ALART: A Novel Lidar System For Vegetation Height Retrieval From Space

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ABSTRACT

We propose a multi-kHz Single-Photon Counting (SPC) space LIDAR, exploiting low energy pulses with high repetition frequency (PRF). The high PRF allows one to overcome the low signal limitations, as many return shots can be collected from nearly the same scattering area. The ALART space instrument exhibits a multi-beam design, providing height retrieval over a wide area and terrain slope measurements. This novel technique, working with low SNRs, allows multiple beam generation with a single laser, limiting mass and power consumption. As the receiver has a certain probability to detect multiple photons from different levels of canopy, a histogram is constructed and used to retrieve the properties of the target tree, by means of a modal decomposition of the reconstructed waveform. A field demonstrator of the ALART space instrument is currently being developed by a European consortium led by cosine | measurement systems and funded by ESA under the TRP program. The demonstrator requirements have been derived to be representative of the target instrument and it will be tested in an equipped tower in woodland areas in the Netherlands. The employed detectors are state-of-the-art CMOS Single-Photon Avalanche Diode (SPAD) matrices with 1024 pixels. Each pixel is independently equipped with an integrated Time-to-Digital Converter (TDC), achieving a timing accuracy that is much lower than the SPAD dead time, resulting in a distance resolution in the centimeter range. The instrument emits nanosecond laser pulses with energy on the order of several μJ, at a PRF of ~ 10 kHz, and projects on ground a three-beams pattern. An extensive field measurement campaign will validate the employed technologies and algorithms for vegetation height retrieval.

Keywords: Lidar, Single Photon Counting, Vegetation height retrieval, Earth Observation, Space instruments

1. INTRODUCTION

Altimetry is generally defined as the measurement of the height of points on a celestial body from a given reference surface. For the Earth, the heights are usually referred to the Earth gravitational surface reference, designated as ellipsoid. In the most elementary form, a spaceborne laser altimeter (Lidar) determines the distance from the satellite to a target surface by measuring the satellite-to-surface round-trip time of a laser pulse. The target surface height is then conceptually retrieved as the difference between the satellite altitude and measured range. The first laser altimeters in space have been used on the Apollo missions in the early Seventies, for measuring the height of the spacecraft above the Moon's surface, achieving a measurement accuracy of 10 meters between adjacent measurement points. Since then, Lidars have been used in orbit around the Moon, Mars, Mercury. Since 2003, Lidars have been measuring ice sheets and sea ice thickness around the Earth. Although the basic concept of Lidar operation has not changed, recent technological progress in electronics and data processing, as well as in detectors technology, has paved the way to more advanced observations, exploiting the laser ranging technique in a multitude of innovative areas [1-4], as demonstrated by measurement campaigns on board of aircrafts [5].
Among the others, it is worthwhile mentioning:

- Bathymetry: measurement of the sea depth in shallow water zones;
- Snow depth and ice thickness mapping;
- 3D imaging of ground surface;

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- Canopy height and shape retrieval: distribution of the scattering elements from the top of canopy down to the ground.

Lidars traditionally rely on a detailed time analysis of the full waveform (FW) analogue return signal, and not only on the measurement of the time of flight (TOF) of a single laser pulse. This method allows the retrieval of physical parameters characterizing the target scattering elements along its depth.

On the other hand, in a Single Photon Counting (SPC) Lidar instrument the arrival of single photons triggers the detector, delivering a digital output. The delay of the triggering photon with respect to the laser pulse (TOF) provides the information on the height. In fact, a detection event is expected to occur with higher probability at the time instant corresponding to the return signal. Anyway, it could also be originated by a background photon. Moreover, one of the single photon detectors main criticalities is that, after a detection event, the device becomes disabled for a short period of time (detector dead time). Although recent technological developments have led to substantial performance improvements, this effect cannot be neglected. Although SPC lidars suffer from long dead-times and are prone to unwanted triggering events due to background photons, they provide great advantages for space operation. Reduced power consumption is achieved through the limited pulse energy. Moreover, the use of high Pulse Repetition Frequency (PRF) is the key to overcome the low signal intensity limitations, as many return shots can be collected from nearly the same scattering area, while the platform is orbiting.

