3D-VegetationLab

Proposal to the European Space Agency in response to ESA Invitation to Tender ESRIN/AO/1-6529/10/I-NB

VOLUME 1
Version 1.0

Executive Summary
Technical Proposal

© Matthew Borrett (CDN), www.onyxtree.com

Prepared by:

Felix Morsdorf, Jason Brazile, Jan Clevers, Matt Disney, Jean-Philippe Gastellu-Etchegorry, Philip Lewis, Zbynek Malenovsky, Hans-Gerd Maas, Norbert Pfeifer, Jan Pisek, Radek Pokorný, Michael Schaepman, and Jean-Luc Widlowski.

Approved by:

Michael Schaepman

Released by:

Felix Morsdorf

Distribution:

ESA, all contractors.

TABLE OF CONTENT

CHAPTER 1 – Executive Summary

This proposal responds to ESA ITT ESRIN/AO/1-6529/10/I-NB outlining the bidding teams plans for establishing a 3D VegetationLab based on detailed description of vegetation sites (3DVegLab).

The team is composed of a principal investigator (RSL, *CH*), four full partners (TU Wien, *AUT*, UCL, *UK*, CESBIO, *F,* Netcetera, *CH),* one observer (JRC, *I)* and two additional subcontractors that will be chosen from at project kick-off. RSL will be responsible for the overall execution and implementation of the project. The team at RSL is composed of Prof. Dr. Michael Schaepman (head, RSL, overall responsibility), Dr. Felix Morsdorf (project responsible, laser remote sensing scientist) and Dr. Zbynek Malenovsky (optical RS and RT specialist).

The subcontractors will be responsible for providing data and access to the sites on which the 3DVegLab will be established. We present a list of 6 sites, and based on an extensive site description and availability of auxiliary data. Jointly with ESA, we will select two of those sites in the first phase of the project, but no later than at CDR. The sites selected will then be complemented with consultants and measurements missing.

The observer, Dr. Jean-Luc Widlowksi (JRC, *I*), is responsible for complementing gaps in the above team composition, with independent long-term experience in radiative transfer.

Four specific work packages (WP) are proposed to address seven tasks (T) specified in the project proposal Statement of Work (SoW). WP1 will deal with the project management, including the meeting organization and communication between project participants including ESA authorities, keep the deliverables on track and report the results. WP1 is additionally comprised of Task 7, which focuses on the dissemination of the project's results through publications and conference/workshop participation and the scientific demonstration study (Task 6). WP2 (Toolbox design and implementation) will cover the project tasks 3 and 5. Within these tasks the design of toolbox will be carried out (T3, including the definition of capabilities and interfaces), while in Task 5 the toolbox will be implemented according to TS and DDF delivered by Task 3. In WP 3, the requirement baselines for the 3DVegLab are defined based on literature review and consulting within the consortium (T1). In addition, WP 3 comprises the definition of field protocols for data acquisition (T2) and the actual gathering of the data itself (T4).

The proposal's contents map the SoW-defined tasks within four work packages, preserving the same task numbering scheme. As usually for ESA projects, the proposal is divided into two volumes. The first volume encompasses the cover letter, this executive summary, and the technical study proposal. The management and financial proposals are presented in the second volume.

With the exception of proposed changes to the draft contract, which concern publication rights and penalties, and which are detailed in project proposal Volume 2, Chapter 5., Section 5.8., the draft contract provisions are accepted.

It is foreseen that all work will be performed by members of staff of the participating institutions listed above.

CHAPTER 2 – Technical Proposal

2.1 PURPOSE

The purpose of this proposal is to meet the needs of the European Space Agency and the need of the scientific community to obtain comprehensive and reliable standardised multi-scale and multi-temporal data sets (including in-situ, airborne and spaceborne EO data) and suitable tools to support and stimulate the development, cross-comparison and validation of novel algorithms and products, as specified in the Invitation To Tender (ESA, 2010).

2.2 INTRODUCTION

Understanding the dynamics of the global carbon cycle is one of the most crucial scientific and societal problems of the 21st century. A key part of this understanding is being able to measure and monitor the magnitude of terrestrial carbon sinks, by mapping their horizontal and vertical structure, their rapid as well as long term changes as a result from natural and human-induced disturbances (e.g. deforestation, fire and desertification) and the subsequent recovery processes. Earth observation has always played an important role in assessing the spatial extent and the wealth of terrestrial ecosystems and optical sensors (such as the ones being operated by ESA) have been proved to provide a key source of data to derive global geo-information products on forest and vegetation dynamics. ESA has maintained exploitation activities such as GlobCarbon, which have demonstrated their capacity to deliver long-term consistent data sets at global scale to the scientific community. In addition, the GMES forest related activities have paved the way for an operational use of ESA data in forest mapping and monitoring applications.

The coming generation of ESA Operational mission (the Sentinels) will enhance that capacity providing novel observations with unprecedented accuracy and resolutions. This enhanced capability will provide operational institutions and the scientific community with an excellent tool to enhance forest and vegetation monitoring and to improve our understanding of the carbon cycle and land processes.

An important aspect of vegetation canopies is structure, which is relevant for e.g. ecosystem or habitat assessments and will impact as well remote sensing estimates of height, biomass, density, albedo. However, in passive optical remote sensing structure can as well have negative influence, effectively decoupling EO signal from radiometric properties of vegetation. Thus, the derivation of e.g. leaf biochemistry can severely impacted if the effect of vegetation structure is not known. These limitations can be overcome by understanding and exploiting the signal (e.g. by radiative transfer models), particularly in conjunction with multi-angular observations, and the incorporation of new methods and tools, especially with direct measurements of vegetation structure by such things as terrestrial laser scanning (TLS) and airborne laser scanning (ALS).

In this context, the 3D-VegetationLab aims at establishing a scientific support tool to answer some of the main open scientific questions and the research needs in the thematic area of vegetation processes and land dynamics. A preparatory workshop was held in Jülich, Germany in Summer 2009, where the scientific community was invited to present new technologies and methods and to identify challenges and gaps.

2.3 OBJECTIVES

Three main conclusions were drawn from the ESA consultation workshop in Jülich, which focused on exploring the possibilities offered by new technologies that directly provide estimates of the three-dimensional vegetation structure, namely by the Arborne Laser Scanning (ALS) and the Terrestrial Laser Scanning (TLS):

1. "*Improved knowledge about the 3-D vegetation structure is of fundamental importance for a wide range of applications including radiative transfer and process modelling*." - from ESA summary of Jülich workshop

While many of these gaps are associated with the unknown vegetation structure, some of them are associated with other properties, for instance with issues such as an inadequate description of the optical properties of canopy elements, atmospheric effects, physical effects (e.g. horizontal fluxes) and not well characterised soil and understory components. A large international effort was made through the RAMI (Widlowski et al., 2008) series of experiments to benchmark and inter-compare different radiative approaches and codes. RAMI showed that, provided all structural, spectral and illumination relate characteristics of a canopy target are known exactly, at least 3-D radiative transfer models agree within 1% of each other and with respect to analytical solutions (where these are available). In its latest incarnation RAMI-IV offered very explicit scene descriptions that accounted for individual needles in conifer shoots when representing canopy stands at the 1 hectare scale. Although inspired by inventory data from actual test sites, the structural, spectral and illumination related detail provided on the RAMI-IV website for these scenes could not be satisfied on the basis of available field measurements alone. Instead, simplifications regarding the spatial variability and directional scattering properties of the background and foliage elements had to be applied to fill the gaps. Similarly, the foliage orientation and branching patterns in individual tree crowns had to be artificially generated by using software packages devellopped by the computer graphics industry. In some cases the required spectral data had to be taken from measurement campaigns carried out on different stands and during different seasons. All these items, and also the fact that the background was always assumed flat in RAMI-IV, are perfectly acceptable when it comes to assessing the quality of the physics contained in canopy reflectance models. However, when the goal is to match air or space borne observations over actual targets then all
of the above data may actually have to be available. This in turn is a challenging undertaking (and might not be fully obtained through this project) since the degree of detail required for a faithfull reconstruction of a lant canopy may depend on the site, illumination and observation characteristics as well as the accuracy of the measurements associated with space/air borne sensor that is to be simulated.

2. "*Forests pose the biggest problems since they are spatially heterogeneous and strong effects of the structure on the processes have been identified*." - ESA summary of Jülich workshop

Thus, one objective of the proposed work is to define a comprehensive and standardised multi-scale dataset incorporating in-situ and 3D canopy architecture using a combination of newly available TLS and ALS with traditional field measurements to fully charactrerise a site in possibly all aspects that are relevant for radiative transfer within the vegetation canopy. The dataset will be complemented by airborne and spaceborne EO data describing different types of vegetation structures. If applicable (depending on the site chosen), the multi-temporal aspect will be assessed by dedicated in-situ sampling as well as by several EO data acquisitions.

