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Europa Jupiter System Mission and Marco Polo Mission: Italian partecipation in studies of laser altimeters for Jovian moons and asteroids exploration

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Abstract. CO.RI.S.T.A. (Consortium for Research on Advanced Remote Sensing Systems) is member of international science teams devoted to the studies of laser altimeters to fly on Europa Jupiter System Mission (EJSM) and Marco Polo Mission, currently under study of ESAs Cosmic Vision program as L-class and M-class mission respectively.
Both the studies will focus on the assessment of alternative technical approaches that would reduce the mass, size and power requirements. In particular a Single Photon Counting (SPC) device will be studied taking into account the robustness against false detections due to harsh radiation environment in the Jupiter system.
Innovative technical aspects which will characterize the studies of laser altimeters in the scenarios of EJSM and MarcoPolo, which will permit us to make major contributions to the science goals of the two missions.

Key words. Europa Jupiter System Mission – Marco Polo Mission – Laser Altimeter

1. Introduction

The basis of the laser altimeter measurement is the timing (Δt) of short pulses for round-trip propagation ($2{\cdot}R$) at the speed-of-light (c) between the space probe and the surface to be measured (Bufton 1989):

$$R = (c{\cdot}\Delta t)/2 \tag{1}$$

Hence, a $1ns$ delay is around $15cm$ range.

A laser altimeter consist essentially of three subsystems: a laser transmitter unit, a receiving subsystem (telescope and detector) and electronic unit. Laser altimetry can provide measurements of the structure and albedo of the target surface in addition to the straightforward range measurement (Gardner 1992) (Harding et al. 1994). Surface structure (i.e. the height distribution or slope within the laser footprint) is determined by the analysis of the backscattered laser pulse shape through

Send offprint requests to: M. R. Santovito analog processing or high-speed digitisation. The transmitted laser pulse width is typically optimised to be very short ($1 - 10ns$) for high-precision ranging. After interaction of the laser footprint with a rough or sloping surface, the backscattered pulse may contain several nanoseconds or more of pulse spreading or distortion. The application of gigahertz bandwidth digitisation to this received pulse waveform provides pulse shape data. The backscattered pulse width (or rms pulse spreading) that is derived from these data is usually a sufficient measure of surface structure. The total area under the received pulse is proportional to the pulse energy and it is a measure of surface albedo at the monochromatic laser wavelength. Effective use of this albedo data requires at least a calibration of laser backscatter from different surfaces and a normalisation by laser transmitter energy.

From 1971-72, when three Apollo missions carried laser altimeters to the Moon, to the Mars Global Surveyor mission (1996) operating the MOLA (Mars Orbiter Laser Altimeter) instrument for nearly 1000 days, the number of planetary ranges has increased by more than five orders of magnitude, and accuracy by nearly three orders. High resolution Moon contour maps were created from Apollo orbiters metric camera stereo images, using control from laser altimeters (Margot et al. 1999). Coverage was modest, laser transmitters were short-lived but the Apollo altimeters were adequate for their primary purpose, giving ranges for photographs, with a precision of about $4m$.

Two decades after the Apollo orbiters, a Laser Image Detection and Ranging (LIDAR) experiment was designed to measure the distance from the spacecraft to a point on the surface of the Moon (Nozette et al. 1994) (Smith et al. 1997) and flown on Clementine, a joint mission of NASA (National Aeronautics and Space Administration) and the Ballistic Missile Defence Organisation. This allowed an altimetric map to be made, which can be used to identify the morphology of large basins and other lunar features.

In February 2000 the NEAR (Near Earth Asteroid Rendezvous) spacecraft, which carried the NEAR Laser Range (NLR), reached the asteroid 433 Eros, one of the largest and most intensively studied near-Earth asteroids (Cheng 2000) (Cole 1998). The overall NEAR mission objective was to provide information about the origin and nature of near-Earth asteroids, whose characteristics are suspected to provide clues about the formation of the inner planets, including the Earth. The NLR made highly accurate measurements of asteroids shape and detailed surface capability.

