International Workshop on Vegetation Lidar and Application from Space

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Waveform simulations and analysis of Lidar data for the development of a space-based vegetation lidar system

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General context

- Vegetation structure is the driver and the result of forest ecosystem ecological functions
- Structure measurements provide information on processes and on biophysical parameters and are needed
  - to advance our understanding on forest ecosystems functioning
  - and to sustainably manage forests
- Spaceborne Lidar missions are currently the best solution to expand forest structure measurements in space and time
- Several missions are planned or under study by space agencies: GEDI/NASA , MOLI/JAXA, LEAF/CNES

Outline

- LEAF, the vegetation lidar mission under study in France
- A modeling framework developed in the frame of an ongoing experimentation/validation study
- Results on vegetation representations for RT modeling
- Instrumental studies
- Research avenues to improve forest parameters assessment from Lidar
- Perspectives

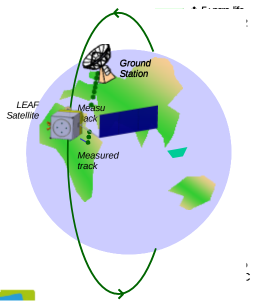
LEAF: Lidar for EArth and Forests A vegetation mission under study in France

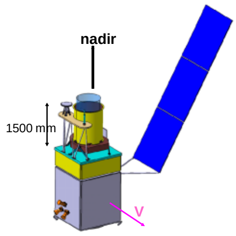
- 2014 : Recommended as a possible mid-term mission following the scientific prospective seminar of CNES

LEAF mission

LEAF a satellite mission coupling a Lidar and an imager

- **Primary objective** is to provide spatialized information on **forest 3D structure and on its dynamics**
- Secondary objectives :
  - **Ground altimetry data** for Geodesy, Geohazards and Cryosphere studies
  - **Continental water level data** for Hydrologists
- Design by Airbus Defense and Space (former EADS Astrium) with the support of CNES





A standard satellite platform
- Square modular structure
- ± 3° depointing capability
- 870 Kg launch mass

A small launcher (Vega- ESA)

LEAF: current design

- LEAF instruments

Fullwaveform lidar system
- ***NIR wavelength : 1064 nm (eye safety)***
- *Pulse duration < 2ns*
- ***Footprint diameter: 20 m with an array detector (4)*** ***slope***
- ***Energy : 86mJ*** *laser output =>* ***60mJ instrument output***
- *Signal sampling = 1 ns* *Vertical resolution = 15 cm z res.*

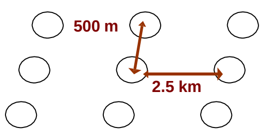
\+

on the shelves
VHR XS Imager
- *Panchromatic + B,G,R,NIR*
- *2m resolution, 14 km swath width*
- *Co-registered with the Lidar*

Enhance geolocation
Improve accuracy of forest parameters
Provide data for extrapolation of lidar results

- Spatial and temporal sampling characteristics
  - 15 Hz repetitive rate
  - 3 year revisit period
  - 5/6 years lifetime

After 3 years

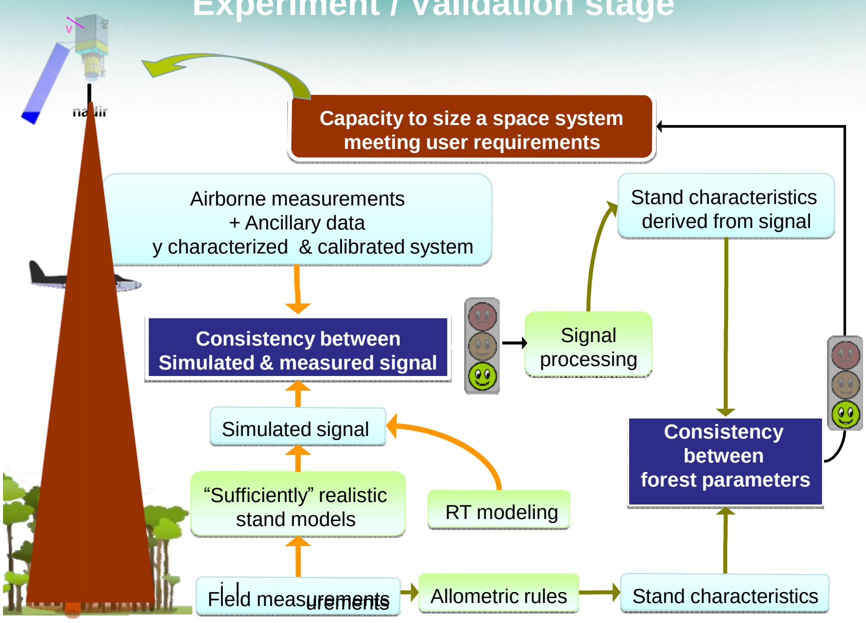


LEAF concept is not set in stone

- Models used to size the system are considered to be insufficiently reliable still pending issues to optimize the mission and enhance its capacity to monitor forest
- This led CNES to implement an experimentation/validation stage
- **Objective for LEAF:** size a system providing complete vegetation profiles even for dense forests without any risk of calling into question the concept or the system architecture in the latter mission project phases