3. *"LiDAR observations are instrumental to characterize 3-D structures over complex terrain. Both airborne and ground based lidar measurements would be needed to cover different features from individual trees and branches to canopy stands."* - ESA summary of Jülich workshop

The statement above is pointing out the complementarity of airborne and terrestrial laser scanning in terms of scales (typical laser footprint sizes are at least one order of magnitude apart), another important difference between those active remote sensing methods is the perspective. It may be a trivial difference (ALS samples the forest from above, TLS from beneath), but it severely impacts the explanatory value of both ALS and TLS alone, e.g. ALS may not be well suited for understory characterisation and TLS misses important information on the crowns in denser stands. In addition, the exploitation of these active remote sensing technologies currently faces two great challenges, that are area of research and not yet fully solved. Thus, these challenges will impact **how** these technologies can be applied within the context of the proposed work.
The first challenge is to understand the physical nature of LiDAR vegetation returns. Here, for ALS the largest problem is that the scattering objects contributing to the return signal are smaller that the illuminated area (commonly called *footprint*) and thus their abundance, distribution, orientation and optical properties influence the backscattered signal in an unknown fashion, as these effects can not be separated. For TLS, this problem is not as large, as the footprint size is in some cases in the order of the size of the scattering elements. However, the constriction "*in some cases*" already hints at another issue, which has an impact on the explanatory value of TLS data. Opposed to ALS data, where the footprint size does not alter much within acquisitions (at least in moderate terrain), in TLS, the footprint size is highly variable within a single scan, as the variation of range distances is very large, from some centimetres to something like 50 meters. Thus, close to the scanner, a laser echo might be representative of only a few square millimetres, while further away it might be several square centimetres. The second, current gap in science and a large area of research is how to exploit the semantic information contained in point clouds. While visualisations look conceiving for the human eye (as **we** can extract information such as tree and stem locations), it is a non trivial task to automate this segmentation in a case of machine perception. This is mostly attempted by using methods of computer vision and image interpretation, which have to be adapted from 2d raster images to a 3d point cloud with its unorganised data structure and not easily defined/computed neighbourhoods. In the following, we will briefly summarise current approaches and then lay out, why we think that methods that do not attempt either automation (for semantics) or are fully automatised, but with low semantics (e.g. voxel based approaches) might be better suited to reach the aims of 3DVegLab.

The proposed work in the following document will basically follow a low risk strategy of applying established technologies and methods that are present within the consortium. However, we are going to analyse the identified gaps in current knowledge to be able to further minimise the difference between the outputs of the 3DVegLab and actual remote sensing data. All partners within the consortium have research agendas that are aimed at closing these gaps, be it on the side of establishing new technologies for in-situ measurements or by advancing the knowledge about the radiative regime

2.4. TASK 1 (T1): REQUIREMENTS CONSOLIDATION

(Responsible person: Dr. F. Morsdorf, RSL, *Switzerland*)

2.4.1. Problem & Inputs

Input:
Requirements and specifications of the SoW complemented by the proposal
Recommendations of the Remote Sensing of 3D-Vegetation Structures Workshop

2.4.2. Approach & Activities

This task is mainly focused on reviewing the needed functionality and thus, the scope of application of the tool to be developed in the course of this project. One aspect of the toolbox's implementation is the simulation of upcoming and future missions, with special emphasis on Sentinel 2 & 3. We will identify the needed modules that will comprise the tool based on a review of the capabilities of the RT models available for this project, and establish a functionality set required to meet the additional aims of being able to provide support for prototyping of novel algorithms. We will look into detail at the sites available for the project and will establish a ranking based on their suitability for the simulation task (e.g. site complexity) as well as the availability of data that would be hard to obtain through this project (e.g. airborne laser scanning data). The associated networks maintaining the sites will be evaluated in respect to their compliancy with the long-term goal of establishing super-sites that endure after termination of this project. Special emphasis will be given to links between remote sensing scientists locally involved with scientists that look at processes within in the forest, where vegetation structure plays a dominant role (e.g. radiative regime or turbulent fluxes). Additionally, we will review existing approaches to derive canopy structure from ALS and TLS (see Figure 1 as an example) and place recommodations in the RB as which approaches are feasible to reach the aims of the toolbox. We will select at least two study cases to show the potential of the 3DVegLab. Among our current ideas (as of writing this proposal) are study cases such as to test methods for the derivation of advanced (Level 2) products from Sentinel 2 and prototyping of a novel technology, namely multi-spectral canopy LiDAR for the joint assessment of vegetation structure and physiology. The former will be carried out, if the Sen4Sci project (lead by RSL as well) will come up with a definition of a new, advanced research product for the vegetated land surface. The retrieval accuracy of that respective product can then be tested using the toolbox established within this project. The latter has gathered some momentum within the science community, with one group in the UK (University of Salford, Prof. M. Danson) actively developing a ground based LiDAR with two wavelengths and another UK group (under the lead of University of Edinburgh, Dr. I.H. Woodhouse) is currently pursuing the idea of a spaceborne multi-spectral canopy LiDAR, SpeCL,within ESA's EE8 call. Strong links to both these projects exist within the 3D VegLab team (both Prof. Lewis and Dr. Disney are named collaborators on the Salford project and Dr. Disney, Dr. Morsdorf and Dr. Schaepman are members of the SpeCL bid). Those new technologies are expected to provide better estimates of green biomass (and thus carbon fixation) and the possibilities but as well limitations for such products could be well tested with the 3DVegLab toolbox. Depending on the choice of study cases (e.g. prototyping a multi-spectral LiDAR would need LiDAR RT modules), the requirements for the toolbox might go beyond what was requested in the SoW and the consortium would need additional funds to carry out those experiments not explicitly demanded by the SoW, but as expressed as well in the links above, the consortium has intrinsic motivation to explore these options.

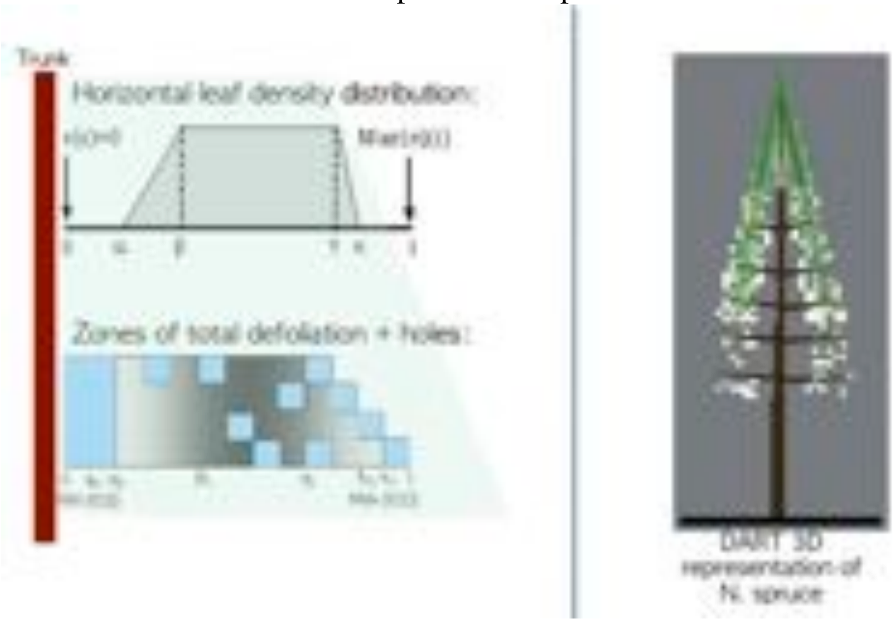


Figure 1: Example of a "medium"-tech approach to derive foliage distribution from terrestrial laser scanning. The distribution of needles is modelled as a function of height and stem distance for a single species on a specific site. The modelled trees are reconstructed based on the function parameterized with either field or ALS based estimates of tree height and crown dimensions. From Malenovsky et al., 2008b.

2.4.3. Deliverable

D1.1: Requirement baseline (RB), comprised of scientific requirements review, analysis of existing sites and networks and specification of the required toolbox functionality.