In September 1997 the Mars Global Surveyor (MGS) entered into orbit around Mars. One of the four scientific instruments on MGS was the Mars Orbiter Laser Altimeter (MOLA) which mapped the topography of the planet to unprecedented accuracy (Abshire et al. 2000) (Neumann et al. 2001).

In August 2004 NASAs Discovery Program launched MESSENGER (MErcury Surface, Space, ENvironment, GEochemistry and Ranging) spacecraft with Mercury Laser Altimeter (MLA) and other six scientific instruments on board. The goal of MESSENGER mission is to analyse the planet Mercury in order to understand how terrestrial planets formed and evolved (Solomon et al. 2001). MLA will start its observations on 2011 measuring the topography of the Mercury northern hemisphere via laser pulse time-of-flight.

About Europe, the BepiColombo Laser Altimeter (BELA) is among the instruments that have been confirmed for flight aboard BepiColombo, which is the European Space Agencys cornerstone mission which in the future, from 2018 onward, will collect data of planet Mercury (Santovito et al. 2006). BELAs primary goal is support the development of a full surface topographical map of the planet at a grid space of around 20km and should in principle allow for the retrieval of the tidal forces elevation of order of one meter.

BELA, MLA, MOLA and NLR, along with the laser altimeter of the lunar mission Clementine, represent a new class of active remote sensing instruments for conducting science in the solar system. A summary of the

Table 1. Main feature of already flown laser altimeters (Clementine, NLR and MOLA) and of MLA and BELA, which will start their observation around Mercury on 2011 and 2018 respectively.

	Clementine	NLR	MOLA	MLA	BELA
Destination	*Moon*	433*Eros*	*Mars*	*Mercury*	*Mercury*
Altitude	$400 - 8300km$	$35 - 50km$	$400km$	$200 - 15000km$	$400 - 1500km$
Pulse energy	$171mJ$	$15.3mJ$	$42mJ$	$20mJ$	$50mJ$
Pulse width FWHM	$4.2ns$	$5.1ns$	$3.4ns$	$2.5ns$	$3.4ns$
Laser beam divergence	$500\mu rad$	$235\mu rad$	$370\mu rad$	$80\mu rad$	$50\mu rad$
Pulse repetition frequency	$0.6Hz$	$1/8, 1, 2, 8Hz$	$10Hz$	$8Hz$	$10Hz$
Receiver telescope diameter	$13cm$	$9cm$	$50cm$	$10.6cm$	$25cm$
Field of View	$500\mu rad$	$1.5mrad$	$425\mu rad$	$200\mu rad$	$200\mu rad$
Range resolution	$40m$	$32cm$	$30cm$	$15cm$	$30cm$
Instrument mass	$2.37kg$	$4.9kg$	$26.2kg$	$7.4kg$	$12kg$
Instrument power consumption	$6.8W$	$15.1W$	$28W$	$23W$	$43W$

main features of these instruments are reported in Table 1.

All of them make use of a Nd:YAG laser operating at the wavelength of $1064nm$ to generate pulses to be reflected by the planetary surface and adopt a silicon Avalanche Photodiode ($SiAPD$) as a detector. Pulse repetition frequencies are different, according to the scientific and technical requirements of the missions.

2. Laser altimetry for the EJSM

The two spacecraft (JEO and JGO) foreseen for EJSM have to carry out the following main science investigations of Jovian moons:

- determine figure parameters to establish accurate reference surfaces;
- determine the dynamical rotation state;
- measure topographic variations relative to the reference figures;
- establish a geodetic network based on accurately measured positions of prominent topographic feature;
- measure tidal deformations of the surface;
- constrain surface roughness, local slopes and albedo variations from backscattered light-curve analysis;
- assist in interpretation of gravity signal by providing essential information on topography.

The laser altimetry measurement on board JEO and JGO will permit to achieve the following EJSM main science goals:

- characterization of Jovian moons subsurface ocean
- understand the geologic history of the icy Jovian moons
- investigate the moons deep interior
- measure surface characteristics (important also for landing-site selection)
- understand the dynamical history of the moons

The EJSM main science phase will be during the orbital phase around Europa (JEO) and during the elliptical and circular orbital phase around Ganymede (JGO), respectively. Additional data will be collected at close flybys of all four Galilean Moons (Io, Callisto, Europa, Ganymede).