  Establishment of a working plan to address pending issues

Experiment / Validation stage



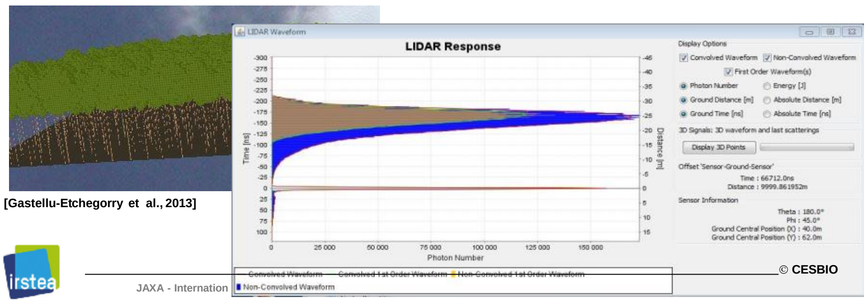
A modeling framework developed in the frame of the experiment / validation study

Accurate modeling requires to develop

- An efficient and reliable radiative transfer model
- “Sufficiently” realistic stand models

1- Radiative transfer model

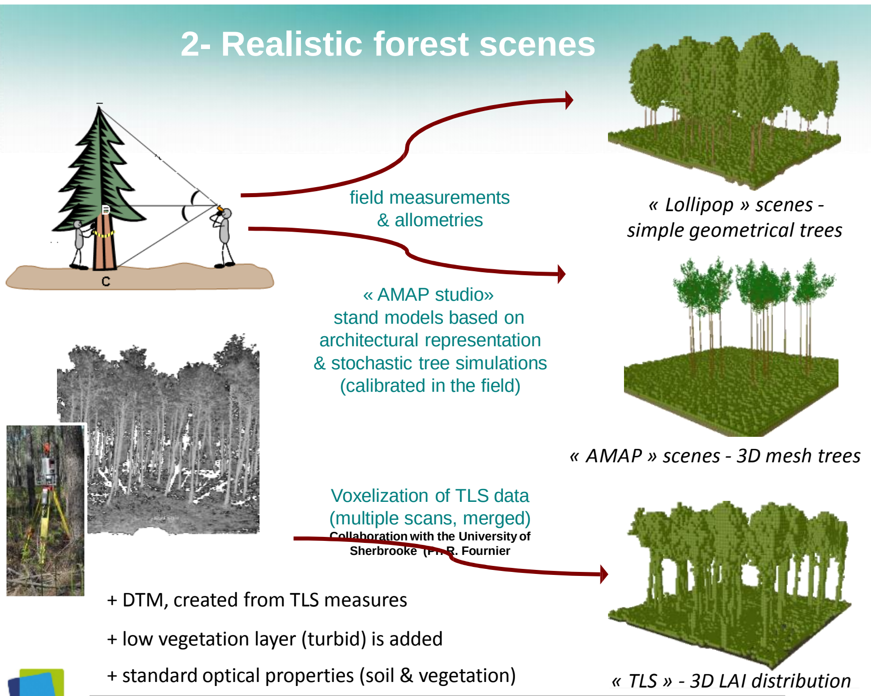
- DART - Discrete Anisotropic Radiative Transfer (CESBIO) :
  - “Ray-Carlo” method (combination of ray tracing and Monte-Carlo methods)
  - DART can model
    - *Any lidar system (position, angular divergence, and pulse characteristics)*
    - *Multiple diffusions*
    - *Interactions between lidar signal and atmosphere*
    - *Solar noise*
  - Compatible with complex and realistic vegetation representations



[Gastellu-Etchegorry et al., 2013]