In this paper we report about the development of the ALART instrument, a multi-beam SPC lidar instrument for vegetation height retrieval from space. In section 2, we present the instrument concept, the detector technology and the height retrieval approach, while in section 3, the development of the ALART demonstrator is reported, together with a description of the test location and campaign. Conclusions and further project developments are discussed in section 4.

2. ALART: A SPACE INSTRUMENT FOR VEGETATION HEIGHT RETRIEVAL

2.1 A multi-beam, high PRF, SPC Lidar instrument

ALART has been conceived as a SPC, multi-beam and high PRF lidar instrument for vegetation height retrieval, supposed for operation on an Earth observation platform and capable of working over a wide range of latitudes (from -70° to 70°).

High PRF (multi – kHz) laser altimeters are a recent and valuable alternative to the traditional high-energy and low-pulse-repetition SPC lidars [1-4]. As the mean number of signal photons detected per laser shot may amount to few photons only, a Poisson statistical analysis is applied to the measurement process. Because of the high PRF of the laser source, several return pulses are expected to come from nearly the same scattering area. Their set represents a frame, defined to correspond to a relatively homogeneous scatter target and hence giving nearly the same return for each pulse. Therefore the frame size, i.e. the number of returns within the frame, will decrease with the footprint motion velocity and increase with the PRF. The target characteristics determine the validity of the homogeneity assumption. More return shots can be combined in the observation of smoothly changing surfaces than for rough terrain or vegetation canopy with irregular and abruptly changing profile. In theory, the number of return shots corresponding to nearly the same target properties could be increased with higher emitter PRF. The return of a multi-kHz signal from an illuminated area may present a wide and complex profile over time in the range gate, as a consequence of high slopes or multi-reflections/scattering targets [6-8]. In that cases, the instrument needs to distinguish different signal echoes at the required measurement resolution and retrieve the specific characteristics of each echo. In order to achieve that, a complex histogram (analogous to the FW signal) must be constructed. By means of a modal decomposition of the reconstructed waveform, several physical properties of the target tree, such as height and shape, can be retrieved.

To maximize the altimetry across-track swath and its sampling, the ALART instrument has been conceived to exhibit a multi-beam design configuration. Besides the increase of the target area, a multi-beam Lidar provides the possibility to determine terrain slopes. The generation of multiple-beams is, in general, not a straightforward operation, as system complexity can significantly increase with the number of required sources. Anyway, as multi-kHz SPC lidars only require a limited pulse energy, it is possible to employ a single laser source. For the ALART instrument, the use of two different devices is envisaged for the separation of the main laser beam into multiple sub-beams: fast Micro Electro-Mechanical (MEMS) scanning mirrors or Diffractive Optical Elements (DOE).

The main ALART figures are reported in Table 1. It exhibits an across-track swath of 10 km, sampled with 5 beams, each of them exhibiting a diameter of 20 m. The target measurement accuracy in height retrieval is of 1 m. The laser pulses are emitted with a frequency of more than 10 kHz, exhibit an energy of at least 60 μJ and a time duration of ~ 2 ns. The detector lead time is required to be limited by 1 ns. The expected minimum mission lifetime is 5 years.

In the next sections (2.2 and 2.3), the detector technology and the height retrieval approach to be employed in the ALART instrument are discussed.