In purview of EJSM, laser altimetry will considerably refine the knowledge of topography of Europa (on local, regional and global scale), Ganymede and Callisto. Furthermore, laser altimetry in synergy with stereo imagery capability on JEO and JGO would allow constructing highly accurate digital elevation models of the surface, providing important context information to invert collected high-resolution altimetry and gravity data for satellite interior structure. Moreover in combination with subsurface radar and high-resolution imaging the laser altimeter will provide major contributions to investigate the relation between near-subsurface and surface processes especially for sites of past or recent activity and for candidate-site for shallow liquid water.

For the EJSM laser altimeter two concepts will be considered during the study:

- a 'classical' laser altimeter with time-of-flight measurement and pulse-waveform analysis capability. As mentioned above the former measures the range from the spacecraft to the satellite's surface, the latter allows for determination of surface characteristics;
- a next-generation laser altimeter system, which is based on a compact microchip lasers firing at kHz rates and a silicon APD, operated as Single Photon Counting (SPC) device. Such laser systems are becoming operational only in terrestrial airborne applications (studied by a DLR-led consortium under ESA contract in 2002) and so far they have not been employed on board of satellite orbiting in the space. Such a new system would have dramatically reduced size, mass, and power requirements. However, besides the development and space-qualification of the detector, a new pulse detection and processing scheme respect to 'classical' laser altimeter must be developed.

The laser altimeter for the EJSM missions is based on techniques, components and sub-assemblies of the European laser altimeter 'BELA' which, as described above, is part of the payload of the BepiColombo mission to Mercury (Thomas et al. 2007).

The vertical measurement accuracy of the proposed instrument is less than $1m$ which will allow for determination of the dynamical tidal deformation of Europa or Ganymede for the main tidal cycles of 3.5 and 7.15 days, respectively. The active q-switched Nd:YAG laser will have adjustable pulse repetition rates and output energies in order to work power-efficiently, but with high quality data generation even in different operation scenarios. The

Table 2. Main characteristics of laser altimeter for JGO and JEO.

Laser altimeter for JGO	
Range	400 and 1300km (Ganymede)
Pulse energy	$15 - 26mJ$
Receiver telescope diameter	$10 - 25cm$
Laser altimeter for JEO	
Range	$225 - 625km$
Pulse energy	$5 - 15mJ$
Receiver Telescope diameter	$10 - 15cm$

mass will be around 6kg for classical laser altimeter BELA-like, 3.6kg microlaser with SPC receiver technique.

The main characteristics of laser altimeter for JGO and laser altimeter for JEO are summarized in Table 2.

The instrument will be designed with cold-redundant subsystems where applicable (data processing, rangefinder, power converter, laser electronics, laser optics). A main topic of the study will be the impact of the harsh radiation environment in the Jupiter system on the instrument design. In the development of laser altimeter will be necessary to characterize also the Jovian radiation environment: to perform this analysis our study will base on the available models. The effects of the radiation on the individual parts and on the data analysis (i.e. relation of false detections to number of detected pulses) will yield the information about protection required against the radiation environment and determining the required radiation shielding and recommendations where to locate the instrument electronic. In addition the constraints placed by planetary protection rules will be addressed and taken into account in the process of instrument development.

The main technical developments activities which have to be performed will be devoted to the study of variable laser output energy and pulse repetition rate, Single Photon Counting (detection schemes, link-budget, SPC detectors) and laser specifications (short pulses, high peak-power, high repetition rate). Other activities will be essentially related to the jovian radiation-hard environment as the study of detector diode, diode for laser-energy measurement, electronics, optical coatings.

Table 3 report the results of performed Technology Readiness Level (TRL) analysis, supposing to investigate SPC detectors, appropriate electronics and detection algorithms from now until 2014.

