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PRELIMINARY STUDIES FOR A VEGETATION LADAR/LIDAR SPACE MISSION IN FRANCE

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ABSTRACT

This paper gives an overview of French studies realized in the frame of the CNES (French Space Agency) working group on spaceborne lidar missions. These studies include (1) the development of forest scenery and radiative transfer models for the simulation of lidar waveforms under forest cover, (2) preliminary instrumental studies to ensure the feasibility of the scientific requirements and (3) evaluation and improvement of inversion methods to retrieve forest parameters from large footprint lidar data.

Index Terms— Spaceborne vegetation lidar, forest, carbon stock, biomass, remote sensing, fullwaveform lidar.

1. INTRODUCTION

Forests cover 30% of continental surfaces and are a major contributor to the carbon cycle and to the regulation of the global climate through carbon sequestration in forest biomass, while they are sensitive to climatic changes in turn. Forests also play a key role in energetic supply and biodiversity conservation. Sustainable management of forests, with the aims of maintaining all their functions, is thus critical for the future of mankind.

Development of ecological and earth vegetation-atmosphere interaction global models, essential to improve knowledge of forest ecosystem working and to define appropriate management practices, is hampered by a lack of consistent information on forest structure and biomass and on their dynamics at a global scale. If a tight integration of space-, airborne- and ground-based information is now widely advocated, acquiring suitable, consistent and extensive data from space is a technological challenge we have to face to address forest sustainable management.

No current Earth Observation (EO) System provides vegetation vertical structure and biomass estimations with the required accuracy. By its ability to measure land cover vertical structure, lidar opens new perspectives towards this objective [1, 2]. Airborne lidar technology is highly qualified for forest applications but, despite the success of ICESat, the 1st EO lidar mission (2003-2010), developing a spaceborne vegetation system remains challenging.

To overcome this challenge, CNES (the French Space Agency) set up a working group on spaceborne lidar missions in 2008 and supported scientific and technological projects to study the potential of space lidar for Earth Observation and to define appropriate instrumental specifications. It resulted in the 2010 submission to the 8th Earth Explorer missions ESA call for ideas of 2 missions with forest monitoring as primary or secondary objective: LEAF (Lidar For Earth and Forests) [3] and Z-Earth [4] resp.. This paper gives an overview of on-going studies, focusing on design optimization of a spaceborne vegetation lidar. Their main outputs will be: (1) Stand and radiative transfer (RT) models, for simulating lidar waveforms of forests, (2) ICESat data analyses and instrumental studies, including the development and test of a prototype, to ensure the feasibility of a system that will meet mission requirements and (3) Evaluation and improvement of processing methods to retrieve forest parameters from large footprint lidar data.

2. SIMULATION OF LIDAR SIGNAL ON FORESTS

Lidar signal depends on many factors either environmental (geometrical and optical properties of ground, vegetation and atmosphere) or instrumental (wavelength, emitted signal, both horizontal and vertical resolution, instrumental noise, pulse duration…). RT modeling can allow the linking of remote sensing data and Earth surface biophysical properties. Lidar waveform simulation is thus a prerequisite for designing space missions. However for complex environments like forests, it requires an accurate modeling of vegetation scenes and of RT within these scenes, both challenging tasks. Few physical models (*e.g.* [5-7]), as

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opposed to analytical models that use strong simplifications, address the backscattering specificities and technical characteristics of lidar systems. Most of them require simplified descriptions of 3D vegetation structure, *e.g.* trees modeled as turbid ellipsoids, which hampers an accurate modeling of multiple scattering. Using more detailed plant models (*e.g.* in [8]) results in high computational time and such models do not exist for tropical rainforests trees, which are among the most constraining terrestrial environment for designing a vegetation lidar system. Moreover, moving from tree models to realistic stand models is still an issue. Our aim is thus to develop and validate optimized modeling approaches based on realistic forest scenes that will allow accurate signal simulation even in tropical forests.