© CESBIO

2- Realistic forest scenes



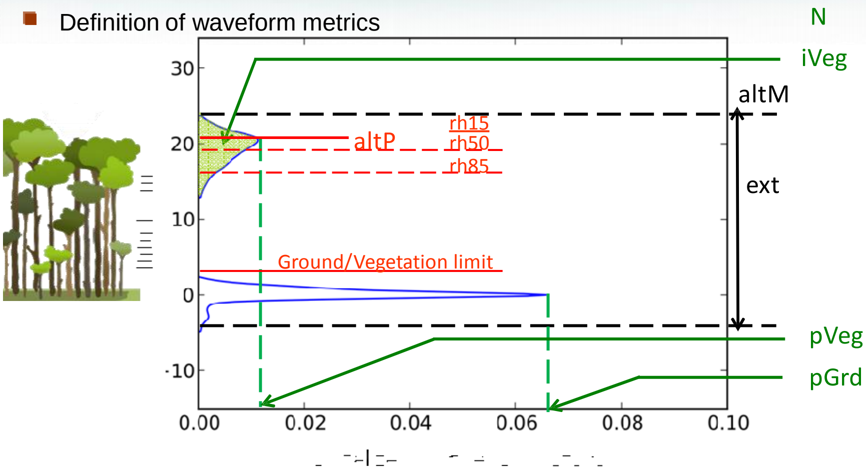
+ DTM, created from TLS measures

+ low vegetation layer (turbid) is added

+ standard optical properties (soil & vegetation)

3- Analysis & validation of simulated waveforms

- Definition of waveform metrics

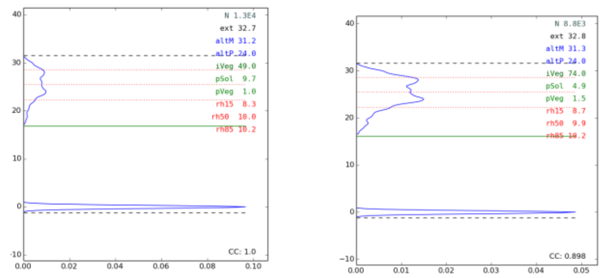


- Stand height related metrics: ext, altM
- Energy related metrics: N, iVeg, pVeg, pGrd
- Vegetation profile related metrics: altP, rh15, rh50, rh85

3- Analysis & validation of simulated waveforms

- Waveform comparison

Reference WF *Simulated WF*



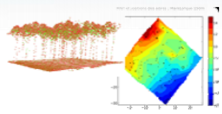
- Absolute percent error computed for each metric

$$APE_i = ABS\left(\frac{METRIC_{i\_simulation} - METRIC_{i\_reference}}{METRIC_{i\_reference}}\right) * 100$$

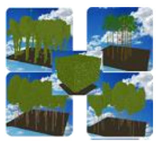
- Bravais-Pearson Coefficient of Correlation (CC)

Simulation plateform

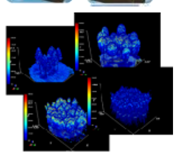
Integration of field measurements and preprocessing of ALS and TLS data



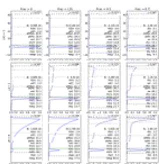
1 Building forest scenes (3 types)



2 Simulation of ALS and large footprint Lidar data with DART



3 Analysis and validation of simulated Lidar data



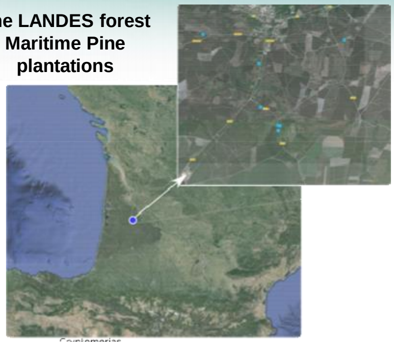
Preliminary studies on vegetation representations

Questions:

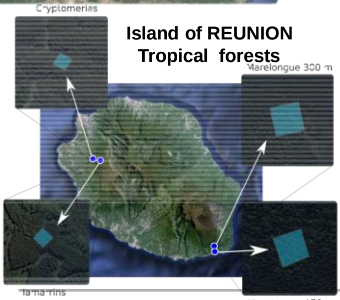
- What is the best way to represent a forest plot in RT model for lidar signal simulations?
- What are the impacts of uncertainties of the inputs used to create forest scenes on the simulated waveforms ?

Data sites

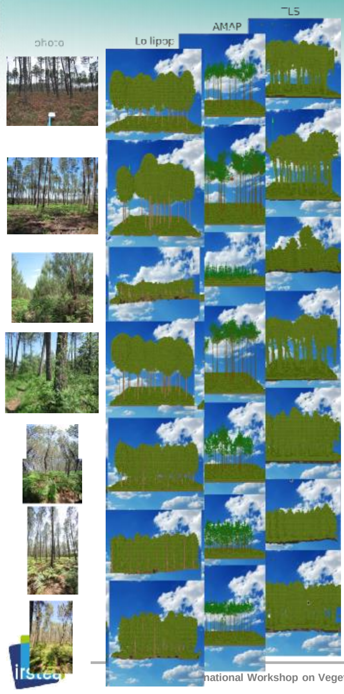
The LANDES forest Maritime Pine plantations