2.5. TASK 2 (T2): PREPARATION OF DATA COLLECTION

(Responsible person: Dr. F. Morsdorf, RSL, *Switzerland*)

2.5.1. Problem & Inputs

D1.1: Requirement baseline (RB)

2.5.2. Approach & Activities

The consortium will, based on the existing experience of providing data for the characterisation of field sites, extend the protocols used for this work and adapt them reflect the additional information needed for the simulation of *actual* remote sensing data. A first assessment of this information and how it will be obtained can be found in the table below:

Variable	Method(s)	Scale(s)	Sampling	Expected Accuracy
Tree height & location	Field measurement (dGPS and Hypsometer) and ALS	Full stand (e.g. 300 m by 300 m)	exhaustive (all)	< 1 m for height and location
LAI	Hemispherical Photographs and/or LAI 2000	subplots (e.g. 30 m by 30 m)	Valeri plots	< 20%
fractional cover	Hemispherical Photographs and ALS	subplots (e.g. 30 m by 30 m)	Valeri plots	< 10 %
Crown dimensions (height & diameter)	Field measurements (FieldMap system)	individuals	exhaustive (all)	< 10 %
3D structure	TLS	mm-m	individuals, subplots (e.g. 30 m by 30 m) or whole stand (100m by 100 m)	?
Biochemical leaf properties (chlorophyll, water, dry matter content)	Laboratory analysis	Leaf samples of selected trees within full stand	Stratified sampling	< 10 %
Spectral properties of foliage and background objects (understory/soil)	ASD, Integrating Sphere	Full stand (e.g. 300 m by 300 m) or subplots (30 m by 30 m) and leaf samples of selected trees	Random tree selection and Valeri plots	< 10 %

Special emphasis will be given to the issues of scales and sampling. Regarding sampling, we will adhere to the sampling schemes recommended by the CEOS LPV. However, these might need to be adapted, since new technologies (such as TLS) will bring their own constraints towards reproducible and accurate usage in forest canopies. The scaling issue is more problematic and it seems unfeasible to scan a whole 300 m by 300 m area with TLS, thus it might be smarter to use scans of single areas to produce estimates that can be extrapolated to the whole stand. One example for this would be using replication procedures for three-dimensional reconstruction of single trees, a method often used in modelling of complex forest environment (Disney et al., 2006, Morsdorf et al., 2009). For instance, the RAMI IV experiment builds upon a certain number of generic tree representations, which were positioned and scaled according measured tree locations and dimensions. The field protocol will define how to use the instruments in order to reach the expected measurement accuracy, as well as prescribe a sampling scheme that is adequate to characterise the field sites. The latter could be partly done using the established RAMI sites, since different sampling schemes might be adequate for different sites, depending on the heterogeneity of the distribution of canopy materials, however such a scientific study seems unfeasible within the short time frame of the envisaged project.

Regarding the reconstruction of canopy geometry from TLS based point clouds, the method envisaged will be prepared using four steps which are listed below:

Step 1: design of an interactive explicit tree reconstruction algorithm with automation in parameter estimation (e.g. branch diameter)
Step 2: implementation of Step 1 using standard software (Matlab, GIS-tools, etc.) and sparse development of new code (C++, Python, etc.)
Step 3: testing, using existing data, collection of experiences with respect to scanner (wavelength, measurement principle), point density, depth of reconstruction, quality
Step 4: improvement of the program and the automation (if necessary and feasible)

These steps will be evaluated and any constraints arising from those for the field measurements will be placed in the field protocols, e.g. such as that the method might not produce accurate results for data acquired on windy days or how many scans in which configuration are actually needed to fully characterise a forest stand. The tasks related to TLS described above might need to be revisited in task 4, as unforeseen constraints during data acquisition might impose the applicability of different approaches for reconstruction.
Regarding sites, we present a list of 9 sites in five countries, spanning a large range of forest types as well as terrain types. The sites are presented along information on data availability in the Appendix of this document. Two of these sites shall be chosen at the CDR following requirements given in the special tender conditions. Additionally, we will define a protocol for auxiliary information, such as the acquisition of meteorological data for atmospheric correction and soil spectral information (spatially resolved). This information is vital in assessing actual EO data, as the atmosphere can have large influence on the radiances at sensor level and the whole approach of the 3DVegLab would fail, if atmospheric effects can not be corrected.
Multi-scale EO data will be achieved by combining the airborne and space-borne sensors. Very high spatial resolution of airborne data (imaging spectroscopy and laser) is typically between 2-5 m pixel size. Only laser airborne data over deciduous forest study site will be acquired in a multi-temporal fashion (winter and summer). Airborne imaging spectroscopy data will be collected only once in high vegetation season due to the limited resources and demanding logistic in organizing a complex field/flight campaign that would fulfil all the requirements of the 3DVegLab project. Multi-temporal space-borne datasets of two resolution are planned to be acquired for the selected study sites. High spatial resolution CHRIS/PROBA images (18 m pixel size), and medium spatial resolution MERIS/ENVISAT full-swath full-resolution images (300 m pixel size) will be collected for the study site over the high vegetation season (summer) mainly for a toolbox testing purpose.

Limited number and broad full-width-half-maximum of the multispectral sensors (ALOS-AVNIR, Formosat, IRS-P6, Landsat, SPOT) is resulting in limited spectral dimensionality of the image data, and consequently in a limited number and accuracy of the retrievable vegetation parameters. Therefore, the image data of very high spectral resolution and sampling interval (CHRIS/PROBA and MERIS imaging spectroscopy data) are planned to be used for testing the 3DVegLAb performance regarding the retrieval of biochemical-physical vegetation parameters.

RSL has access to the state-of-the-art airborne imaging spectrometer APEX, which is proposed to be used within the 3DVegLab airborne campaigns. The right choice of the flight altitude and spectral binning will assure the suitability of the airborne imaging spectrometer data spatial and spectral resolution. An appropriate full-waveform Airborne Laser Scanning system will be ordered from a commercial provider. Most of the proposed study sites are registered as the CHRIS/PROBA test sites, therefore, CHRIS images of these forest stands can be ordered in advance. Finally, MERIS FF data can be acquired from the ESA rolling-archive facility. Since RSL is PI for the Cal/Val activities of Meris and CHRIS, data can be made available to the public (agreement of ESA given).

3DVegLab will possibly also team up with the organisations conducting the ESA field/flight campaigns. At least two ESA campaigns of a suitable nature were announced for 2011: Sentinel-2 and FLEX space demonstrator campaign. Apart of the ESA activities, the national airborne campaigns are planned to be conducted by the 3DVegLab study site providers (e.g. by Institute of System Biology and Ecology, Czech Republic). RSL has a preliminary agreement to access these national level campaigns if the study sites will be chosen.

2.5.3. Deliverables

D1.2: Field Protocol (FP)
D1.3: Site and data set specification (SDS)

2.6. TASK 3 (T3): TOOLBOX DESIGN

(Responsible person: Prof. P. Lewis,UCL, *United Kingdom*)

2.6.1. Problem & Inputs

- D1.1 – Requirement baseline (RB)
- Requirements and specifications of the SoW
- D1.2 - Field Protocol (FP) relevant for the specification of data input & interfaces
- D1.3 Site and data set specification (SDS)

Description

Task 3 addresses the design of the 3DVegLab toolbox. The implementation of this design is undertaken in task 5. Both of these tasks are addressed as components of WP 2 (WP 2.1 and WP 2.2

respectively). To achieve this, the deliverables from Task 3 are: D1.4 a Technical Specifications Document (TS); and D1.5 a Design Definition File (DDF). The major input to the task is the Requirements Baseline from D1.1, resulting from a scientific requirements review, analysis of existing sites and networks and specification of the required toolbox functionality. The details of the design will also be constrained by D1.3 – Site and data set specification (SDS) and D1.2 (Field Protocol) resulting from Task 2 activities.

In the absence of the review and SDS at present, we outline below our vision for the toolbox functionality, conditioned by the minimum requirements specified in the statement of (SoW).

Elements from the SoW of relevance to the TS are (SoW, p.6):

- Observed in-situ parameters shall include measurements of the 3-D vegetation structure (by terrestrial lidar and ideally airborne lidar ALS), biophysical canopy characterization and auxiliary information (e.g meteorological observations, soil moisture, land cover).
- Intensive in-situ measurements shall cover at least the pixel extension of a medium resolution EO sensor (e.g. MERIS) as well as be representative for the phenological variability of the respective selected site. The general sampling scheme of the in-situ measurements shall be representative on the stand level.
- The toolbox capabilities shall be capable of supporting the development and improvement of EO retrieval methods of Sentinel-2 and Sentinel-3 level 2 products
- The toolbox shall simulated top of canopy and top of atmosphere reflectance based on validated physically-based radiative transfer models
- The software shall be developed as open source code and as an BEAM plug-in. The final toolbox shall be freely available to scientific community
- The toolbox shall enable a comprehensive canopy parameterization of complex canopies based on detailed in-situ data, including a realistic tree reconstruction
- The toolbox shall follow a modular structure and be extendable to accommodate for future requirements.
- The format requirements of the toolbox shall be flexible, so that different data sets can easily be processed

In the text below, we concentrate the discussion of the problem to be solved on aspects of the requirements for the toolbox from the point at which a definition of the structure of the vegetation is defined. Detail relating to the generation of this information is contained in the presentation of task 4. Whilst these issues clearly impact the design of the toolbox and will form a significant part of the input to the TS and DDF, they are also closely associated with field data collection, as so dealt with there.

The main ***aim*** of this study can be phrased as constructing and demonstrating a framework for testing algorithms that infer information about (primarily) the (vegetated) land surface from remote radiometric measurements. As we shall see, the design, using 3D scene specifications and numerical solutions for radiation transport is a realisation of a ‘virtual laboratory’ within which there is a known (virtual) ‘truth’ that is used to drive the model and provide a basis for the assessment of information inferred from the radiometric signals.