Table 1. SPC altimetry requirements for space instrument

Space altimeter requirements	Value
Across-track coverage (width)	10 km
Across-track sampling	5 samples
Footprint size	20 m
Along-track sampling	500 m
Accuracy	1 m
Pulse frequency	> 10 kHz
Pulse energy	> 60 μJ
Pulse width	< 2 ns
Detector dead time	< 1 ns
Timing resolution	< 1 ns
Minimum mission lifetime	> 5 years

2.2 ALART detector technology

High detection sensitivity is required when working with LIDAR systems operating from space, in order to overcome the attenuation due to the long distance between detector and target scene. Many detector technologies offering single-photon sensitivity have been reported in literature, but SPADs (Single-Photon Avalanche Diodes) are one of the most suitable choices because they offer the best trade-off in terms of low dark-count rate, high photon detection efficiency, good timing jitter (which directly impacts on the measurement resolution and precision), radiation hardness, robustness and cost-effectiveness. The SPAD (also called Geiger-mode APD – Avalanche PhotoDiode) is a solid-state detector based on a pn junction, reverse-biased above the breakdown voltage, working in the so-called "Geiger mode" regime: a single photon generates an electron-hole pair, which triggers a self-sustaining avalanche through multiple impact ionizations in a positive feedback loop [9]. Therefore, the output of a SPAD in response to a single photon is a high-level current pulse that can be easily detected by an external read-out circuit. In order to limit the afterpulsing effect, after each avalanche the detector has to be kept OFF for the so-called hold-off time (lasting few tens of nanoseconds), which sets a limitation to the maximum count rate and hinders the detection of more photons arriving within a short (nanosecond) time interval. Therefore, we employed an array of SPADs as a bucket detector, thus being able to detect more single photons arriving simultaneously or within a short time, e.g. those ones coming back from different distances of the scene under observation.

Since background light strongly depends on the environmental conditions (e.g., day or night, sunny or clouded weather), two different arrays have been employed to obtain the best performance in every situations: one with bigger SPADs and higher fill-factor, suitable for lower illumination level, another one with smaller SPADs and lower fill-factor, suitable for higher illumination level.

The two detectors share the same basic structure (described in [10]), integrating one CMOS SPAD and one, fully independent, TDC (Time-to-Digital Converter) into each pixel, as shown in Figure 1. The detector for low illumination level is made by 16x32 pixels, whose size is 150x300 μm^2, and circular SPADs with 100 μm diameter (fill-factor = 17.4%), whereas the detector for high illumination level is made by 32x32 pixels, whose size is 150x150 μm^2, and 30 μm SPAD diameter (fill-factor = 3.14%). The internal structure for the 32x32 array is represented in Figure 2, whereas Figure 3 shows a micrograph of the detector.

Both the 100 μm and the 30 μm diameter SPADs have been fully characterized in [11]. The DCR (Dark Count Rate) at 20 °C is in the order of 1000 counts per second for the former, and just 30 counts per second for the latter. In both cases, the temporal response is limited by the TDC timing jitter (about 250 ps RMS). The PDE (Photon Detection Efficiency) tops at 440 nm with a 55% peak detection efficiency, reaching 35% at 532 nm.

A sub-nanosecond TDC is integrated in the pixel in order to measure the time delay between a START signal, triggered by the SPAD photon detection, and a STOP signal, which is common for all the pixels and synchronous with the laser emission [2]. The TDC is based on a coarse-fine architecture, in which a 6-bit "coarse" counter counts the number of clock periods between the START and STOP signals, whereas a 4-bit "fine" interpolator improves the resolution down to 1/16 of the TDC clock period. The TDC clock frequency can be adjusted in the range 70 – 160 MHz to tradeoff between resolution (down to 6 cm single-shot resolution when the clock is set to 160 MHz, with 60 m measurement range) and wide measurement range (up to 130 m when the clock is set to 70 MHz, with 13 cm single-shot resolution). The maximum frame-rate is about 100 kHz for the 32x32 array and 200 kHz for the 16x32 one.

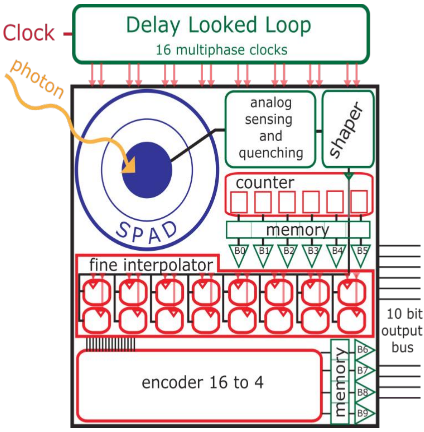

Figure 1. Internal structure of the smart pixel, including the SPAD detector (either 30 µm or 100 µm) and the TDC converter.