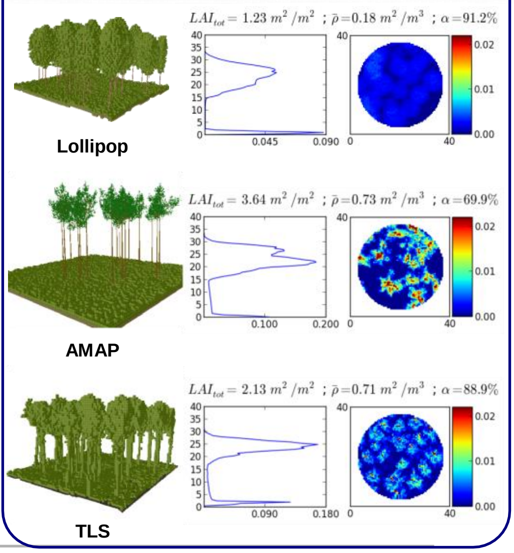
Island of REUNION Tropical forests



7 plots on the Landes site

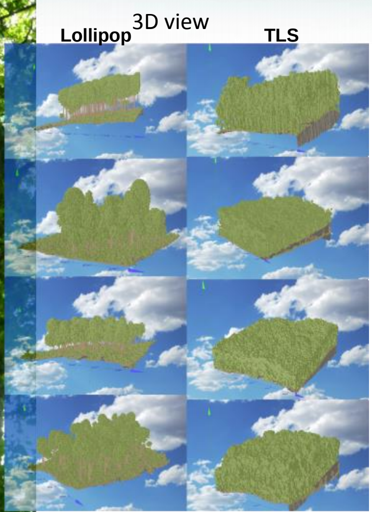


Focus on 1 plot of Landes site : LAI distribution

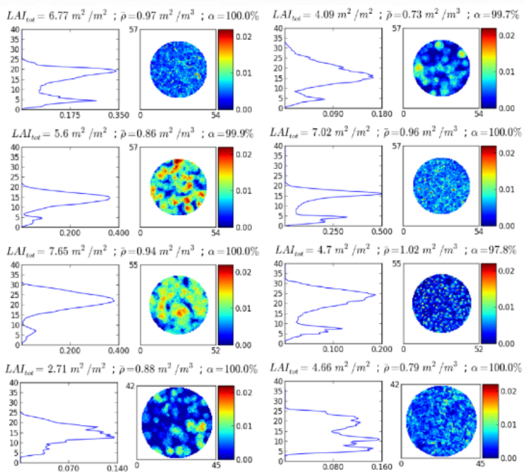


4 plots on Island of Reunion (tropical) site

3D view



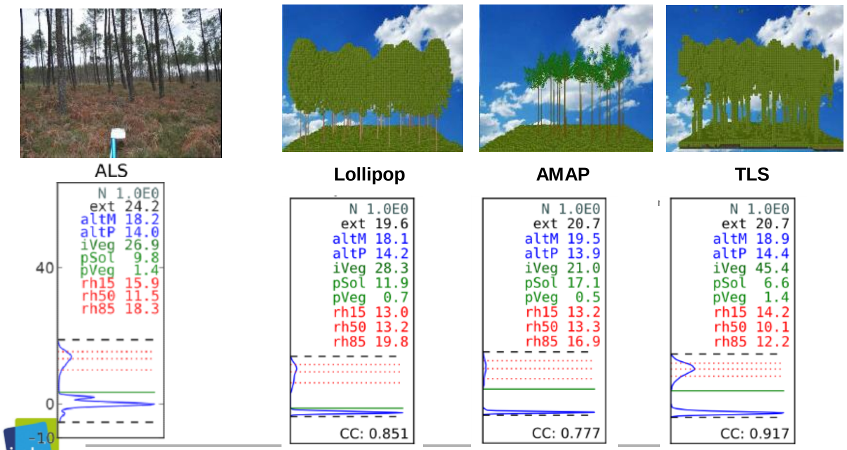
LAI distribution



No architectural models for tropical species no AMAP representations

Analysis

- Evaluation of the quality of the 3 forest representations (Landes site)
  - Reference for waveform comparison = ALS data aggregated at plot level
  - Analyzed waveforms = simulated ALS data aggregated at plot level