In a sense, any statement of the parameters of a radiative transfer model, along with the subsequent simulations of radiometric signals has this capacity. In most such approaches however, pragmatic decisions are made to simplify e.g. the assumed spatial distribution of canopy elements, variation in radiometric properties over the canopy, and treatment of multiple scattering etc. to arrive at models with a relatively small parameter set that can be executed quite rapidly and that might be used in optimal estimation approaches to estimate the parameter set from EO data. Whilst such models are of great value to remote sensing inference, they are generally not flexible enough to provide realistic scenarios with which such inferences can be tested. The use of the same or similar assumptions in deriving a forward model as are used in an inverse model do not provide a test of the model assumptions and resultant model uncertainty. Even if the model parameters can be robustly inferred from some remotely sensed data, there is no guarantee that the parameters are reliable estimates of the quantities we wish to infer. For that reason, it is generally accepted that model and algorithm assessment requires at least some element of physical measurement of the quantities of interest. However, a limiting factor in many studies is that ground measurement campaigns are expensive to conduct, are generally of rather limited spatial and temporal extent, and may contain significant measurement uncertainty (that is mostly quite difficult to specify). Further, many approaches to the characterisation of 'biophysical quantities' such as Leaf Area Index (LAI) themselves rely on remote measurement technologies (e.g. based on transmission of radiation) which often have very similar assumptions to those used in the canopy radiative transfer models such measurements are used to test. For example, a gap probability-based estimate of LAI that takes no account of spatial clumping of vegetation will provide a measure that we can refer to as the *effective* LAI (i.e. that consistent with the measurement and the assumptions made). Such a measure can be entirely consistent with the LAI we might estimate from above canopy radiometric (EO) data, but can be entirely different to the true amount of one-sided leaf area per unit ground area.

The idea of a 'virtual laboratory' is that we have a complex and as full as possible description of a scene, e.g., as in the case of Disney et al. (2006) where the explicit location of every needle on a (Scots pine) tree is specified in the model, and numerical solutions to radiation transport are used that make *as few simplifying assumptions as possible*. For some given (complex) scenario then, we can simulate (forward model) a set of remote sensing signals, and then use these in an information inference algorithm to estimate the biophysical quantities. We can then compare these parameters with the (virtual) 'truth' to assess and improve algorithm performance. Whilst the cost of setting up these virtual vegetation canopies is clearly rather high (and, indeed, the fieldwork requirements even more onerous than typically considered), once we have set up a particular canopy scenario (based on ground characterisation and measurement) we can quite easily 're-use' the models to generate canopies with similar arrangements of plants (e.g. of the same density but with different plant locations) and expand the range of scenarios that can be simulated.

One caveat to that is that because plants are responsive to the particular local environmental conditions (e.g. light conditions) that they grow in, whilst we might consider e.g. generating a new scene with the same plants but a different density, we would ideally also change the vegetation structure in response to this. This issue highlights a fundamental distinction between what have become known as Functional-Structural Plant Models (FSPMs) and 'structural' or 'architectural' models (see e.g. Vos et al., 2007). Models of canopy development based on radiation interception, photosynthesis and assimilate partitioning have been around for many decades, particularly aimed at crops, but later forests and other cover types. These are 'process-based' models within which plants characterised by mean attributes over the canopy respond to environmental conditions. Historically, structural models were the next to be developed, importantly using concepts developed by Lindenmayer in the 1960s, but really taking off with the growth of computer graphics in the late 1980s and 1990s (Prusinkiewicz, and Lindenmayer, 1990). Such models initially had no interactions with the environment, but sought instead to provide simple closed system rules capable of simulating plant-like structures. The more recent advance of FSPMs provides for many forms of environmental interaction that can directly affect the structure of vegetation. 'Function' is generally modelled at the organ level (e.g. interception of radiation by a single leaf) although this may be considered at different scales, and a canopy then is viewed as the ensemble of individual plants, conditioned by their interactions and competition for resources: the interaction of function and structure. FSPMs then could be seen as the ideal models to use in this toolkit, but there are several reasons this is not currently possible. First, forests are rather slow growing, and there is unlikely to be the opportunity to measure the forest growing over many years for most users. Second, it is still very far from a solved problem to integrate detailed canopy measurements (of the sort proposed here) with detailed FSPMs: it would be an extremely difficult task to 'grow' the forest models into the measurements to get a representation of the forest at a *particular* site, as required here. Third, a major focus of an FSPM is to test ideas concerning plant functioning, and that is not the major purpose of models in this context. Models integrating function and structure have of course been used within remote sensing simulation studies, and developments in the field should be brought to bear on how we approach this sort of modelling in remote sensing, but, following Lewis (2007) we suggest that structural models will be sufficient for the task here.

Figure 2 shows an example of a structural model from a recent ESA study by Lewis et al (2010). Here, a set of generic tree structural models were modified to represent various classes of tree in an African Savannah and distributed according to the general spatial characteristics measured during a field campaign. The understory is represented by simple geometric models of grass blades and a model of the impact of fire implemented in the lower panel. Whilst that study was complemented by more abstracted radiative transfer modelling work (using a hybrid geometric optics model), the generalised nature of the canopy description in those models could not adequately describe the complex structural effects involved. When the models were used to test a new algorithm developed to quantify wildfire impact, the simpler models gave a general picture of the likely behaviour of the approach, but the 3D modelling study gave a much more stringent test, examining complex geometric interactions found on the ground that could not be looked into with the simpler approach.

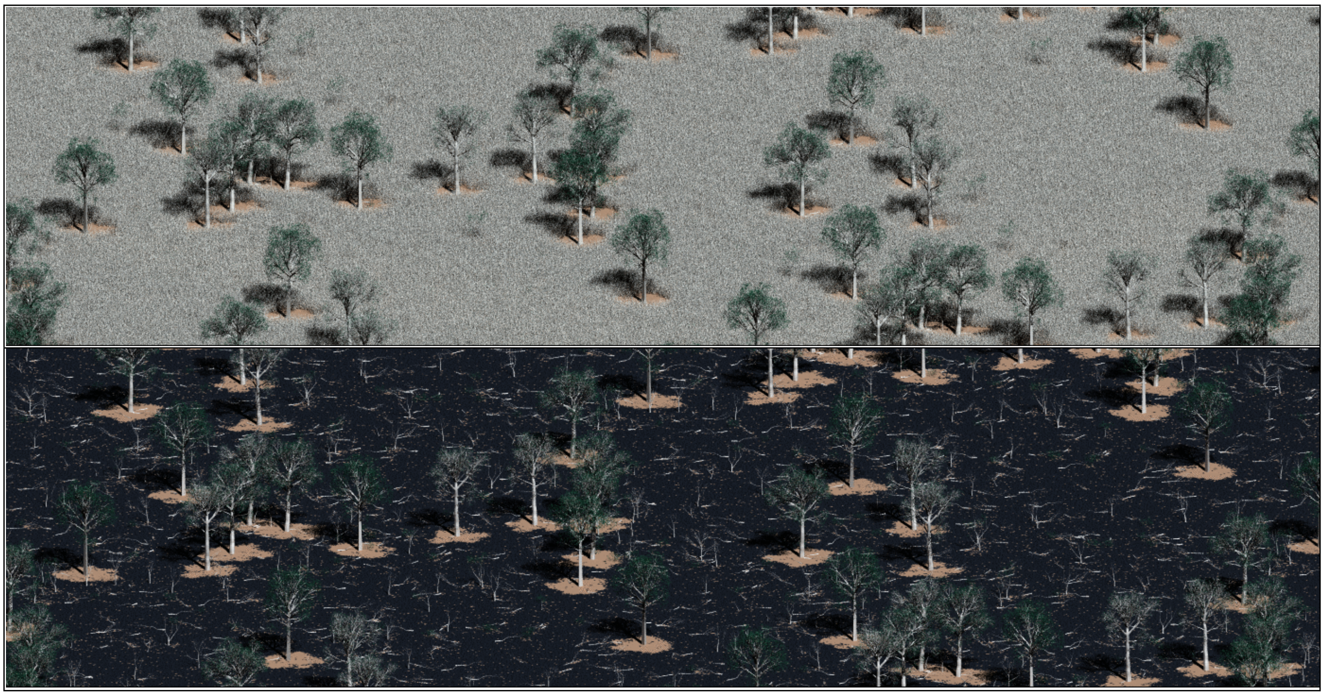


Figure 2. Example of structural models used to simulate the impact of fire in the canopy understory

We suppose then that *structural* (or 'complex geometric' (Goel, 1988)) models should form the basis of vegetation modelling in this toolset (although this would need to be confirmed through the RB) and can now consider some of the advantages of these models over domain-averaged models.

