10 pps, thereby yielding laser pulses with optical power of the order of 1 MW. The laser energy per pulse should be made as high as possible because according to Reddy et al., (2008) the 2001 SN263 is a type-C asteroid which means that its albedo should be relatively low at 1064 nm. Thus, taking an empirical energy output of 0.1 J per cc of Nd: YAG crystal rod (Kolker and Weiss, 1969), the volume of the crystal rod should be at least 0.1 cm^3. Also, the higher the repetition rate, the better the horizontal resolution is along the track on asteroid terrain. However, a compromise between horizontal resolution, power consumption and heat dissipation has been set the repetion rate at 1 pps. Beam divergence and pattern are primarily determined by the geometry of the optical cavity and they impact upon the footprint size on the asteroid terrain.

3.1.2 Transmit optics

The transmit optics considered up to now is the coaxial and reflective setup in the form of a Schmidt-Cassegrian telescope as shown in Fig. 5. Both mirrors will be made of a hard and tough material such as SiC or aluminum being the latter much lighter. In the coaxial setup, both transmitter and receiver share the same primary optical elements but an electrooptic switch is required. Such a switch should not have any moving parts being consisted only by a Pockels cell combined with a polarizer. In this manner, selection may be imposed on the polarization state of the output pulse and the echo pulse. Because the time interval between transmission and reception of the laser pulse will range within 0.3 ms and 66 μs during the mission phases, fast switching times are not needed making such a shutter technically very feasible. Note that in this type of telescope a cone of light with one divergence angle is converted into a cone with a different angle. In order words, an incoming beam can be expanded to an outcoming beam with divergence reduced by the same factor. This applies to transmission as well as to reception. The cone conversion should be done in a manner that spherical aberration, coma, and astigmatism are minimized. A compromise between mirrors diameters and focal lengths should be reach in order to obtain a footprint size up to 200 m on the asteroid terrain at 50 km of elevation.

3.2. Receiver design

The receiver block diagram is shown in Fig. 6. After passing through the receive optics the echo pulse is converted to a pulse of electrical energy by a Si avalanche photodetector (APD) for wavelength of 1064 nm. As mention before the range gate is utilized to activate the photomultiplier during reception of the return pulse. This method will reduce the effect of thermal noise and solar background, thereby increasing the S/N ratio. The range gate routine has to be programmed in the data storage bank via the uplink channel. After suitable amplification, the electrical signal is then fed into a centroid locating circuit. After the centroid of the return pulse is located, a stop signal is then sent to the range clock. The reading of the clock is transferred to the data storage bank for telemetry to ground station network on Earth. This technique is the most accurate way of measuring the range. In addition, the electrical signal is fed into a circuit that determines the pulse shape. Such information is very useful to estimate the topography of the asteroid terrain.