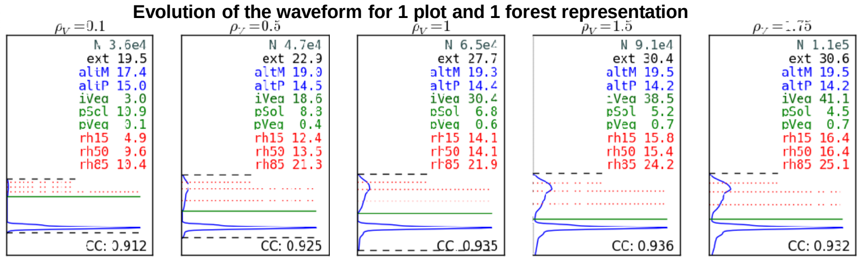


Analysis

- Sensitivity analysis to evaluate the impact of uncertainties of the inputs on the simulations (2 sites)
  - Reference = large footprint simulated waveform
  - Compared to waveforms obtained by changing initial parameters
    - *Simplification of AMAP 3D mesh*
      - *Changes in : ρ_{veg}, ρ_{ground}, total LAI, LAI distribution, $LAI_{underlayer}$, slope*

Example : Impact of change in Vegetation reflectance

Evolution of the waveform for 1 plot and 1 forest representation



Mean evolution for all the plots

Results

- Which representation is compatible with RT modelling?
  - Lollipop representation: inaccurate crown shapes → poor results
  - AMAP & TLS: shape of the vegetation peak well reproduced but differences in energy metrics were observed
  - Different calibration needs
    - *TLS : only reflectance*
    - *Lollipop: LAI calibration (+allometry)*
    - *AMAP (3D mesh) : very complex calibration*

Increasing needs for calibration

TLS based approach appears to be a good candidate to represent forest scenes

- Sensitivity analysis :
  - Shape metrics are stables (except when slope changes)
  - Energy related metrics are very sensitive to changes in ρ_{veg}, LAI, ρ_{ground}
- No absolute validation at this stage → future experiments will include
  - Characterization of the airborne lidar system
  - Additional field measurements (spectroradiometer, atmospheric condition)
- Simulations with errors in WF metrics < 10% can be expected

irstea

Instrumental studies

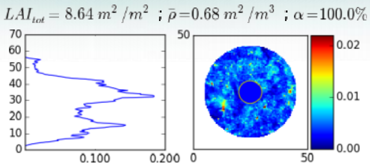
- Impact of systems characteristics for high energy fullwaveform systems
- Evaluation of a low energy photon-counting Lidar solution as an alternative to high energy FW lidar

Sensitivity analysis a FW system

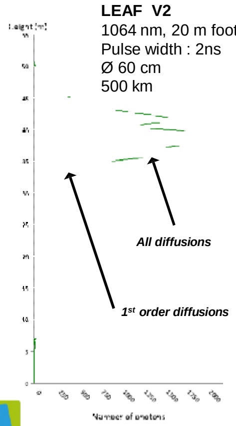
- Sensitivity analysis to evaluate the impact on waveforms of:
  - viewing angle, footprint size
  - atmospheric condition
  - solar noise
- Main conclusions
  - Intensity of ground and vegetation peaks decreases with viewing angle and footprint size due to the signal spread risk to miss the ground peak in dense forest
  - Minor impact of sun and atmospheric noises
  - Instrumental noise is likely to be the most significant source of noise and a determining characteristic to size the system

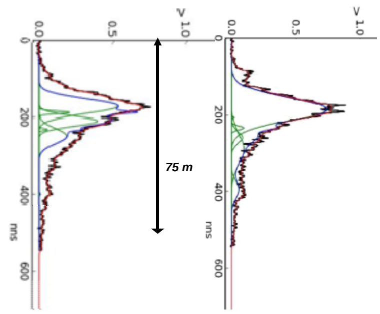
Simulation of LEAF waveforms on tropical forests

$LAI_{tot} = 8.64\ m^2/m^2$; $\bar{\rho}=0.68\ m^2/m^3$; $\alpha=100.0\%$



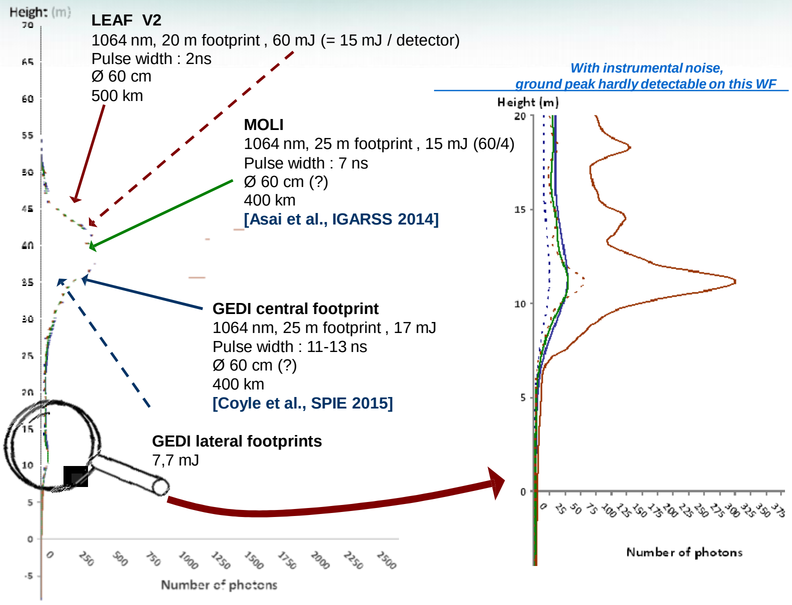
LEAF V2
1064 nm, 20 m footprint , 60 mJ,
Pulse width : 2ns
Ø 60 cm
500 km