2.1. Models development

2.1.1Vegetation modeling

AmapSim is a structural plant simulator that dynamically produces detailed 3D plant models [9]. It is based on theoretical botanical concepts of plant architecture that interpret plant development as a sequence of growing and branching processes [9, 10]. They are stochastically simulated in AmapSim through a set of virtual buds whose activity is calibrated by on field measurements (shoots distribution, internode lengths, branching angles,…) at different development stages. The method is thus highly species dependent, but allows us to realistically mimicking individual plant architecture with some variability (Fig. 1a). The level of details reachable, up to annual shoots and leaf flushes, is particularly adapted for an *in silico* sensitivity analysis of backscattered lidar signal. The challenge within the framework of spaceborne lidar studies is threefold: (1) accounting for plant-to-plant interactions in the AmapSim 3D stands simulator; (2) calibrating stands mock-ups on real forest data, which also requires calibrating site-specific stand allometric envelops; (3) generalizing the approach to highly diverse tropical forests, which requires defining more generic, *i.e.* less species-dependent, architectural archetypes. 3 research avenues currently investigated by UMR AMAP.

2.1.2. Radiative transfer modeling

CNES supported the development of 2 models. Both use ray tracing methods. LidART, developed by AMAP, manages non parametric object meshes. It processes architectural plant models for which each plant element or growth unit has its own polygonal representation. It works also with volumetric turbid objects, whatever their shape. It is part of the AMAPstudio software suite that includes several integrated applications for simulating forest scenes and editing / analyzing plant architecture (*e.g.* biometric extraction from virtual plant models and scene elements radiation balance).

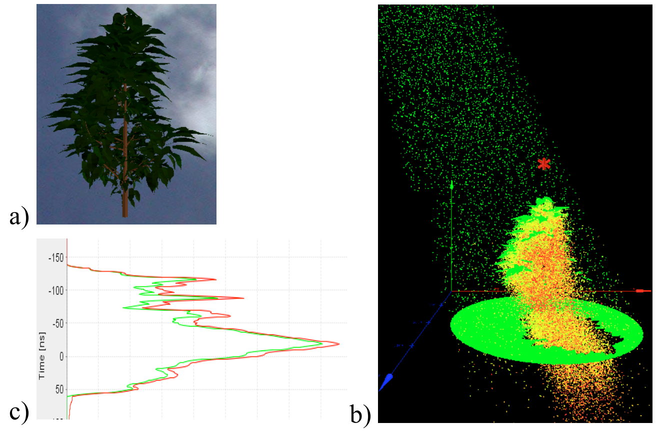

Fig.1: Cherry tree (AMAP) (a) and its 3D (b) and 2D (c) waveforms - Atmosphere: "mid-latitude summer" gas model and "rural V=5km" aerosol model.

DART, developed by CESBIO [11], processes volumetric and surface objects, with a great flexibility for changing the analysis scale of landscapes. It simulates accurately satellite lidar data (Fig.1) and radiometer images from the visible to the thermal infrared for any landscape (vegetation and/or urban with topography and atmosphere) that it creates or imports. It can also transform objects (*e.g.*, trees) and landscapes with a polygonal representation into turbid representation, which allows one to process large landscapes while retaining the polygonal modeling realism. For lidar it computes both instrumental system (position, angular divergence, pulse parameters…) and solar noise. Paul Sabatier University provides free licenses to the scientist community (http://www.cesbio.ups-tlse.fr/us/dart.html).

2.2. Model based studies

Pending availability of stand models, which require important field and modelling work, first analyses allowed to validate the capacity of the RT models to study the impact of several factors on the signal, *e.g.* atmospheric effects, multiple scattering, simplification of forest scenes…

Comparison of simulations with real lidar waveforms are planned to consolidate the 2 models. Sensitivity studies will allow 1) to optimize forest models by finding a trade-off between the level of detail of stand models and the computational time for RT modeling and 2) to optimize some system parameters for forest applications. Simulations will be also highly valuable to improve inversion models.