3. Laser altimetry for the Marco Polo Mission

The Marco Polo Mission is foreseen to rendezvous with a Near-Earth Asteroid and to return a sample from the asteroid to Earth (Marco Polo Study Team 2009). Before sampling, the spacecraft will fly in formation with (or orbit) the asteroid to undertake a comprehensive study of the object by a host of remote sensing techniques. The mission is involving around 660 scientists from 25 countries.

The laser altimeter is one of the main instruments on board. It will derive global shape models of the asteroid and study its rotational motion. Also, surface roughness and albedo (at the laser wavelength) will be studied. Both types of measurements combined will help the study of gravity field parameters of the asteroid and will help maneuvering of the spacecraft in the irregular gravity field of the object.

The instrument will operate during approach to asteroid and during the spacecraft orbit phase. Nighttime observations and daytime observations (which have to overcome the solar background noise) will be equally possible. In addition, during dedicated calibration

Table 3. TRL analysis for individual components of the laser altimeter for EJSM. *It is supposed to investigate SPC detector, appropriate electronics and detection algorithms until 2014 in order to reach the given TRL.

	Today		2014	
Sub-assembly	MicroLaser SPC detector	BELA-like Classical laser	MicroLaser SPC detector	BELA-like Classical laser
Laser or laser components	3	4	6 – 7	8
Laser pump diodes	5	5	8	8
Receiver telescope	5	5	6 – 7	8
Detector	4	5	6*	8

Table 4. Main characteristics of the three laser altimeter configurations for Marco Polo mission.

	BELA-like	MARCO *I*	MARCO *II*
Laser energy	$50mJ$	$3mJ$	$0.1mJ$
Wavelength	$1064nm$	$1064nm$	$1064nm$
Laser pulse width	$8 - 10ns$	$8 - 10ns$	$8 - 10ns$
Telescope aperture	$0.02m$	$0.05m$	$0.02m$
Range to target	$10km$	$10km$	$10km$
Laser spot on surface (@$10km$)	$1m$	$1m$	$1m$
Total photon electrons	8248	1050	5
Operation power	$50W$	$33W$	$26W$
Dimension	$23x16x14cm$ current BELA dimensions	$15x10x10cm$ TBC	$10x5x5cm$ TBC
Total mass	$5kg$	$4kg$ TBC	$3kg$ TBC

sessions, two-way range measurements to terrestrial ground stations will be carried out for instrument alignment calibration, performance tests, and also, to support the tracking of the spacecraft. Hence the laser ranger will contribute to the characterization of the target asteroid and to the navigation of the spacecraft by providing accurate range data from the spacecraft to the target but also from the spacecraft to the terrestrial ground station.

The Laser Ranger of the Marco Polo mission has the unique requirement that it has to cover a wide range from $10km$ down to $0.1km$. A Laser Ranger designed for a higher range can of course operate at lower ranges: the challenge is to design the Laser Ranger in a way that the laser output energy can be adjusted according to range and that all other instrument subsystems like detector, rangefinder, thermal control etc. can support this variation of output energy. The feasibility of a variable laser output energy will be studied. This includes laser link calculations, trade-offs for power requirements and effects on the laser type and laser design.

Three potential instrument configurations, termed BELA-like, MARCO *I* and MARCO *II* will be studied. The main characteristics of the configurations are reported in Table 4.

BELA-like is a safe configuration, using BELA laser altimeter as basis. In particular, the space-qualified transmitter from BELA could be adopted, with the receiver optical system to be adjusted to account for the different measurement geometry, i.e., the closer range to the target.

Alternatively to BELA-like, in MARCO I configuration is considered the development of a new laser system with performance parameters specifically designed for the mission. This would reduce size, total mass, and required power. The instrument would rely on the classical laser altimeter principle.

As a second alternative, in MARCO II configuration is considered the development of an entirely new laser altimeter system based on a compact microchip Lasers firing at *kHz* rates and a silicon APD, operated as Single Photon-Counting device, as already described for the innovative configuration foreseen for the EJSM laser altimeters. Marco Polo laser altimeter TRL (NASA Technology Readiness Levels) are mainly derived from the current BELA development for BepiColombo mission. As showed in Table 3, once the BELA development is finished, the BELA TRL will be 8.

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