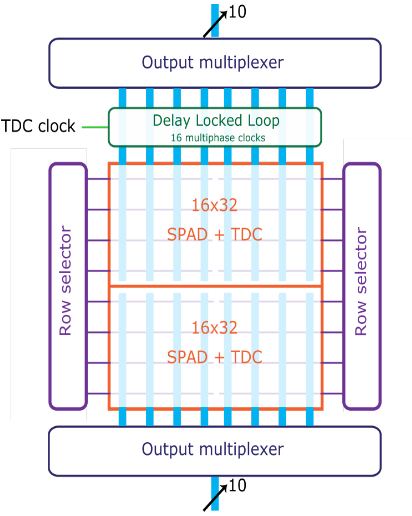

Figure 2. Global structure of the 32x32 SPAD+TDC array, which is split in two halves to increase readout speed. A similar structure is employed for the 16x32 one.

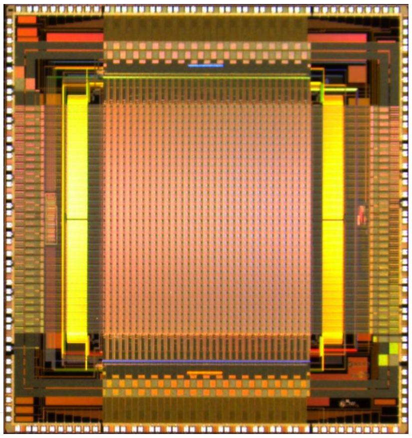

Figure 3. Micrograph of the 32x32 SPAD+TDC array.

2.3 Data processing and height retrieval approach

Approaches for the determination of vegetation height in the context of Single Photon Counting (SPC) lidar can be divided into two groups: (a) from a sensor-based perspective using a single SPC histogram or a group (stack) of SPC histograms, and (b) from a (geo-)spatial perspective.

Among the first group, the approaches can be further divided into ones that aim for the detection of discrete returns in an SPC histogram or stack of SPC histograms and into ones that derive vegetation height as a feature of distribution of the histogram.

In the literature, various approaches are found belonging to the first group, among them (cross-)correlation techniques [12-13], Maximum-Likelihood estimation of the number of returns and subsequent fitting of mixtures of base functions, e.g. Gaussians and/or Generalized Gaussians [14-15] (see Figure 4 for an example) or adaptive optimization and update of the model complexity by the method of "Reversible Jump Markov-Chain Monte Carlo" (RJMCMC) [5].

As mentioned before, vegetation height can be further derived by analyzing the distribution of histograms, e.g. by taking the 5% and 95% percent quantiles as representatives for canopy and ground return [16]. Additionally, the HOME measure, i.e. the Height Of Median Energy of the entire histogram above the mean noise level. It has been proven to be a well-suited representative for biomass and structural attributes in tropical forests [16-17].

The height difference between the first and last return, derived via appropriate georeferencing of these returns, can be regarded for as vegetation height. However, this requires (a) the laser ray penetrating the vegetation to the ground and its return being strong enough to be detected, and (b) the terrain surface being horizontal.

The limitations for deriving vegetation height from single and aggregated histograms give the motivation to consider vegetation height in a bigger, spatial context. The primary goal is to reliably determine the ground surface in vegetated areas and is known as "virtual deforestation" [18], e.g. by applying a block-minimum filter [19] or hierarchic robust interpolation [20]. While the first is an iterative coarse-to-fine grid-based approach, the latter derives filter values and weights for each point iteratively in order to classify the point cloud into terrain points and off-terrain points. After the calculation of a digital terrain model (DTM), an equivalent for the canopy top (canopy height model, CHM) is to be derived. The vegetation height at a specific location then results in the height difference between CHM and DTM at the respective location.