3. ICESAT DATA AND INSTRUMENTAL STUDIES

Studies focused on system specifications and meet requirements in terms of measurement sampling, geolocation, and absolute z and vegetation height measurements. For forest applications height is indeed a key parameter from which other biophysical parameters, *e.g.* above-ground biomass or stem volume, are derived thanks to allometric relationships.

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3.1. ICESat / GLAS data analysis

As lidar data are in the optical domain, their quality depends a lot on cloud presence. It implies a sampling that may affect the quality of forest parameter estimations. Thus, it is important to anticipate the impact of meteorological conditions for optimising data availability.

A global analysis of GLAS (Geoscience Laser Altimeter System) shot viability over tropical forests (latitude ∈ [23.5°N 23.5°S] showed that 20.1% of the 52.4 million shots were nonviable, according to the criteria defined by the National Snow and Ice Data Center. The ratio of non viable data naturally depends on the transmitted energy (the 42.2 % for transmitted energies < 5 mJ decreases to 20 % then stabilizes for transmitted energies > 15 mJ) and on the relative humidity of the lower cloud layer (14% for humidity < 20% and 29% for humidity > 80%). Filtering viable waveforms as suggested in many forest studies (e.g [12]) led to a global percentage of 32.8% exploitable data. However, this result was obtained without decoupling the effects of transmitted energy and cloud layer humidity. Thus, it underestimates what could be obtained with a stable and sufficient energy source. On a set of waveforms associated to high transmitted energy acquired over French Guiana, we found that ≈60% of ICESat data were not affected by clouds.

An evaluation of cloud cover evolution during both day and year was realized by Météo-France on 9 areas at different latitudes and characterized by contrasted climatic conditions. These data will allow to optimize the local time for satellite overfly.

3.2. Instrumental studies

3.1.1. Theoretical studies

Preliminary studies to identify which instrumental parameters will be critical to mission performance have been started. Two separate approaches have been taken. Comparison of these approaches has shown significant correlation. A simplified instrumental simulator has been developed using Gardner's [20] analytic approach. Using the DART model for sceneries and radiative properties, an end to end Monte Carlo instrumental simulator has also been developed. This simulator allows us to generate noisy lidar waveforms (see Figure 2 for a LEAF like signal) and by repeated random sampling of instrumental parameters to evaluate their influence on the altimetric performance. Comparison with the Gardner simulator has shown significant accord between the two models on the altimetric error variations for different instrumental parameters such as spot size, telescope size, pulse duration etc.

3.1.2. Lidar prototype development by CEA (Commissariat à l'Energie Atomique)

With the aim to get an instrumental simulator for assessing space lidar error budget for forest studies, the ULICE lidar,

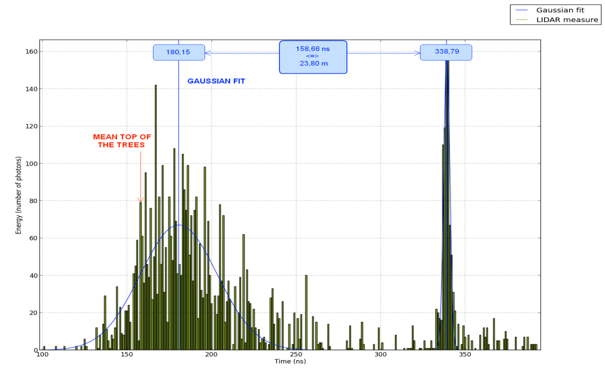

Fig.2: Noisy LIDAR echo following LEAF specifications over simulated Landes forest in the Bordeaux area. Turbid model used for canopy, surface scattering from triangles is also possible.

