*A new rangefinder system for microsatellite

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ABSTRACT

CO.RI.S.T.A. (*Consortium of Research on Advanced Remote Sensing Systems*) performed a feasibility study funded by Italian Space Agency (ASI) to develop a rangefinder system as payload for microsatellite. The satellite considered for the study is UNISAT, an Italian academic satellite. The studied rangefinder offers the possibility to correct the systematic error of stereoscopic images acquired by MHRRC camera (*Miniaturised High-Resolution Reconnaissance Camera*) integrated on board the satellite. In order to carry out a compact and reliable altimeter for satellite UNISAT a review and comparison have been made with rangefinder systems both for the microwaves (radar systems) and for the visible infrared wavelength range (laser systems). A pulsed laser altimeter system based on *Time Of Flight* measurement appears the more suitable for the aforementioned application.

Keywords: Rangefinder, laser altimeter, radar altimeter, microsatellite.

1. INTRODUCTION

Altimetric technique allows to determine the altitude of a spacecraft above ground, by measuring an electromagnetic wave round trip delay time. The signal can be transmitted either into the microwaves, in which case we employ a radar altimeter, or into the visible infrared, in which case we employ a laser altimeter.
Over the past three decades, satellites equipped with radar altimeters have collected different kinds of information concerning our Planet's physics, chemistry and dynamics. These instruments have given a precious input to scientific disciplines as oceanography, geodesy, geophysics, glaciology and meteorology. Their huge data records allowed studying geophysical phenomena over a wide range of temporal and spatial scales, monitoring the ocean variability in near real time, predicting global climate anomalies and acquiring data over those regions badly covered by in-situ observations.
SKYLAB (NASA, 1973) has been the first satellite equipped with a spaceborne radar altimeter operating from an altitude of 453 km and with a resolution around 15m and an accurancy of no more than 90cm. It was only the beginning of satellite altimetry [1]. Two years later, within the US National Geodetic Satellite Program, *GEOS-3* presented improved performances over its predecessor. Beginning from higher altitude and better Earth's coverage, up to the fact that the on-board ALT radar altimeter first used a linear frequency modulation technique (chirp), thus greatly improving the resolution (even if still measured in meters). Successive radar altimeters all adopted the *pulse compression technique* [2, 3].
The *Seasat* ALT radar altimeter (Applied Physic Laboratory –APL–, Johns Hopkins University, 1978) was the first high performing altimeter. *Seasat* has been the first satellite specifically planned for oceanography [4]. Its technical solutions were so successful to become a standard for future altimeters. Moreover, this mission demonstrated how altimetry data could be used to retrieve sea-ice characteristics.

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Starting from 1985, the US Navy's *GEOSAT* (*GEOdetic SATellite*) 5-year mission had the task to provide high-resolution data about Earth's surface. The radar ALT operated at an altitude of 800 km and it was similar to the *Seasat* altimeter, but with reduced noise level. It provided the scientific community with first long-term high quality geophysical data, and definitively showed all the potentiality of satellite altimetry [1, 5].

TOPEX/Poseidon (NASA and CNES, France, 1992) is the first satellite in history specifically dedicated to altimetry. During the last ten years, *T/P* has successfully mapped basin-wide current variations, monitored effects of currents on global climate change, studied large-scale phenomena such as El Niño and long-term ocean features, produced the first global views of seasonal current changes and precise global tidal maps, tested ocean circulation models, improved knowledge of Earth's gravity field [6].

On July 1991 the European Space Agency (ESA) launched the first European Remote Sensing Satellite, ERS-1, based on the MMP (Multi-Mission Platform) developed for the SPOT series of French imaging satellites. It was a sun-synchronous orbiting remote sensing satellite, operated until March 2000. The main task of this sophisticated mission was to observe in detail atmosphere and ocean, but even sea-ice (cryosphere) and land surfaces [7], extending monitoring to regions that previously had both lack of regular observations and very demanding constraints. On April 1995 a nearly identical satellite, ERS-2, has been launched to assure similar acquisition of ERS-1 conditions for stereo imaging and interferometry [7].