In the context of ALART, the approaches for retrieving returns by cross-correlation and fitting Gaussian Mixture models have been implemented, as well as deriving returns from histogram quantiles and the HOME measure. Block minimum filter and hierarchic robust interpolation implementations are available in software packages developed at TU Wien. While most components have been implemented as rapid-prototyping solutions in MATLAB, the algorithms performing best in the field tests will be ported to C++.

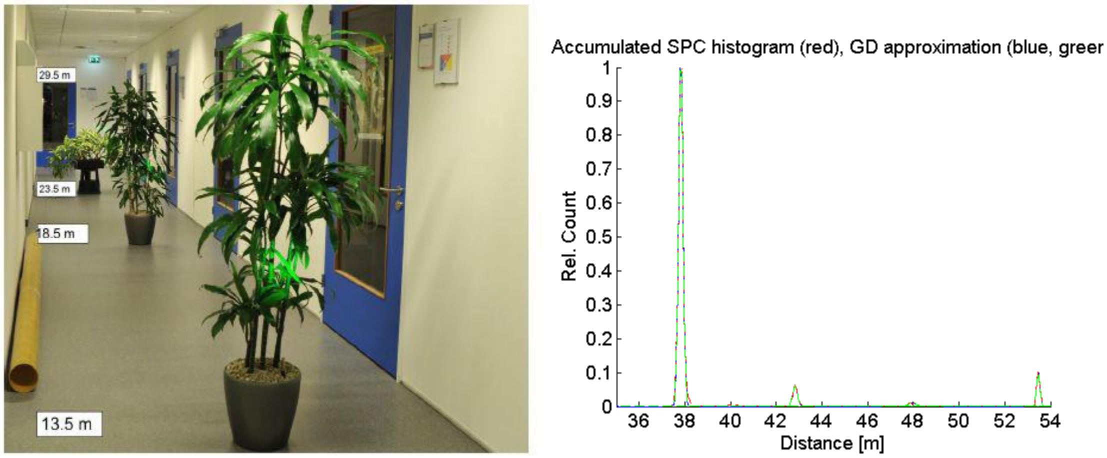

Figure 4. Left: Test scenario at cosine | measurement systems for determination of vegetation height using an SPC lidar instrument. Right: Cumulative SPC histogram (red curve) and fitted Gaussian Mixture Model (MATLAB implementation). The reconstructed vegetation “height”, i.e. the distance between the foremost plant and the background wall resulted in 15.7m whereas the reference was 16m.

3. THE ALART INSTRUMENT DEMONSTRATOR

3.1 Demonstrator description

In the framework of the ALART project, funded by ESA under the TRP program, an European consortium led by cosine and comprising Politecnico di Milano, Technische Universität Wien, Entner Electronics KG and Logikon Labs, is developing a demonstrator of a Multi-beam Lidar instrument for vegetation height retrieval.

The main figures of the demonstrator have been determined in order for it to be representative of the space ALART. Nevertheless, it has been not possible to simply scale them down through the ratio of the operating heights (orbit and tower height). Indeed, this approach would have, for example, lead to an extremely small beam footprint (diameter in the millimeter range), which would have been not adequate for a representative testing of an instrument conceived for being employed for vegetation height and shape retrieval. On the same line of argument, it was not possible to scale down the laser pulse energy according to the operation height difference (applying the standard Lidar equation), as the background signal is much more relevant on ground than in space. Therefore, the pulse energy has been chosen to keep the demonstrator Signal to Noise Ratio (SNR) approximately equal to the space instrument one.

The ALART field demonstrator has been designed to operate in the green range (532 nm). The transmitter optics creates a pattern of three beams on ground, exhibiting a footprint of 80 cm at a distance of 50 m and covering a linear distance of ~4,20 m. The receiver collects the radiation reflected by the beam footprints and concentrates it on three detector matrices. The instrument main parameters are summarized in Table 1.