1. First, we note that the EO signal is a function of the spatial arrangement of vegetation elements in a canopy. This is true beyond the optical domain, although specific features of reflectance in that part of the spectrum arising from structural arrangement (e.g. the hot spot) can be traced to path correlations that are dependent on vegetation structure. Whilst many domain-average models may consider such effects, they are generally treated as 'corrections' rather than naturally falling out of the solution to radiative transport as they do in models that consider structural impacts more fully (e.g. Huang et al., 2008).
2. A strong definition of vegetation structure provides a route for data synergy across different forms of EO measurement. Examples of this include the optical-microwave numerical modelling by Disney et al. (2006) and the lidar-hyperspectral fusion by Koetz et al. (2007).
3. Confidence in the generality of the solution allows for new measurement concepts to be tested with such models, such as simulations of multi-spectral canopy lidars (Hancock et al., 2008a,b).
4. Some knowledge on canopy structure can be used as a direct constraint on estimations of canopy biophysical characteristics from EO. Kimes et al. (2002) demonstrated this with a voxel representation of canopy structure to estimate canopy cover, LAI etc. Defining plant architecture within a model (be it an explicit 3D representation, voxel cell representation of overall stochastic treatment) is potentially a very strong constraint on information extraction (provided it is a relevant structural constraint). This may be particularly useful if the structural model is *dynamic* (a weaker form of FSPM that is a function of time or integrated thermal time, such as that used by Saich et al. (2003)).
5. Complex structural representations of vegetation form can form the basis of investigations into, simplifications of, and testing radiative transfer models. This is demonstrated by the RAMI exercises and the ROMC tool for testing alternative formulations (Widlowski et al., 208), but also by studies such as that of Smolander and Stenberg (2005) (shoot clumping impacts) or Disney and Lewis (2007).
6. A particular feature of simulations of radiation transport with detailed structural representations is their ability to calculate high-resolution imagery and texture as spatial heterogeneity can be explicitly dealt with in the models. Examples of this include Lewis et al., (1999) for a barley canopy, Izzawati et al. (1998) for a voxel-based microwave model investigation of texture and the DART model investigations of Bruniquel-Pinel, and Gastellu-Etchegorry (1998).

Some of these features can of course be achieved with radiative transfer models of lesser complexity, but experience with model testing and intercomparison within RAMI suggests that numerical solutions based around explicit spatial (or high resolution volumetric) representations provide the most robust and flexible solutions. The trade-off (comparing with other solutions) is mainly in terms of speed (numerical solutions take longer to process) and, up to a point, in setting up the structural scenes. To this end, the six models used to generate reference datasets in ROMC are: DART (Gastellu-Etchegorry et al., 2004), drat (Lewis, 1999), FLIGHT (North, 1996), Rayspread (Widlowski et al., 2006), raytran (Govaerts & Verstraete, 1998) and Sprint3 (Goel & Thompson, 2000). We strongly recommend that models from this set, or alternatively models that be proven to act similarly over a range of scenarios within RAMI or ROMC, form the basis of the toolbox radiometric simulation. We can group these models into two main classes: those with explicit spatial representation and those with localised volumetric representation of the scattering and absorbing media. Whilst model developments mean that it is quite possible to have both approaches within newer versions of these models, two representative codes that we propose to use here are: DART and drat, the latter (partially to avoid confusion with model names!) being referred to here via the library of functions developed from this model in recent years, librat[1].

So, the core of a toolbox designed to meet the requirements of this study is a set of numerical radiative transfer models that can be driven by some structural and radiometric description of the scene we wish to simulate. Questions surrounding model uncertainty with the models we propose using have in the main been already addressed through RAMI, although this should be seen as a continuing activity, and it would make great sense for 'RAMI tests' to form part of the functionality of the toolbox. If the toolbox can provide methods for interfacing with alternative radiative transfer models (or developments of those cited) then it would significantly contribute to RAMI community efforts.

A significant part of the required toolbox design is clearly the generation of 3D scene models to drive the radiometric simulations.

Of course, end-to-end testing by comparison with independent radiometric (EO) measurements will be required to gain confidence in the model's ability to simulate remote sensing signals over the test sites, but part of the design concept must also be to provide tools to facilitate testing of the structural representation itself. If we cannot do this, we cannot easily elucidate the causes of any discrepancies between our simulations and measurements. There are no generally agreed ways to achieve this, but we can suppose two main routes to this: (i) testing of the structural fidelity of individual plant models; (ii) testing of integrated structural measurements over the canopy. Given that the individual plant models are to be derived from lidar and other measurements, the way to tackle the first of these would seem to be through cross-validation studies: leaving out some of the measurements in generating the model and using these to test what we have simulated. This could, for instance be done with ground-based lidar data by incorporating a redundant sampling location in the data collection, constructing the vegetation models from data from other locations, and then comparing the test point data with the models. In many ways, testing of the integrated structural information is more straightforward as this can quite readily be achieved with gap probability data, e.g. for a given 3D scene, simulate within canopy gap probability with the radiometric simulation tools and compare these to measurements derived from hemispherical photography data. This approach was taken by Lewis et al. (2010) in creating the scenes in Figure 2 and this is demonstrated in an example in Figure 3.

[1] http://www2.geog.ucl.ac.uk/~plewis/bpms/src/lib/

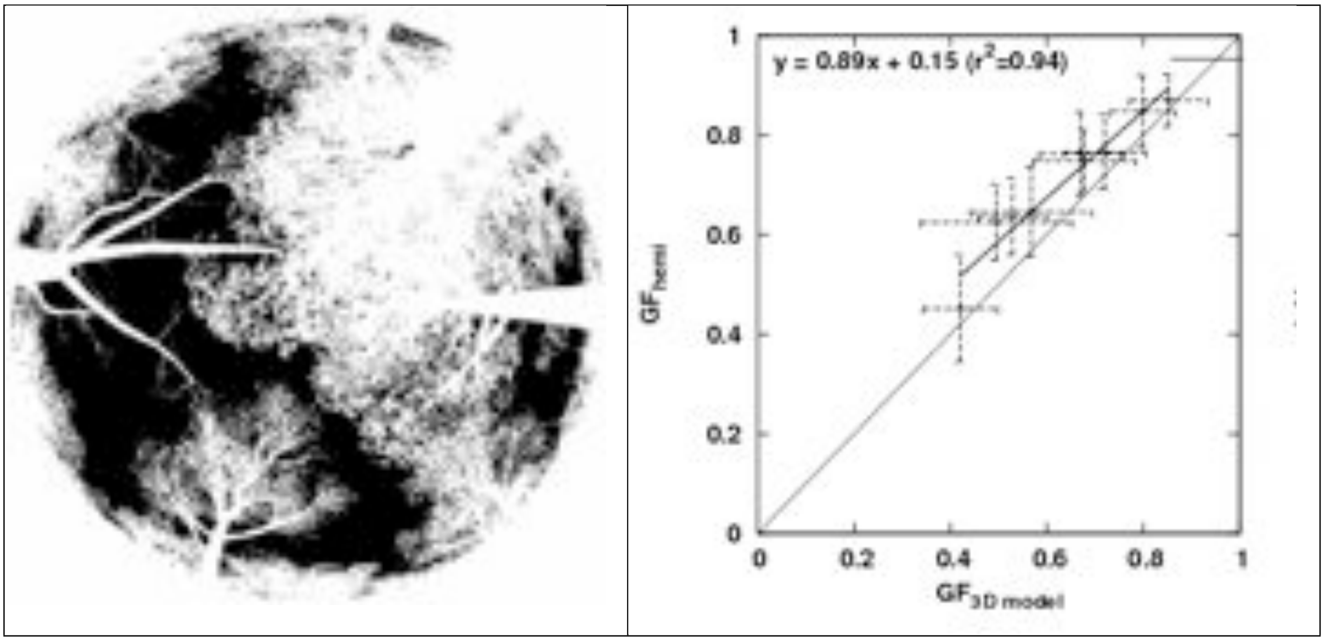


Figure 3: Left panel: 3D model-simulated hemiphoto (left). Right panels: estimates of gap fraction (GF) derived from processing simulated hemiphotos (y-axis) against values derived directly from 3D models (x-axis). From Lewis et al. (2010).

The panel on the left of the figure shows a simulation (using librat) of a binary field indicating canopy gaps (black). From a series of these we can estimate average gap fraction statistics for the model canopy, and these can in turn be compared with data interpreted from in-field measurements. Further, we can investigate uncertainties in the *measured* gap probability information due to e.g. image spatial resolution, thresholding effects etc. by applying the same algorithms to measured and simulated hemispherical photo data and directly comparing this with the 'true' (pointwise) gap probability derived from the model structural data (right panel of Figure 3). Similar concepts can be applied to other gap probability measures, such as vertical canopy cover.

A significant part of the context of the toolbox design here is that these should be directed at testing algorithms deriving information from optical measurements, particularly those from the forthcoming Sentinel 2 (MSI[2]) and 3 (SLSTR and OLCI[3]) instruments. This framework is to be implemented via the 'Toolbox', a set of linked computer codes and associated datasets that allow this aim to be fulfilled. From the above discussion of some of the major considerations underlying the issues and options, we can propose Figure 4 as an overview of a toolbox functionality. The toolbox will contain a user-friendly GUI, for instance for setting up simulation conditions, as well as having support for a batch mode for some of the tasks that take significant processing resources. It will also include functionality for data visualisation (e.g. graph and BRF plotting).