The GEOSAT *Follow on* mission, launched in 1998, mounted on board the well performing RA-1 radar altimeter, operating at 800km of altitude and with a significant reduction of around one-third in power (71W) and mass (30.4kg) compared to the GEOSAT radar altimeter [8].

Launched on February 2002, as a part of the European Earth-Observation Programme of ESA, the European ENVIronment SATellite (ENVISAT) is actually the most powerful tool for Earth monitoring [9,10,11]. This huge and advanced satellite is equipped with many innovative instruments and has got the capability to merge their data so to observe the Earth with unprecedented richness in details. With the ENVISAT mission scientists all over the world have the possibility to study the evolutions of complex environmental phenomena such global warming, natural disasters, sea level rising, ozone hole, atmospheric pollution, El Niño through timescale of over ten years. On board ENVISAT second-generation radar altimeter RA-2 is installed [12,13].

The laser altimetry technique had its beginnings in space-based observations with the Apollo's missions in the early 1970s [14]. From then significant progress have been done and laser altimeters have been a tool of the space programs to accomplish a variety of engineering and scientific objectives.

Among the most recent space missions using laser altimetry technique we would like to mention CLEMENTINE (1994), NEAR (*Near Earth Asteroid Rendezvous*, NASA, 1996), MGS (*Mars Global Surveyor*, NASA, 1996) and ICESat (*Ice, Cloud, and Land Elevation Satellite*, NASA, 2003).

The Clementine 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. Clementine mission demonstrated new, efficient, diode-pumped laser technology [15,16,17].

NEAR Laser Rangefinder (NLR) was an altimeter that used a solid-state pulsed laser to measure distance between the spacecraft and the surface of the asteroid 433 Eros. It was one of the five facility instruments onboard the NEAR spacecraft and made highly accurate measurements of the asteroid's shape and detailed surface structure. The NLR was the first spaceborne laser altimeter to have continuos in-flight range calibration capability [18,19].

Mars Orbiter Laser Altimeter (MOLA) is one of the four instruments onboard NASA' s MGS spacecraft. The primary objective of the MOLA investigation is to determine the global topography of Mars for addressing fundamental questions in planetary geology and geophysics. Secondary objectives are to characterise the 1064nm surface reflectivity of Mars, to contribute to analyses of global surface mineralogy and seasonal albedo changes, to assist in addressing problems in atmospheric circulation, and to provide geodetic control and topography for assessing future Mars landing sites [20,21].

For ICESat mission the Geoscience Laser Altimeter (GLAS) has been designed to measure ice-sheet topography and associated temporal changes, as well as cloud and atmospheric properties. In addition operation of GLAS over land and water will provide along-track land and ocean topography. The ice-sheet measurements will address fundamental questions about the growth or shrinkage of the polar ice-sheet and their contribution to current and future global sea level rise or fall [22,23].

From 1971-72, when three Apollo missions carried laser altimeters to the Moon, to the Mars Global Surveyor mission operating the MOLA (Mars Orbiter Laser Altimeter) instrument for nearly 1000 days, the number of planetary ranges has increased by more than 5 orders of magnitude, and accuracy by nearly 3 orders [24]. All these scientific achievements are also the result of breakthroughs in solid-state laser and in high speed electronic technology.

With regards to Europe, ESAC (*Earth Science Advisory Committee*) of ESA *(European Space Agency*) pointed to laser altimeter as payload for topographic missions [25].
It now appears possible to develop laser altimeters with a fraction of size, weight, and power of Apollo days adequate to be operated on small unmanned aerial vehicles and microsatellites.
Taking into consideration the described state of art for radar and laser rangefinders, Co.Ri.S.T.A. (*Consortium for Research on Advanced Remote Sensing Systems*) performed a feasibility study funded by Italian Space Agency (ASI) to develop an altimeter as payload for microsatellite. The studied rangefinder has to offer the possibility to correct the systematic error of stereoscopic images acquired by a camera integrated onboard.