The block diagram in Figure 5 describes the conceptual structure of the Laser altimeter demonstrator. Four main blocks can be identified:

- Transmitter block, comprising the laser head and its control electronics, the multi-beam generation optical system and the SPAD triggering generation electronics;

Table 2. ALART demonstrator main parameters

Parameter	Value
Number of beams	3
Instrument height	50 m
Footprint on ground diameter	0,80 m
Footprint separation	0,90 m
Swath	4,20 m
Operation wavelength	532 nm
Pulse energy	~10 μJ
Instrument volume	24 x 27 x 15 cm^3

- Receiver block: comprising the receiving optics, including background suppression filter, and the detectors;
- Front end electronics: comprising processing electronics for time of flight measurement.
- Back end electronics: providing power conditioning and interfaces to all the subsystems and data storage. The user can access this module directly in order to perform real time monitoring of the results.

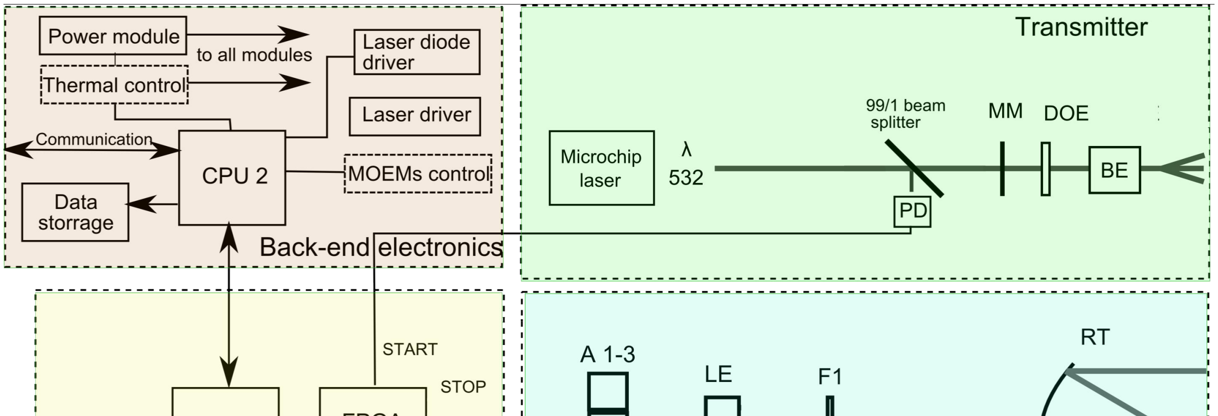

Figure 5. Block diagram of the field demonstrator

Similarly to the ALART space instrument, for the generation of the multiple beam pattern, two different devices have been considered as baseline

- Diffractive optics element (DOE)
- Micro-electro-mechanical system (MEMS) scanning mirror.

The use of the DOE enables the simultaneous generation of multiple beams, among which the laser power is distributed. On the other hand, a single beam with full power is shone if the MEMS mirror is employed. MEMS mirror offer advantages for SPC altimetry and in the case of multiple wavelength operation. Given the advantages provided by both devices, the ALART demonstrator has been designed in order to ensure the possibility of alternatively using either the DOE or the MEMS mirror.

The transmitter optics is as an afocal system, i.e. a system capable to image a collimated output beams. The minimized divergence of the beams impinging on the target is essential for a correct operation of a LIDAR system. The laser beam is first expanded in order to obtain the desired footprint size on ground. The transmitter optics angular magnification has been properly chosen in order to match the desired angular beam spacing. A beam sampler is integrated in the transmitter optics to direct part of the laser radiant energy to a photodiode (PD), generating a start pulse for the time measurement electronics. At a distance of 50 m, approximately equal to the tower height, the beam divergence angle is nearly diffraction-limited, their footprint has a diameter of ~80 cm and the center of the two side beams have a distance of ~3,40 m.

The receiver optics is in charge of collecting the radiation reflected from the three footprints on ground, illuminated by the laser light shone by the transmitter, and to convey it onto the three detectors.

In the proposed design, a front-end mirror-lens collects the radiation coming from the scene and images it on an intermediate focal plane. The images of the different footprints on ground are separated by means of a proper baffling system. To suppress background radiation to the maximum extent, a laser-line filter, whose pass-band is matched with the laser emission wavelength is inserted in the receiver optical system.