ICESAT data on tropical forest – emitted energy : 75 to 87 mJ

Comparing LEAF, GEDI & MOLI



Low energy Lidar: a viable alternative solution?

- Operating high energy lasers in space (e.g. full waveform systems with few 10 mJ at few 10 Hz) is associated with risks: laser induced damage, contamination, eye safety…
- The design of ATLAS on ICESat-2 shows that alternative approach is possible (few 10-100 µJ/shot at 10 KHz)
- ATLAS design optimized for hard ground targets, vegetation (tree height) comes as secondary goal.
- Study conducted by Airbus Defense and Space to verify if the low energy approach is suited for tree height determination

[Lochard, J et al., SilviLaser 2015]

Technical point on emission & detection parts

- Two main options considered

	Crystal amplified lasers	Optical fiber amplified lasers
Advantages +	High TRL for space mission	-Reduced alignment constraints -Lower sensitivity to vibrations and to contamination - Better thermal dissipation…
Drawbacks -	Complex production	-Limitation in peak power -Concern on the resistance to radiations

- Two candidates identified

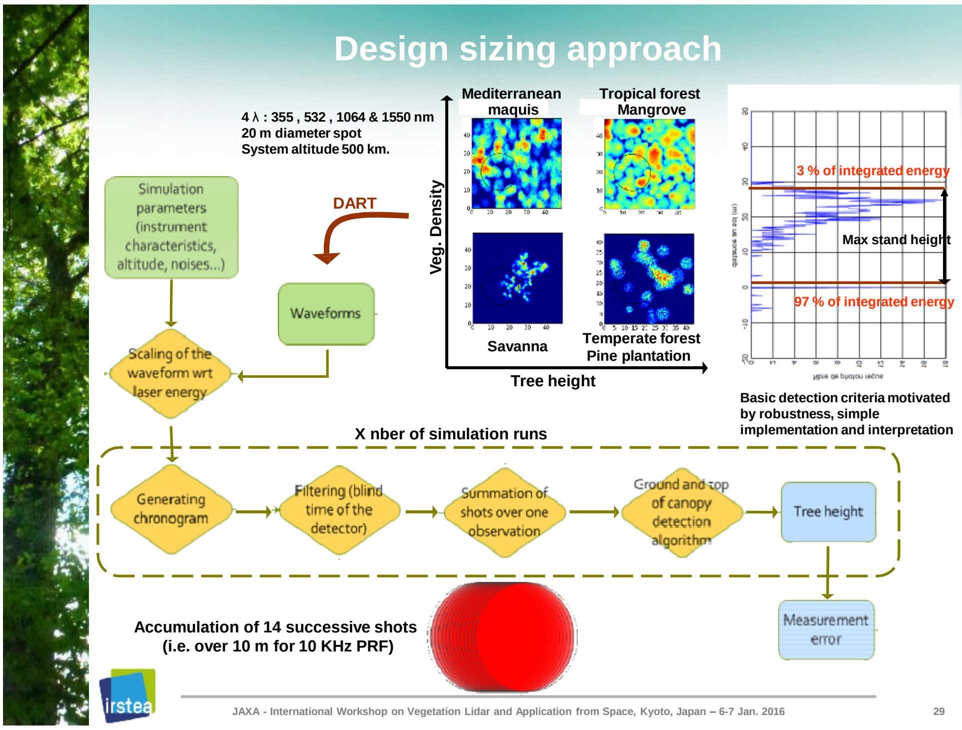
	Photo-multiplier tubes (PMT)	Avalanche Photodiode (APD)
Advantages +	-Higher TRL (Caliop, soon ICESat-2 - Low dark current - No blind time	-Large accessible spectral domain (UV to IR, with various substrates) - Higher quantum efficiency
Drawbacks -	Reduced spectral domain [0.3µm-0.9µm]	Need to operate at lower temperature for IR

[Lochard, J et al., SilviLaser 2015]

Performance and design sizing approach

- Performance requirement:
  - Measurement noise < 2 m rms (= random error on tree height)
  - Bias < 4 m

- Overall approach toward instrument design:
  - Definition of reference scenes and waveform simulations
  - Performance estimation through performance model and comparison to the requirement
  - Setting of a threshold value for the lidar product (laser energy x telescope collecting surface)
  - Instrument design based on the lidar product.