The 'core' of the toolbox is a computer representation of the structural and radiometric properties of the area we wish to perform simulations of. From the study requirements, this will be over an area of 300m x 300m for the test regions we develop, but clearly the toolbox must not have fixed limits for such scenes. We can call this representation the '**world scene**', in that it will be explicitly defined in a real world coordinate system. The world scene may be defined through descriptions of the explicit location, orientation and radiometric attributes of a set of geometric primitives that each radiative

[2] http://esamultimedia.esa.int/docs/S2-Data_Sheet_131108.pdf

[3] http://www.esa.int/esaLP/SEMTST4KXMF_LPgmes_0.html

transfer model is aware of (triangular facets, ellipsoids etc., but also 'super' primitives such as digital elevation models that describe a set of e.g. triangular facets representing terrain or soil structure). It may also contain volumetric primitives (e.g. voxel cells or other bounded geometric objects (e.g. spheroids) with given scatterer density, size and orientation distributions), or a mixture of the two. The driver for the world model then is the scene element (structural primitive) characterisation and the radiometric characteristics associated with these. In the context of this study, these data fully specify the vegetation canopy for further radiometric simulation.

A **radiometric simulation** module, using numerical solution to radiation transport is then fed by the world model, a characterisation of any intervening media (the atmosphere) and sensor and illumination specification. A control to the radiometric simulation relates to the desired quality of the simulation (e.g. number of primary ray samples for Monte Carlo simulations, maximum sampling of ray trees etc.).

The set of attributes defining the desired **sensor characteristics** includes wavebands, sensor location, and pointing, instantaneous field of view (IFOV), modulation transfer function (MTF) etc. For some sensors such as lidar additional characteristics are required, such as sampling frequency. The **illumination characteristics** often have many parameters in common with those of the sensor, particularly if active illumination is considered (so, illumination IFOV, MTF, location, pointing). For solar illumination, it is usual to assume a point source at infinite distance from the scene with a particular angle to the world scene z-vector, but more detailed descriptions can be considered.

In many ways, we could consider the **atmospheric characterisation** as part of the world scene specification, and concepts such as this are present in models such as DART which can represent the atmospheric scattering and absorption processes by defining atmosphere voxel cells. Other models however decouple the surface scattering and atmospheric processes, although they may e.g. consider a directional distributions of downwelling sky radiance as a weighting to the illumination conditions. One argument for the decoupling is that the computational cost of the surface interactions will tend to override that of the 'volumetric' atmospheric model simulation, so it often makes sense to simulate BRDF for the surface and then couple this as a LUT to atmospheric scattering so that a wider range of atmospheric conditions might be considered. Further, some ways of approaching the surface scattering problem lend themselves to spectrally invariant treatments (Lewis and Disney, 2010b), a concept that cannot directly be applied to the atmospheric component of the radiation transport. The details of whether the atmospheric characterisation is an integral part of the world scene or not are not of vital importance for the design of the toolbox, but implementing a variety of ways to couple the surface scattering with the atmosphere may be advantageous.

The main purpose of the simulation is to produce an estimate of some radiometric (EO) measurement over a vegetation canopy for a given atmosphere, acquisition geometry and sensor spectral sampling characteristics and this, the **simulated EO signal** is in many ways the primary output of the toolbox. However, an equally important aspect is that we have tools that can perform some (non radiometric) analyses on the world scene. This might be something as simple as calculating the total LAI that is defined for the world model (and might therefore be part of the quality checks within scene generation), but other things we will need to be able to do are e.g. convert between an explicit 3D representation and a volumetric (voxel) representation of the scene (or vice-versa), calculate canopy cover or other gap probability measures. We can identify then a need for a **scene analysis** module, driven by some description of the task required (e.g. from a list of tasks in the toolbox implementation) and control parameters for each task. The result of this is various forms of description of scene characteristics (LAI, voxel representation, gap probability, etc.), the **scene characteristics**.

It is not yet clear to the team whether the toolbox functions described above would be conveniently implemented in the BEAM environment, as suggested in the SoW. The final part of the toolbox however, the **EO data analysis** module would very likely be usefully implemented within that environment. This module will take in synthetic EO data over the scene of interest, along with appropriate model validation data (the scene characteristics) and produce an analysis, typically comparing the results of some algorithm being tested with the synthetic EO data (e.g. biophysical parameter retrieval) against the (virtual) 'truth' (the scene characteristics). We suppose that the reason for suggesting integration with BEAM is to allow the various EO functions and algorithms within

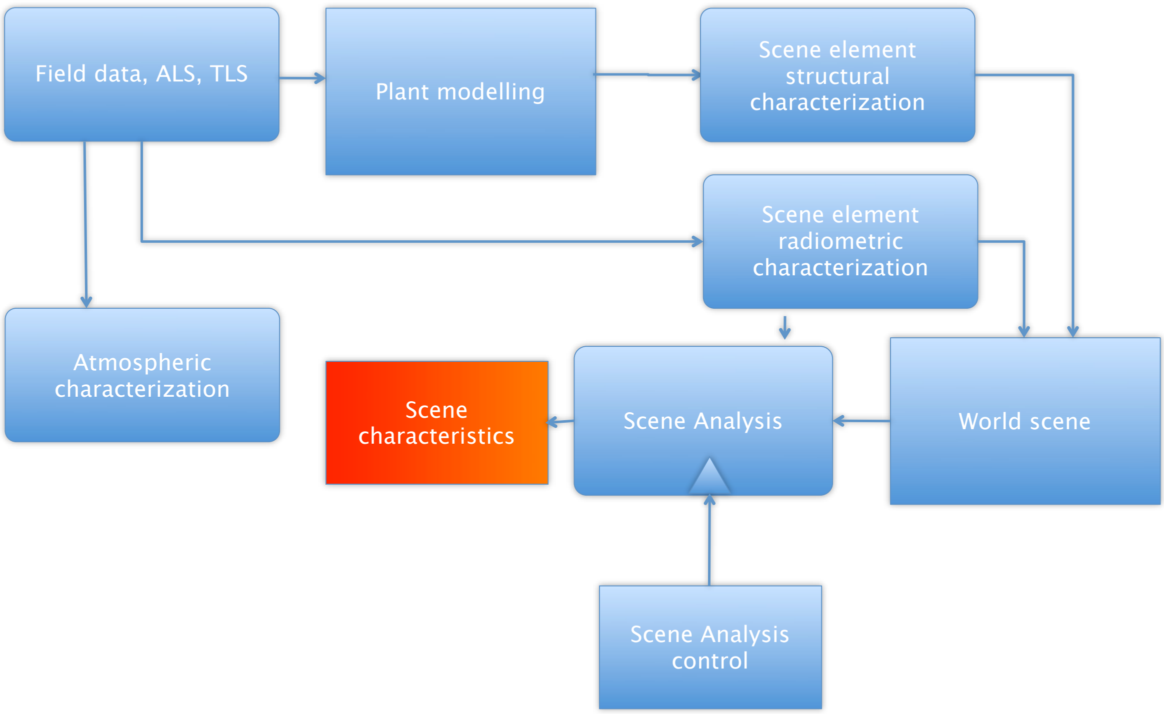


Figure 4. Main route for scene creation.

BEAM (many of which representing significant ESA investment) to be exploited and agree that this is desirable. Clearly some GUI to producing the simulated EO and scene characteristics must be defined and implemented for the toolbox, but various ways of integrating this with BEAM might be considered, the simplest and most flexible, as suggested, being an interface with BEAM for EO data analysis. This must be further assessed and refined as part of the RB.

2.6.2. Assumptions & Preconditions

This proposal is written in response to the SoW and other documents for this project. As noted in this section, some of the details that will feed through to the TS and ultimately the DDF are dependent of choices between some options and agreement with ESA over the RB and cannot be finalised in this document.

However, we can briefly review the relevant elements of the requirements stated by ESA and comment on how this proposal will meet these.

1. Observed in-situ parameters shall include measurements of the 3-D vegetation structure (by terrestrial lidar and ideally airborne lidar ALS), biophysical canopy characterization and auxiliary information (e.g meteorological observations, soil moisture, land cover).

This is discussed in more detail in the section on field data collection, but we believe the strategy we have outlined will make the fullest use of ALS and TLS to generate the 3D plant models. We have identified that there may be some risk with a strategy that attempt to use these methods to measure all plants in the (300m x 300m) plots and so have proposed two approaches that will be used, one deriving explicit representations and the other a volumetric method. A module will be provided to allow users to generate 3D tree models based on TLS data. To fit in with this dual strategy, we have proposed two numerical modeling streams. It should be possible to use either data source with either model through suitable filtering and transformation of the data, but each fits more ‘naturally’ with one of these approaches. Other biophysical canopy information (including gap probability measures) will be used to generate and/or assess the fidelity of the models generated. Ancillary information on e.g. atmospheric state will be used to simulate specific EO datasets in testing the model in end-to-end tests.