The satellite considered for the study is UNISAT, Italian academic microsatellite [26]. UNISAT is a multi-mission microsatellite for scientific research and educational purposes. To meet the multi-mission requirement, the microsatellite has been designed in order to be easily modified to accommodate scientific payloads for different space missions on sun-synchronous circular orbits at altitudes ranging between 400km and 1000km. In table 1 the main characteristics of UNISAT are reported.

Satellite parameter	**Characteristic and value**
Orbits	Circular, sun-synchronous
Operating altitudes (km)	From 400 to 1000
Minimum lifetime (months)	8
Bus mass (kg)	40
Bus size (cm)	45x45x45
Electric power (W)	64 (average) – 77 (peak)
Downlink	S-band, 2.2 GHz
Downlink data rate (Mbps)	1
Payload mass (kg)	Up to 10
Payload average power (W)	10

Table 1: UNISAT main characteristics [26].

A miniaturised high-resolution camera is integrated on-board the microsatellite. The MHRRC camera (*Miniaturised High-Resolution Reconnaissance Camera*) is a panchromatic passive remote sensing electro-optical sensor operating during daylight conditions only in push-broom mode. It consist of the camera and the electronic unit. The camera is made by two subsystems: the receiving optic (a Cassegrain type telescope) and the FPA (*Focal Plane Assembly*). The FPA consist of a two-dimensional detector array (1024x1024 elements of size 0.013mm) and the relative electronics. Table 2 reports the MHRRC main characteristics.

MHRRC Parameter	**Value**
Ground geometric resolution (m) @ 400km	10
Field of view (°)	0.696
Swath width (km)	10
Spectral range (nm)	500-900
Focal length (cm)	110
Payload mass (kg)	<10

Continuos power	<6W (10W peak)

Table 2: MHRRC main characteristics [26].

In our study we considered the CCD camera axis directed as vertically as possible (angle of tilt less than 3°). In this approximation stereopair images have to be overlapped of 55 to 65 percent to obtain at least 50 percent stereoscopic coverage of the terrain. Taking into consideration the swath on ground (10Km at altitude of 400km) with an overlap of 55 percent and a satellite speed of 7 km/s the MHRRC has to acquire an image every 0.7s to guarantee a range measurement for every acquired image and consequently a stereoscopic coverage .
In this work, after a mention to the stereoscopic correction and a comparison with rangefinder systems both for the microwaves (radar systems) and for the visible infrared wavelength range (laser systems) we present a preliminary configuration of the altimeter for microsatellite.

2. STEREOSCOPIC CORRECTION

In the "real" world, our depth perception comes from to the fact that we have two eyes which do not exactly see the same thing. The brain use of the differences between the two images to reconstitute the relief of things: this is the "stereoscopic vision". Stereoscopic images form the basis for the creation of the three-dimensional model, the DEM (*Digital Elevation Model*).
Photogrammetry is the science and technology of obtaining spatial measurements and other geometrically derived product from digital or hardcopy images. By applying photogrammetric procedures to stereoscopic images it is possible to obtain distances, areas and elevation measurements using equipment, geometric concepts and analytical technique to generate precise DEM, orthophotos, thematic GIS data.
A detailed analysis of the correction of stereoscopic images required for precision processing is out the scope of the present paper and we refer to specific works [27,28,29,30,31]. However correction procedures can take advantage from the knowledge of at least three non-aligned *Ground Control Points* (GCP). These are points that can be accurately located on the image and for which we have information on their ground coordinates and/or elevations (often through GPS data) to calibrate photo measurements. But this process appears too much expensive for space missions owing to the needed information about high numbers of GCPs distributed on the land surface flown over by the satellite. New methods are under investigation to reduce the number of GCPs. One of these methods use GPS (*Global Position System*) positioning and INS (*Inertial Navigation System*) attitude determination and altimeter which acquire in real time information about the flying height [30,31]. Up to now testing of the system only refers to aircraft flight, at least for laser altimeters. Our study is precisely aimed at preliminary design and performance evaluation of an altimeter operating on a microsatellite and able to perform range measurements with an accuracy adequate for stereoscopic correction.