First performance results and operating point

- Low performances
  - For UV and visible linked to low values of both ground and leaves reflectance
  - For the lower stands due to a long dead time of the detector (10 ns i.e. 1.5 m height)

  First instrument design sizing based on to 2 scenes (temperate and tropical forests) and two IR wavelengths.

- Measurement noise set for an accumulation over 14 shots at 0,5 m for the temperate forest

Measurement noise	Nothern forest	Tropical forest	Mediterranean maquis	Savanna
λ=1.064µm	0.5 m	0.8 m	8.2 m	5.3 m
λ=1.55µm	0.5 m	1.0 m	8.9 m	5.9 m

derived lidar product threshold are 0.10mJ.m² at 1.064µm and 0.07mJ.m² at 1.55µm.

Budget and conclusions

- Operating point: a 0,8 m Ø telescope and
  - 200 µJ / shot at 1.064µm
  - 140 µJ / shot at 1.55µm
- Resulting instrument mass: 220 kg (incl. 25 % margin)
- Power budget : 240 Watt (incl. 20 % margin)

Same satellite class than for LEAF with current FW specifications

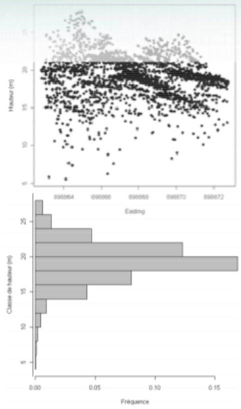
- Simulations show the viability of such an approach for tree height determination with metric accuracy for scenes of major interest including the tropical forests
- Limitations of the study
  - A full error budget would require to consider additional contributors (e.g. uncertainty on the atmosphere characteristics and effects linked to the platform (e.g. pointing, altitude uncertainties))
  - Results highly dependent on the method used to estimate height

Research avenues that could be explored to improve forest parameters assessment from Lidar

- Promising recent studies using ALS data
- To what extend these approaches can be transferred to process spaceborne data?

User requirements not always met with existing ALS based ABA

- ABA approaches are widely used to assess forest parameters (Volume, AGB, basal area) from ALS data
- Metrics are derived from height and density distributions of ALS echoes
- Most explanative metrics are used to build a predictive model

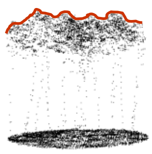


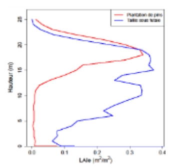
- But low robustness level for such approaches
  - Metrics are highly correlated
  - One model / site
  - Insufficient accuracy for complex stands (e.g. multilayered broadleaved stands), e.g. RMSE > 20% for biomass assessments

Development of new methods to overcome these issues

Explored approaches

- Seeking for new metrics
  - Using normalized vegetation profiles [Bouvier et al., 2015], [Vincent et al., 2015]
  - Penetration distribution metrics instead of height metrics [Vega et al., 2016]
- Using few meaningful metrics to build more general models (one shape)





[Bouvier et al., 2015]

$$\hat{y} = \beta_0 \; \mu_{CH}^{\beta_1} \; \sigma_{CH}^{2\,\beta_2} \; P_f^{\beta_3} \; Cv_{LAD}^{\beta_4}$$

Heterogeneity of the canopy surface — *Vertical heterogeneity*

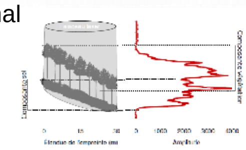
R^2 > 0,85 - RSD < 20%
even for broadleaved multilayered stands

- "Combining LIDAR and growth and yield models" **[St-André et al., SilviLaser 2015]**

- Strengths of each approaches (growth and yield, LIDAR) integrated in a consistent and comprehensive way – not only additive or multiplicative combination of metrics
- No bias among 10 different sites with **a single model** for BA estimation

Remaining challenges

- Transfer these approaches to tropical forests and to large footprint FW lidar signal
- Relief

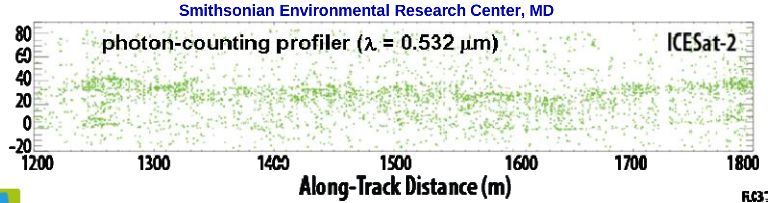


Mix between ground and vegetation signal

One of the limitation when processing ICESat 1

  - Improved height prediction expected with future systems
    - *Smaller footprint*
    - *Local slope assessment (better than SRTM DTM)*
  - Vegetation profile?
- Photon-counting data: vegetation profile?