The receiver has been designed to work in two operation modes: "*dispersive"* and "*imaging"*. In "dispersive mode". three lenslets are used to re-focus the three images at infinity and to materialize the system exit-pupil, in correspondence of which the detector is placed. Therefore, the radiation coming from a given footprint is efficiently spread over the whole detector.

In "imaging mode", the instrument is re-configured as a standard imager, with each sensor pixel being sensitive to only its instantaneous field of view (iFoV). This operation mode relies on the possibility of adjusting the position of the sensors and the re-imaging lenslets.

The field demonstrator is shown in Figure 6. The housing is an anodized aluminum case with chromatized contact surfaces in order to guarantee an good thermal conductivity between the parts. In order to eliminate possible cross-talk effects, emitter and receiver optical systems are accommodated in separated, light-tight, compartments.

Figure 6: ALART field demonstrator

The ALART demonstrator has been designed not only for being compatible with a static platform at a height of ~50 m, but also with the payload platform of a Skyarrow aircraft, to enable future airborne tests.

The estimated mass of the ALART demonstrator is estimated to be approximately 9 kg. Its power consumption is estimated to be 20.5 W while the instrument is in stand-by, raising to ~42 W during operation.

3.2 Test location and campaign

Among different available options, the best suited test site has been identified being an equipped measurement tower, located in Speulderbos, the Netherlands (52° 15' 8.1" N- 5° 41' 25.8" E). Pictures of the tower are reported in Figure 7. The site is operated by the National Institute for Public Health and the Environment (RIVM). The tower is placed within a dense 2.5 ha Douglas fir stand planted in 1962. The tree density is 785 trees per hectare and the tree height was measured to be 32 meters in 2006. The tower is 46 m high. The single-sided leaf area index varies between 8 and 11 throughout the year. The surrounding forest stands have typical dimensions of a few hectares and varying tree heights. Dominant species in the neighborhood are Douglas fir, Japanese Lark, Beech, Scotch Pine and Hemlock. At a distance of 1.5 km east of the tower the forest is bordered by a large heather area. In all other directions the vegetation consists of forest at distances of several kilometers. The topography is slightly undulating with height variations of 10 to 20 m within distances of 1 km.

The tower height, the tree density and the power supply availability make the Speulderbos tower an ideal test location for the ALART demonstrator and its characteristics have significantly influenced its design.

Figure 7: Photos of the Speulderbos measurement tower.

The ALART demonstrator will be installed on a static platform at a height of 46 m. In order to acquire a range of data for different locations on ground, the instrument needs to be rotated. Figure 8 reports a conceptual design of the ALART accommodation. The interface mount is compatible with both the horizontal and vertical bars of the platform so that the instrument can be rotated along two orthogonal axes.

The test campaign has been conceived to provide results which could be representative of the target space instrument. Two different testing configurations have been considered. In the first, a pushbroom motion around the pitch axis is simulated (Figure 9). The three beams are oriented in the across track direction and directed towards the dense canopy structure of the trees, increasing the obscuration to the ground. In the second configuration, a pushbroom motion around the roll axis is simulated (Figure 10). The laser beams sweep the area just under the tower. As canopy structure is present all around the Speulderbos tower, rotating the instrument of ±10°, it is possible to cover the canopy structure of at least two different trees.

The pixel SPAD detectors are triggered every time a laser impulse is emitted. The data acquired per each individual frame is given a time stamp and saved onto the system memory. In post processing it will be possible to reconstruct the