3. RADAR ALTIMETER VS LASER ALTIMETER

Taking into consideration the previous review on radar and laser altimeter some basic differences between microwave and optical instrument can be pointed out. Compared to radar altimeters the laser altimeters offer the advantage of a footprint orders of magnitude smaller that result from the narrow beam of optical radiation [32]. Laser footprints at the surface can be as small as tens-of-meters in size, even from orbital altitudes of several hundred kilometres. The laser altimetry uses very high brightness source that can produce megawatts or greater peak power in a pulse of only nanoseconds duration. When these pulses are transmitted from small aperture (order of centimetres) and received through large optics (order of meters), being involved high power signals and small footprints the result is a very high-quality measurement for individual laser pulses. No pulse averaging is required. Each pulse produces a unique measurements that defines the vertical and horizontal resolution of the laser altimeter.
Compared to radar altimeters the laser altimeters offer the disadvantage to strongly depend on atmospheric conditions [33]. Depending on laser wavelength a number of atmospheric processes can affect the range measured by altimeter: attenuation for molecular absorption, molecular scattering, scattering and absorption by aerosols, atmospheric turbulence. Absorption and scattering by atmospheric molecules affect the laser signal less than scattering and absorption by aerosols, where the attenuation is some km^{-1}. The laser pulse degenerates also for the atmospheric turbulence where turbulent convective motion of air masses with different temperatures drives to a non-uniform refractive index. The result is a fluctuation of laser signal intensity. Turbulence decreases with altitude, so that effects at 100m above the ground, are often very small compared with those 1m above.

Finally we want to underline some specific characteristics of radar altimeters vs laser altimeters: the size of radar altimeters is usually larger than laser altimeters, radar require average on a high number of sample to improve the range measure accuracy and they offer a Signal to Noise Ratio (SNR) lower than laser altimeters. Radar altimeters offer the advantage to operate with any atmospheric condition and *night-and-day*. Nevertheless for our study these radar advantages appear negligible since the MHRRC is a passive sensor which can operate in visible range of spectral radiation. Therefore when the laser altimeter is “blind” also the camera cannot operate.

4. RANGEFINDER PRELIMINARY CONFIGURATION

Referring to paragraph 2 it is evident that an auxiliary system to estimate the range satellite-ground is crucial for stereoscopic correction. As reported in paragraph 3 satellite rangefinder system can be radar or laser. Analysing advantage and drawback of both systems our decision is to use a laser altimeter for the study. Our choice take also in account the possibility for the laser altimeter to reduce weight and size sharing the MHRRC telescope of the camera onboard.

In order to find a good configuration to carry out a compact and reliable laser altimeter for microsatellite we investigated three main aspects which characterised the instrument: the relative position of transmitter and receiver (bistatic or monostatic), the receiver detection method, the transmitter source.

To reduce weight and size of the laser altimeter we decided

1. to use the MHRRC telescope to receive the backscattered signal: for this reason the bistatic configuration is chosen;
2. a single-wavelength laser altimeter system, although a double-wavelength system improve the range measurement accuracy [34].

There are two basic methods to detect the reflected energy: direct or incoherent detection, where the total energy collected by receiver aperture is converted to the signal current; coherent or heterodyne detection receiver, where a local oscillator beam is mixed with the reflected beam from the target to generate an intermediate frequency signal current on the detector face. In most case the coherent detection is more sensitive than direct detection, but it requires a more complicated receiver, an high laser frequency stability (not required in the direct method), it is subject to more efficiency losses due to mismatch and it presents a more complex signal processing compared with the direct detection [33,35]. For these reasons a configuration with a direct detection method has been chosen.