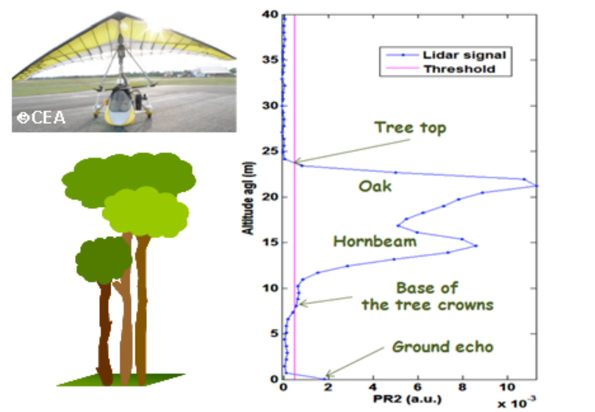

Fig.3: ULICE measurement over an oak-hornbeam forest, South-east of Paris. The footprint size is ~2 m. PR2 is the range corrected lidar signal [13]. After ground echo identification, information on forest structure can be extracted from the lidar profile, *e.g.* canopy top, tree crown base and undergrowth top.

Ultraviolet LIdar for Canopy Experiment, was derived from the homemade system LAUVA (Lidar Aérosol ultra-violet aéroporté) [13, 14]. It is a full-waveform profiling lidar that works at the 355 nm wavelength with a sampling along the line-of-sight between 0.15 and 1.5 m. Divergence can be set from 2 to 18 mrad. Fig.2 gives an example of waveform. Here, the selected carrier is an Ultra-Light Aircraft (ULA) because of its flexibility to perform lidar measurements over small and medium area [13]. The system was already used for different forest types, from coniferous (maritime pine) to deciduous trees (oaks, hornbeams...). The 3-D sampling was conducted thanks to the combination between the high lidar vertical sampling and the ULA maneuverability. To retrieve forest parameters at plot and stand level original approaches were developed to account for the specific spatial distribution of measurements and for the medium footprint size [15]. The integration of a servo-control for the divergence, an array detector at 355 nm and a second channel in the NIR wavelength (1064 nm) is planned.

4. SIGNAL PROCESSING METHODS

Several models that derive canopy height from ICESat / GLAS waveforms were assessed on 2 areas: Brazil Eucalyptus plantations on relatively flat terrains (slope < 7°), and Mayotte Island tropical forest with a wide range of slopes with respectively field inventory measurements and 1m accurate DTM and DCM (Digital Canopy Model) derived from airborne lidar data as reference data. As suggested in [12], ICSESat data were filtered to remove problematic waveforms, *e.g.* with atmosphere contamination, with too low or saturated signals, with an incoherent elevation in comparison with SRTM.

In Brazil, no significant difference was noticed between the tested models [16]. With RMSE=2.2 m, direct model (canopy height = signal beginning - ground peak [17]) provides results almost as good as those from the best statistical model (RMSE=1.9m, r^2=0.92) based on 3 waveform metrics, *i.e.* the extends of waveform, leading and trailing edge (definitions in [16]). In Mayotte, results depend on slope, tree density and tree height distribution and are also method-dependent. For GLAS data recorded in ±1 year from the reference data date and compared to the max. tree height in the footprint (defined as the 99^{th} percentile of the smooth DCM), RMSE and r^2 for the direct model were resp. 9m and 0,23. Statistical models provide barely better results. We expect better results through an improved modeling of slope effects [18], the analyses of simulated waveforms and a combination with high resolution imagery information. Biomass and other biophysical parameters will also be studied.

5. CONCLUSION AND PERSPECTIVES

Since 2008, preliminary studies for developing a spaceborne vegetation lidar gathered momentum and the first outcomes provided the French scientific community with solid bases to keep moving forward. Even if BIOMASS, a system based on a P-band synthetic aperture polarimetric radar that aims to measure forest biomass to assess terrestrial carbon stocks and fluxes [19], was recently selected as the seventh ESA Earth Explorer mission, forest remote sensing scientists are convinced that a lidar system would provide unique accurate vegetation structural profiles that, either processed as measurement samples or combined with other remote sensing data (to achieve wall to wall maps), will help meeting user accuracy requirements and allow to address the challenge of sustainable forest management [1].

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