2. Intensive in-situ measurements shall cover at least the pixel extension of a medium resolution EO sensor (e.g. MERIS) as well as be representative for the phenological variability of the respective selected site. The general sampling scheme of the in-situ measurements shall be representative on the stand level.

For several sites, we have access to existing 3D models that are of rather lower extent than specified here (e.g. the sites in Estonia are characterizations of 100m x 100m). These will have to be extended to meet the requirements of this project to be able to produce simulations of up to 300m x 300m. A strategy for this is outlined elsewhere in this document. It is not feasible to do continuous monitoring at the test sites at the level of detail required for this work, but the sampling will include at least leaf-on and leaf-off conditions for deciduous forest. In one of the proposed exploitation experiments, we suggest that an interpolation between these conditions might be implemented by varying the leaf area on each tree and testing this against EO data between these conditions.

3. The toolbox capabilities shall be capable of supporting the development and improvement of EO retrieval methods of Sentinel-2 and Sentinel-3 level 2 products

This is a core part of what we have proposed here: the toolkit will indeed be capable of simulating data from Sentinel-2 and -3 optical sensors, at least up to a 300m x 300m area. It should of course be noted that we are proposing simulation only in the optical (solar reflective) domain (400-2500 nm). Support for simulation (spectral and spatial resampling) of optical EO missions at variable spectral and spatial resolution is automatically provided by the radiative transfer models selected here. Alternatively, hyperspectral datasets can be generated at relevant viewing and illumination angles at high spatial resolution and these simulations degraded to specific sensor requirements.

4. The toolbox shall simulated top of canopy and top of atmosphere reflectance (400-2500 nm) based on validated physically-based radiative transfer models

We believe our proposal is compliant with this requirement. The detailed 3D models will be used to produce simulations of BRDF or BRF at TOC, which will be interfaced to atmospheric codes to produce TOA simulations. The radiative transfer models we propose to use have been through extensive testing within the RAMI framework, so are ‘validated’ in that sense over relevant parts of the required spectral range. They represent two different approaches to numerical radiation transport within the set of core models used for the ROMC framework.

5. The software shall be developed as open source code and as a BEAM plug-in. The final toolbox shall be freely available to scientific community

The final toolbox will be made available in this way and we have no objections to developing this as open source code. An e-license for the UCL code librat is currently being developed at UCL (with UCL business) but this is only to allow it to be licensed or requested commercial applications. Any issues arising from this can straightforwardly be negotiated with UCL. We have suggested that at least the analysis parts of the toolbox would sensibly be implemented as a BEAM plug-in, allowing the exploitation of other functionality within that tool. There needs to be some assessment made as to the detail of the interface to BEAM for other aspects of the toolbox.

6. The toolbox shall enable a comprehensive canopy parameterization of complex canopies based on detailed in-situ data, including a realistic tree reconstruction

This is a fundamental part of the proposal we are making. We discuss the case for complex representations of vegetation canopies in radiative transfer models and propose two models capable of using such data effectively. We propose a realistic strategy for dealing with tree reconstruction and providing a useful tool to the community.

7. The toolbox shall follow a modular structure and be extendable to accommodate for future requirements.

The design proposal we make considers the toolbox as a set of modules to address different functions and we have made some discussion of the required information interfaces. Within these modules, we will implement a range of operations, with carefully designed interfaces to allow for modular expansion. In particular, having the analysis module as a plug-in to BEAM will mean that mean that the synthetic datasets can be used to develop and test new algorithms for EO products. The toolbox will contain a user-friendly GUI, for instance for setting up simulation conditions, as well as having support for a batch mode for some of the tasks that take significant processing resources.

8. The format requirements of the toolbox shall be flexible, so that different data sets can easily be processed

This is discussed in some detail and both of the radiative transfer models that lie at the heart of this tool can currently accept data in a range of forms. This will be rationalized and extended in this work, either by defining new i/o routines or at the very least providing robust filters to change formats (and in some cases the form of data representation , e.g. explicit to voxel and vice-versa).

2.6.3. Approach & Activities

The overall scheme defined to meet the requirements in the SoW is outlined below.

We can break the tasks down into:

1. Scene creation
2. Scene analysis
3. Radiometric Simulation

4. Analysis

Scene Creation

As noted above, a full discussion of the design aspects of the part of the toolbox associated with data input are dealt with in the presentation of task 4. The core requirement of this module of the toolbox is that it should be able to create a representation of the structure of vegetation within the scene. As discussed above, this could be an explicit representation, giving the explicit location of individual geometric primitives within the scene or a voxel representation. Generally, the former is preferable as the core input, as it can always be generalised to the latter afterwards. In the presentation of task 4, we propose two streams of work targeted at both approaches. This mitigates the risk of any issues associated with the reliability of either method. The main issues for that component of the toolbox are providing a flexible enough format definition format for the interface between the measurement tool and the world model representation and ensuring that the module adheres to the background SoW requirements (from the SoW: "all the software engineering process as required in the ECSS-40B and adequate Tailoring. This standard shall be followed up to the Qualification and Acceptance Test Review. Software shall be developed as Open Source code and as an operation system independent platform").

Figure 5. A section of a field of Barley plants using cloning of 5 individual plants using ararat (Lewis, 1999), the pre-cursor to drat and librat. Note the DEM underlying the plant models to represent soil roughness effects[4].

Although it may prove feasible to use TLS to characterise some number of trees in the required 300m x 300m areas, it is not likely to be feasible to do this for all plants within the site. Further, if very detailed representations of individual trees are to be used, then the dataset size may be prohibitive to practically work with. If trees and other plants are converted to volumetric representations, this is clearly not such an issue, but if we wish to represent fine detail (e.g. needles, Disney et al. 2006) then a more practical approach, mentioned above is to represent only some subset of trees explicitly and to produce virtual copies of these ('clones', Lewis, 1999) to populate a scene. To ensure heterogeneity in the scene, we generally apply a random z-rotation to these cloned trees, and can also apply other simple modifications such as applying a variable height 'pedestal' to the trunk base to vary the trunk height (this latter point being important for lidar simulations, we have found). Using this method, the computer memory requirements are kept to a minimum, at a cost of not representing each individual tree explicitly. Rather, we generate a 'library' of plants, which are then used to populate the scene. This is a useful concept for this toolbox and one that we propose to implement. At a minimum, the library needs to contain one or more representative samples of each 'class' of tree in the area to be simulated. This could, for instance be determined from processing of the ALS data (variation in height are crown dimensions) or from processing a volumetric canopy representation derived from ALS/TLS. It could also, for users without these technologies, be based on manual ground surveys of tree locations and general geometric characteristics. In the extreme, the library could (potentially) contain

[4] http://www2.geog.ucl.ac.uk/~mdisney/ctcd/misc/www_new/science/EO/ba_119_24_06_97.gif

the geometric representation of each plant in a forest, so the scheme is flexible.

This idea of a library can also be used for other plant elements. For instance, in simulating a scene with every needle on each tree represented explicitly in Disney et al. (2006) a set of library 'shoot' objects were created, that were then mapped onto (through a set of linear transformations) particular branches.

Cloning is of course not without its own difficulties. If the plant spacing is very low (as in the barley canopy in Figure 5) and random rotations are applied to plants, then inevitably there will be some conflicts in the canopy description, e.g. leaves of one plant passing through another plant. It is rather difficult to control for such effects, unless very detailed measurements of each plant is used or each plant 'grows' into its own space through some (very) complicated FSPM. On the whole we suppose some small proportion of such effects not to greatly impact the structural representation.

We can now view the processing of the TLS data as fulfilling two purposes: (i) to provide voxel-based representations for moderately large areas of a canopy; and (ii) to provide data on individual tree models that can be used to populate a library of tree objects. ALS and other ground and (airborne) EO data can be used to propagate clones of measured plant objects across a scene.

Another advantage of this approach is that which the toolbox design in this study is aimed at recreating structural representations of a *particular* vegetation canopy (partly, so that the modelling can be verified by comparison with EO data), using a 'library' approach allows the user to generate new spatial distributions of plants and use these in the context of a virtual laboratory as described above to produce many sets of synthetic EO data. An additional advantage is that if a user has their own models generated by any other method, they have simply to transform their representation of each plant into the core format we define for the 3DVegLab to be able to use all other aspects of the tool. Clearly, the toolbox should provide some common filters for common formats to demonstrate this.

Thus, whilst (e.g. Figure 4) we see TLS as the 'core' route for generating plant structural information for use in 3DVegLab, we are able to easily interface the tool with other datasets and models.