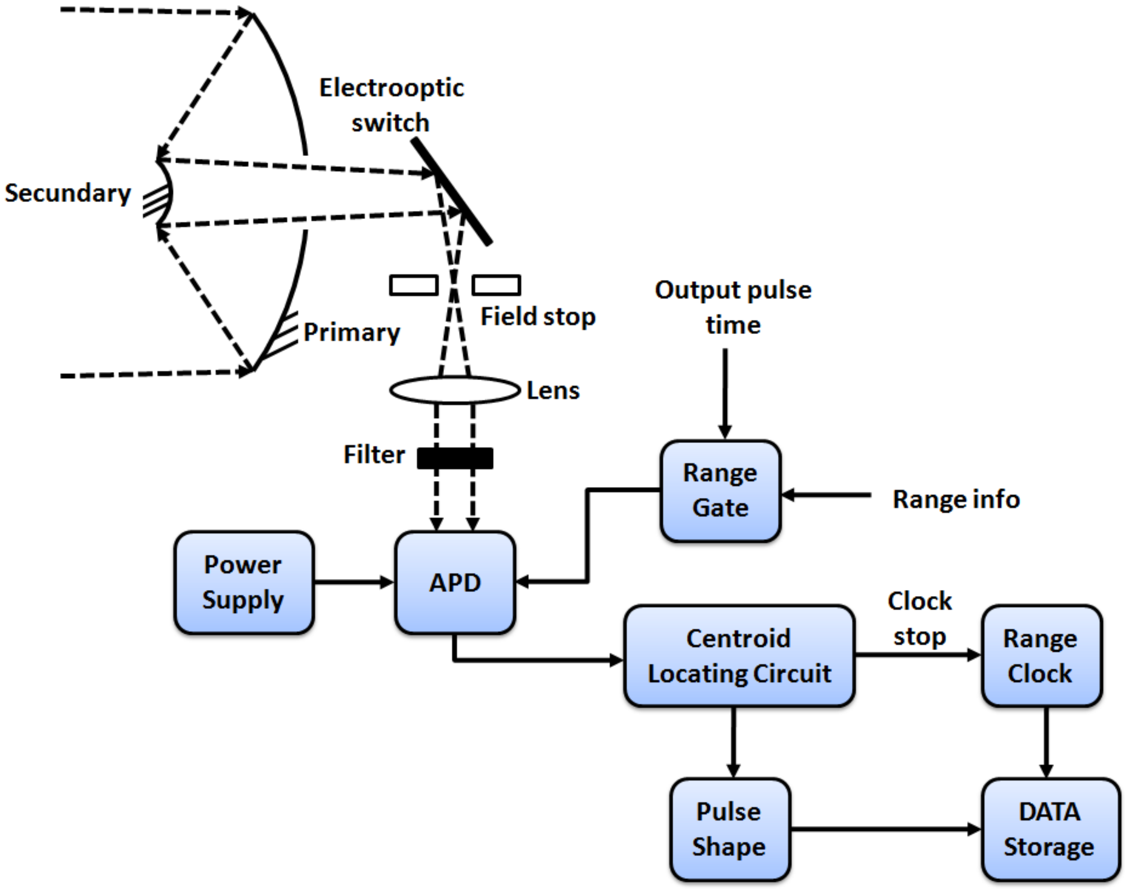

Figure 6. Preliminary design of the ALR receiver.

3.2.1 Receive optics

It was mention that the 2001 SN263 albedo should be relatively low at 1064 nm. Thus, a receive optics able to collect as many photon as possible in combination with closer distances to the asteroids will be needed to increase the S/N ratio. Referring to the receive optics, it is similar to the transmit optics (with respect to primary and secondary mirrors) described before except for the detection system which goes with it (see Fig. 6).

3.2.2 Detection system

The optical setup of the receiver is completed by the detection system which consists of a bandpass filter selected to accommodate the shifts due to temperature of the laser source and the filter itself and orbital velocity (Doppler shift), a collimating lens to bring the cone angle of the return beam down to the acceptance angle of the filter, a field stop to assure that the illuminated footprint is within the field of view (FOV) of the receiver and a another APD for wavelength of 1064 nm. Also, the bandpass filter will block solar background making the detection selective for the wavelength of 1064 nm.

4. CONCLUSIONS

The ASTER deep-space mission will be the first Brazilian deep-space mission (with Russia as a partner) to explore the unknown triple near-Earth asteroid 2001 SN263. The ASTER spacecraft will be an adaptation of the Mars Metnet spacecraft platform which will be equipped with seven scientific instruments including a laser rangefinder for navigation and topographical purposes. The ASTER Laser Rangefinder (ALR) will be fully developed in Brazil. The concept and baseline design of the ALR was preliminarily discussed (mainly, the transmitter and the receiver). While there remains much work to do, the prospects of developing the first Brazilian space laser altimeter appear good.

5. REFERENCES

Arecibo Observatory, 2008. "Arecibo Radar Discovers Triple Near-Earth Asteroid". 14 Feb 2011, <http://www.naic.edu/~astro/>

Chapman, C. R., 1995, "Near Earth Asteroid Rendezvous: Eros as the key to the S-type conundrum", Proc. XXVI Lunar Planetary Science Conference, pp. 229-230.

Cole, T. D., Boies, M. T., El-Dinary, A. S., Cheng A., Zuber, M. T. and Smith, 1997, "The Near-Earth Asteroid Rendezvous Laser Altimeter", Physics and Astronomy, Space Science Reviews, Vol. 82, no 1-2, pp. 217-253.

Cole, T. D., 1998, "NEAR Laser Rangefinder: A tool for the mapping and topologic study of Asteroid 433 Eros", JHU/APL Tech. Dig., Vol. 19, no. 2, pp. 142-157.

Fuse, T., et al., 2008, "Searching satellites of asteroid Itokawa by imaging observation with Hayabusa spacecraft", Earth, Planets and Space, Vol. 60, pp. 33-37.

Hashimoto, T. et al., 2003, "Light weight sensors for the autonomous asteroid landing of MUSES-C mission", Acta Astronautica, Vol. 52, pp. 381-388.

JAXA, 2007. "Digital Arquives". 14 Feb. 2011, <http://jda.jaxa.jp>.

Kolker, M. and Weiss, W., 1969, "Space Geodesy Altimetry Study", Nasa Contractor Report 1298, Washington DC, USA, p. 3-7.

Mukai, T., Abe, S., Barnouin-Jha, O., and Cheng, A., 2008, "Hayabusa LIDAR", NASA Planetary Data System, 14 Feb 2011 <http://sbn.psi.edu/pds/resource/haylidar.html>

Reddy, V., Gaffey, M. J., Schaal, M. and Takir, D., 2008, "Physical Characterization of First Triplet Near-Earth Asteroid (153591) 2001 SN263, Asteroids", Comets, Meteors 2008 held July 14-18, 2008 inBaltimore, Maryland. LPI Contribution No. 1405, paper id. 8244.

Siegman, A. E., 1986, "Lasers", Ed. University Science Books, California, USA, p. 1006.

Sukhanov, A. A., Velho, H. F. C., Macau, E. E. N. and Winter, O. C., 2010, "The Aster Project: Flight to a Near-Earth Asteroid", Cosmic Research, Vol. 48, pp. 433-450.

Yano, H., et al., 2006, "Touchdown of the Hayabusa spacecraft at the Muses Sea on Itokawa", Science, Vol. 312, no. 5778, pp. 1350-1353.

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