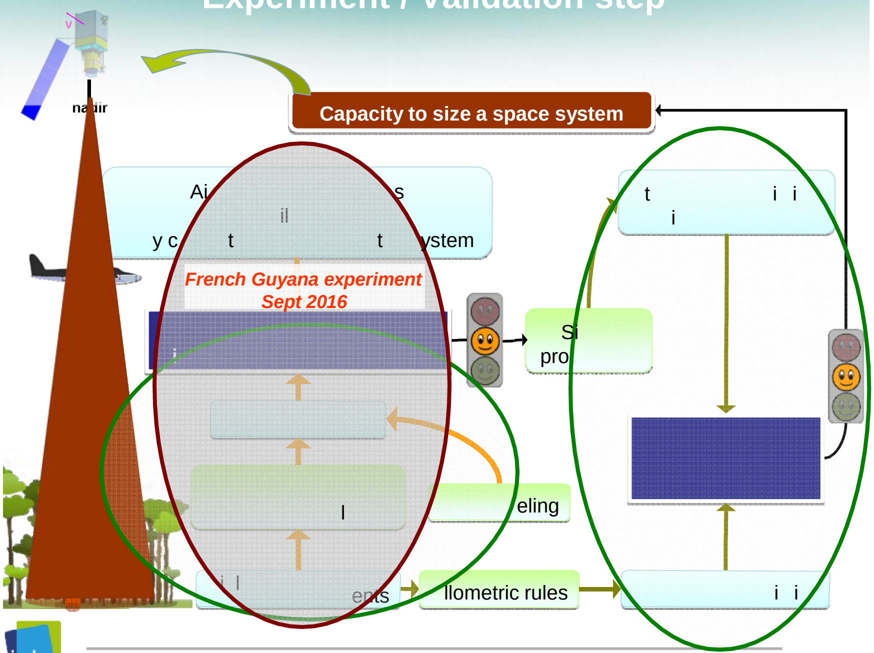
Smithsonian Environmental Research Center, MD



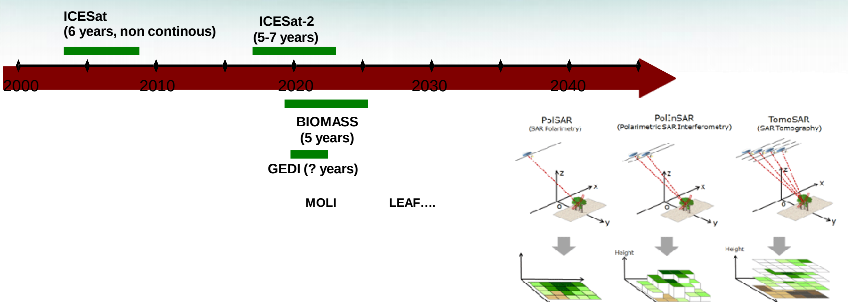
Crédit: R. Nelson, FLORESTA project- 2013

Perspectives

Experiment / Validation step



What can be expected from ICESat2 & GEDI ?



- + Comparison between FW and PC lidars (crossing orbits)
- + Complementarity between green and NIR wavelength
- + Complementarity between BIOMASS and lidar missions to improve biomass assessments
- + Evaluation of several sampling strategies
- \- Boreal forests not covered (~ 30% of the world's total forest area)
- \- The interest of an imager or stereo-imager co-registered with a lidar will not be evaluated

Tree climbing for height and crown architecture studies

Technology is not everything…

- Research is needed to refine and integrate user requirements in link with emerging research topics; e.g. assimilation of lidar data in
  - Biodiversity models
  - Ecosystem models for carbon stocks and fluxes assessment

New global models developed to include inter-grid variability & management practices

- The capacity to meet user requirements is highly dependent on field measurement efforts
  - Allometry

$$\hat{y} = \beta_0 \, \mu_{CH}^{\beta_1} \, \sigma_{CH}^{2\,\beta_2} \, P_f^{\beta_3} \, Cv_{LAD}^{\beta_4}$$

Landes Forest – France - Pine plantations

		Deleuze et al. (2013)	O. Shaiek et al. (2011)	Cacot, (2007)	JY Fraysse et L Cotten
Predictive model for biomass (T/ha)	R^2	0.95	0.93	0.79	0.50
	RSD (%)	12.7	13.0	19.8	32.6
	RMSE	10.8	10.8	18.8	31.3