There are at the present three types of laser sources used for laser rangefinders: mature technology of CO_2 lasers , operating in the infrared between 9-11μm; solid state lasers, operating between 1-2μm; and the infant technology of diode lasers, between 0.7-0.9μm. Analysing features and drawbacks of the different sources, the solid state laser technology appears the more suitable for small light weight space applications [35]. We decided for pulsed Q-switched Nd:YAG laser, at 1064nm, diode pumping, being widely proved [15,18,21,22] these characteristics of the light source guarantee good efficiency in terms of power, good mechanical properties and compactness that are absolutely essential for measurements from microsatellite. The main characteristics for the laser source are listed in table 3. For the pulsed wave altimeters *Time Of Flight* (TOF) the distance is obtained by measuring the time interval between the transmitted and received light pulses. Pulsed systems can generate transmitted signal with very high power with the result of a better optical Signal-to-Noise Ratio (*SNR*) compared to the continuos wave system.

Laser parameter	**Characteristic and value**
Laser	Nd:YAG (Q-switched)
Wavelength (nm)	1064
Pulse Energy (mJ)	50-80
Pulse duration (ns)	<7
Beam divergence (mrad)	0.1
Repetition rate (Hz)	>1.4

Table 3: Main requirements for the laser source.

The only disadvantage of a Nd:YAG laser is related to the safety use. It is a Class IV laser (high power, ocular hazard). The European Standard document for safety use of laser [36] reports the Maximum Permissible Exposure (MPE) level to which the cornea can be exposed without consequential injury immediately or after long time: E_{MPE}=0.05 J/m^2. To operate in safety condition the laser has to emit an energy E satisfying the following condition

$$E < E_{MPE} \cdot A = E_{MPE} \cdot \pi (d/2)^2 = E_{MPE} \cdot \frac{\pi}{4}(H \cdot \theta)^2 = 63 \text{ J}$$

where A is the area of the footprint, d is the diameter of the footprint, H is the height of the laser source (H = 400Km) and θ the beam divergence (0.1mrad).

The height accuracy project required for the altimeter is 1m. Laser altimeter performance analysis shows the achievement of this requirement.

The Q-switching technique permits to generate laser pulses with peak power from 1 to 10W and time duration from 5 to 100ns and it appears suitable for our study: taking into consideration the range accuracy ΔZ=1m the time pulse duration ΔT has to be

$$\Delta T = \frac{2 \cdot \Delta Z}{c} \cong 7ns$$

where c is the light speed.

In order to guarantee a good stereoscopic correction of the area overflown by satellite the laser altimeter has to provide a range measurement for every acquired image of the MHRRC.

Since the camera acquires an image every t_a = 0.7s the repetition rate f of the laser has to satisfy the relation

$$f > \frac{1}{t_a} \cong 1.4\ Hz$$

A preliminary laser altimeter configuration for microsatellite is shown in figure 1. The laser beam is transmitted to the target through a plane mirror mounted on gimbal. The backscattered signal is received by the acquisition channel formed by the telescope, the photon detector and the electronics for acquisition. As previously mentioned the laser altimeter shares the telescope with the MHRRC integrated onboard. A dichroic beam-splitter SWP (*Short Wave Pass*) at 45° respect to the optical axis sends the radiation with wavelength less than 900nm to the camera and the radiation with wavelength greater than 900nm to the photon detector. Before impinging on detector the backscattered signal is collimated by a lens and crosses an interferencial filter at 1064nm (bandwidth around 1nm) in order to reduce the optical noise from diffuse solar light. The photodetector is an APD (*Avalanche PhotoDiode*). Usually the APD has to be preferred to the other photodetectors in aerospace application owing to a good time response, high sensitivity and quantum efficiency. The main characteristics of the APD for the studied laser altimeter are listed in table 4 [37]. The output signal from APD is amplified and filtered in low-pass mode in order to improve the *SNR* and compared to a predefined threshold level of a discriminator [38]. The range counter starts when the optical fibre sends the start pulse and stops when the backscattered signal exceeds the discriminator threshold. The range counter has to sample the time interval between start and stop signal with high resolution in order to reach good accuracy for the range measurements. To minimize the false detection a gate which allows the cross of the signal just after a precise time interval could be used.