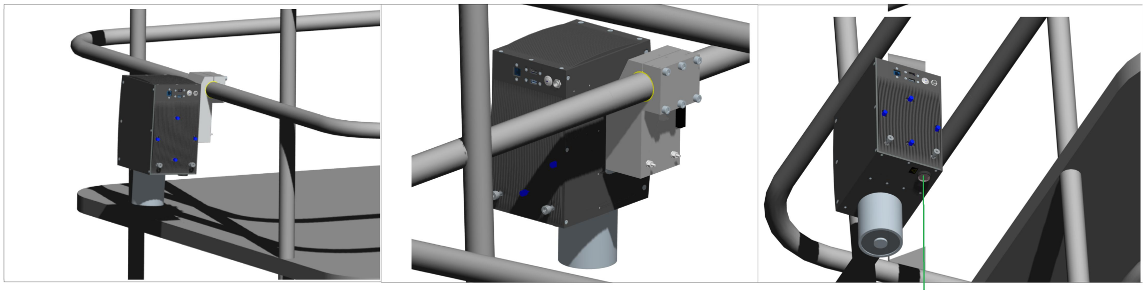

Figure 8: Altimeter demonstrator installed on the measurement tower

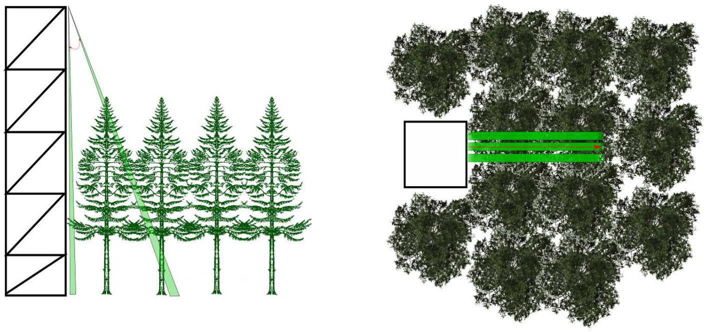

Figure 9: Field test setup: pushbroom configuration around the roll axis.

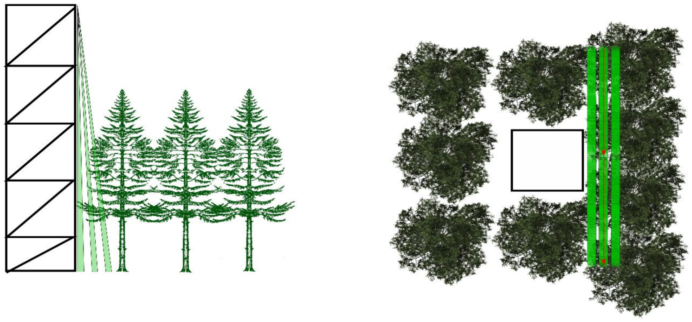

Figure 10: Field test setup: pushbroom configuration around the roll axis

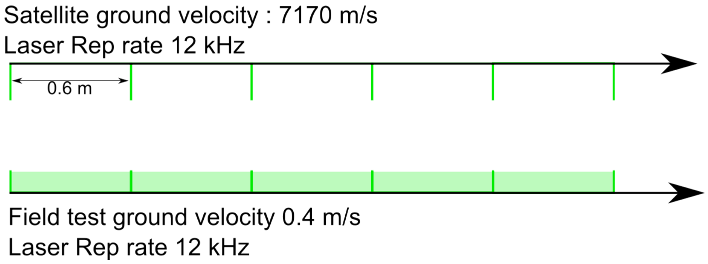

Figure 11: Post-processing reconstruction of the spacecraft ground velocity.

observed scenario reproducing the orbiting satellite by selecting the frames corresponding to the ones which would have been acquired by a moving satellite (Figure 11). The histogram is then reconstructed using only those frames. This approach can be used to simulate different velocities and thus mimicking the conditions that would be encountered in an airborne test or a space flight.

4. CONCLUSION

In this work, we presented the concept of ALART, a multi-beam, high PRF, Lidar instrument for vegetation height retrieval from space, the considered detector technology and the data retrieval approach. In the current development, an ALART demonstrator been designed in order to be representative of the spaceborne instrument. An extensive field measurement campaign will validate the employed technologies and different algorithms for vegetation height retrieval.
A future airborne test will also provide extremely valuable information about the instrument operation, while accommodated on a moving platform.

5. ACKNOWLEDGMENTS

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