Parameter	**Value**
Photosensitive surface	≈ 1mm
Responsivity	10-40 A/W
Time response	≈ 5ns
Quantum efficiency	≈ 40% @ 1064nm

Table 4: Main characteristics of APD [37].

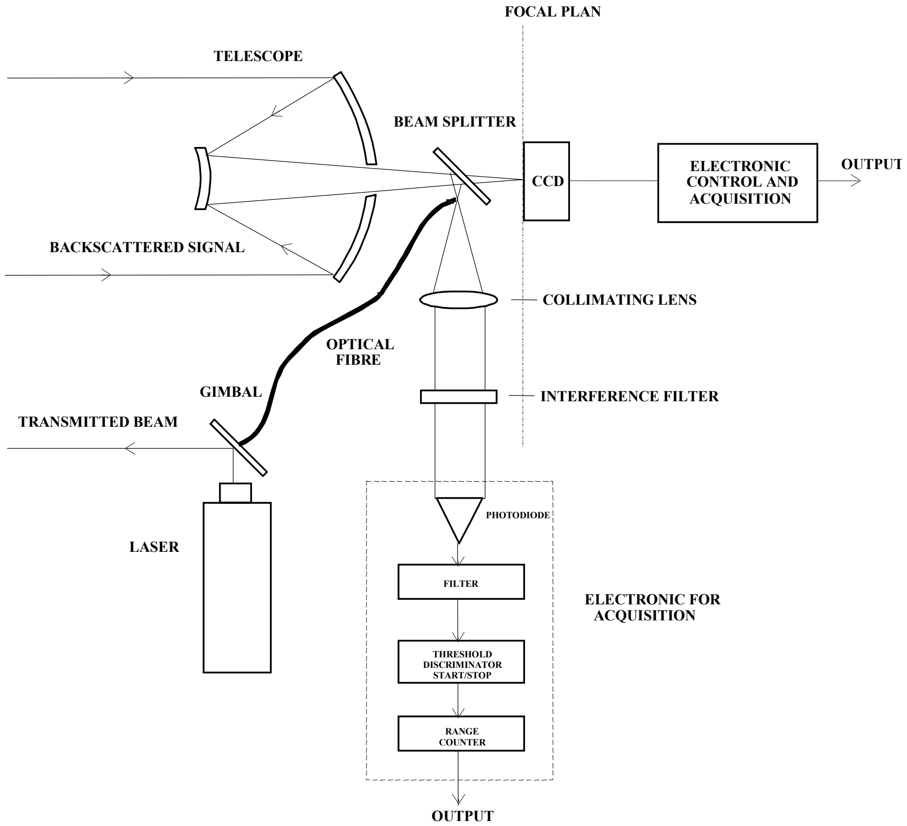

Figure 1: Preliminary configuration for a laser altimeter for microsatellite

5. CONCLUSION

This paper addressed the study performed by CO.RI.S.T.A., under Italian Space Agency contract. The work has been focused on the feasibility study of an altimeter to be accommodated on-board a microsatellite as auxiliary payload to measure satellite height within 1 m accuracy to allow stereopairs correction of images acquired by MHRRC camera integrated onboard.

The performed analysis on rangefinder systems both for the microwaves (radar systems) and for the visible infrared wavelength range (laser systems) showed that a laser altimeter system appears the more suitable for the mentioned application. Moreover our choice takes also in account the possibility for the laser altimeter to reduce weight and size sharing the MHRRC telescope of the camera onboard.

In order to carry out a compact and reliable laser altimeter for microsatellite we investigated many aspects which characterised the instrument: relative position of transmitter and receiver, receiver detection method, transmitter source. The main characteristics of the studied laser rangefinder are: bistatic configuration, single-wavelength system, laser Nd:YAG (Q-switched) 1064nm, pulse energy 50-80mJ, pulse duration less than 7ns, beam divergence 0.1mrad, repetition rate higher than 1.4Hz. In figure 1 a preliminary configuration for the laser rangefinder is reported.

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