The input module may also be able to take advantage of some other ways in which scene representation can be minimised. One example of this is in representing broadleaf shapes. Of course this can be done by simply using a small number (e.g. two) of triangular facets to represent the general leaf orientation, but by 'material mapping' on the surface of such objects, we can define much more complex shapes at only a very slight increase in processing cost and negligible data volume costs. This is illustrated in Figure 6 with librat simulations of a Birch canopy. The impact of this representation is not clearly apparent in the images simulated over larger canopy extent, but at high resolution we can see fine detail represented on the leaf even though only two facets are used to represent the leaf form. This is achieved by mapping two 'materials' onto the leaf shape: 'leaf' and 'transparent'. Sample rays hitting the transparent areas of the leaf simply pass through the object. We can also use this same mechanism to modify leaf area in a canopy without having to generate a new geometric object. Figure 6 also shows how effective the cloning can be in forest representations: it is not obvious that any two trees are identical in the canopy as the tree location variation is the main impact at the coarsest level of representation here. The random rotation of trees about the Z-axis also aids in this.

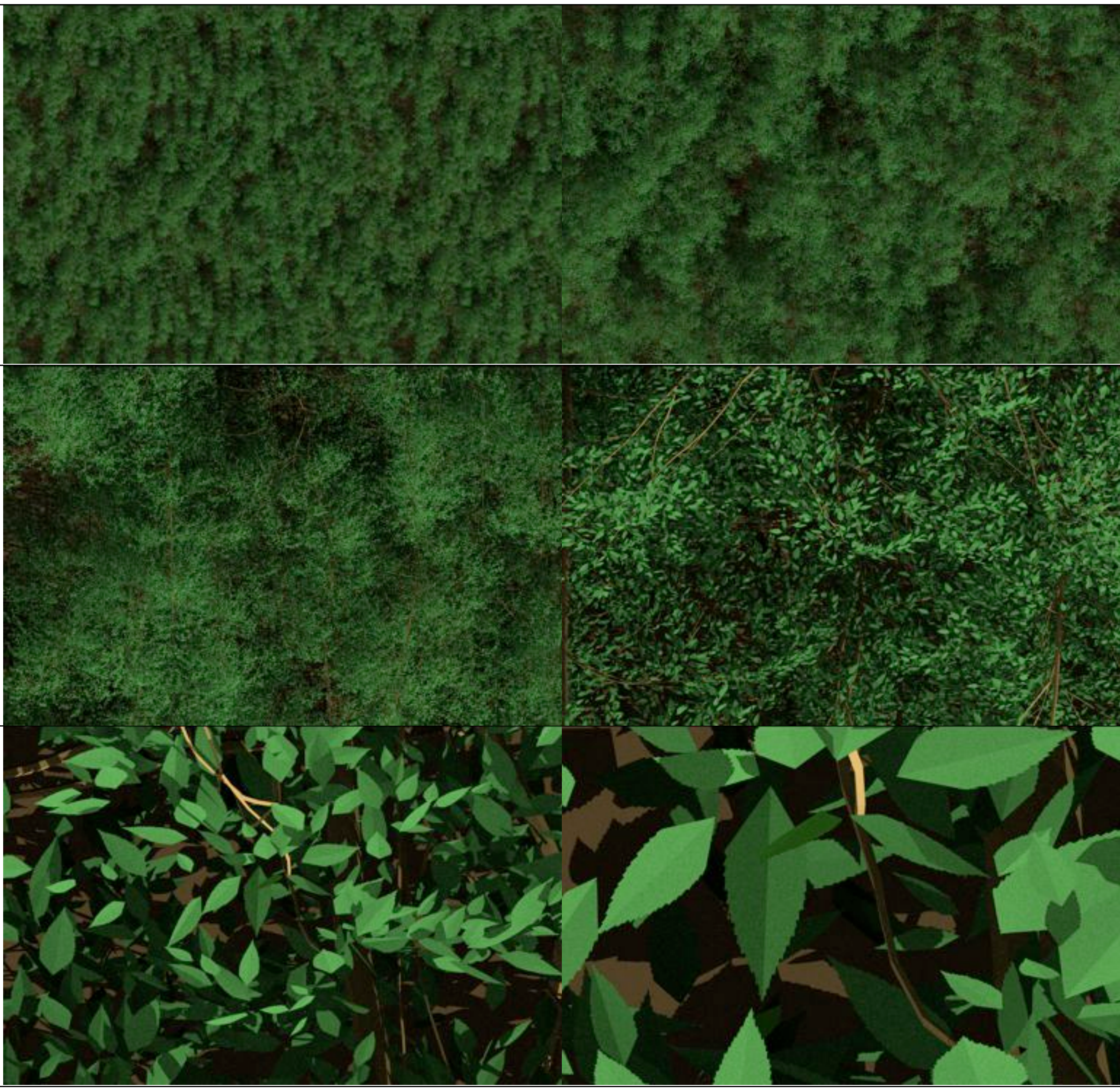


Figure 6. Birch canopy simulation with librat at varying levels of 'zoom' and orientation

Scene Analysis

In the discussion above we outline some of the requirements for the scene analysis tool. This will need to be refined in the RB to provide a set of specifications for the TS and DDF.

The first requirement we have identifies is for a filter to convert from explicit 3D representations to voxel representation. In many ways, this is the core of other analyses that may be required, such as calculating leaf angle distributions, LAI etc. Also, we have identified that there may be a need to translate between some different explicit 3D representations. The modelling will be driven by native representations, which may be different for each radiative transfer model, although any major differences between these should be rationalised as far as possible to ensure direct compatibility.

The second main strand of this is gap probability calculations. There are existing tools for this for example within librat. This is illustrated in Figure 7 where we have generated a height map using librat functionality for an area of a canopy. From this, we can calculate the canopy cover (28.6% here). Other mechanisms include explicit modelling of gap to a point in the canopy (or to random locations in the canopy) to gather average statistics. Further, we can explicitly simulate hemispherical photos from virtual points within the canopy.

A third strand of information is to separate the LAI, leaf angle distribution, canopy cover etc. and report these for different scene materials (e.g. leaf, bark etc.). This can be based on existing methods within librat.

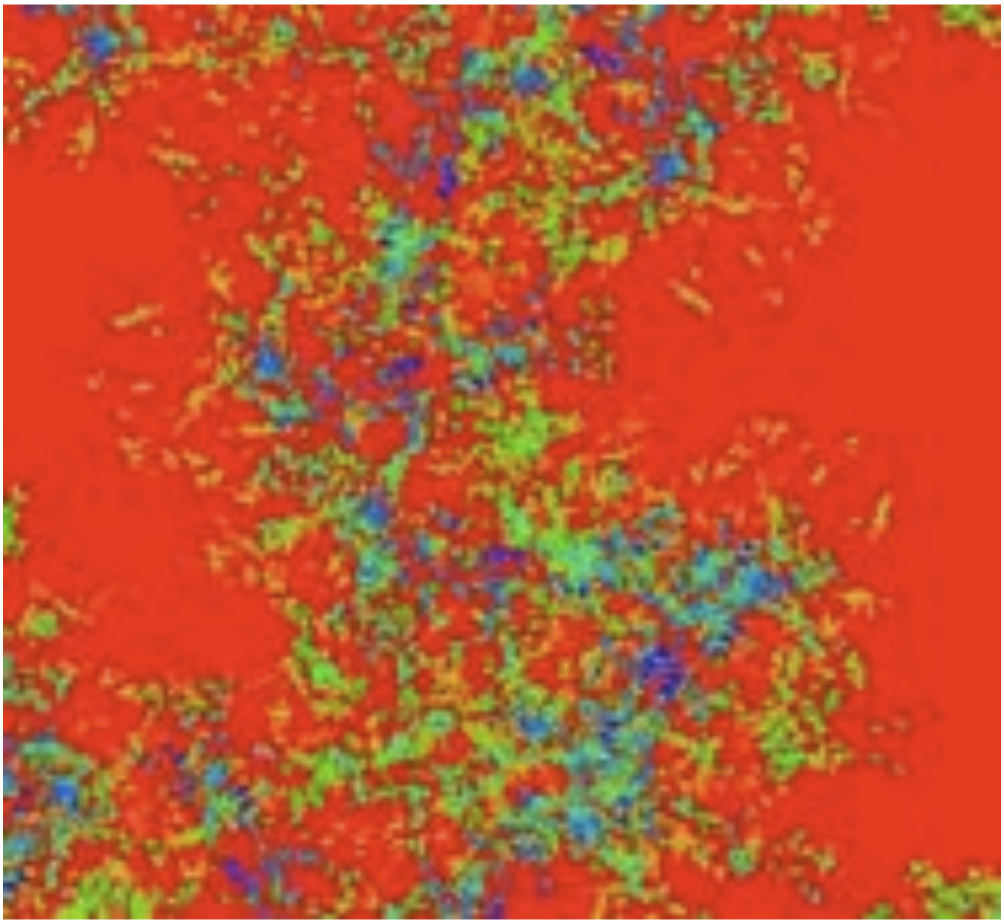


Figure 7. Height map (pseudocolur) of a beech canopy (generated with librat)

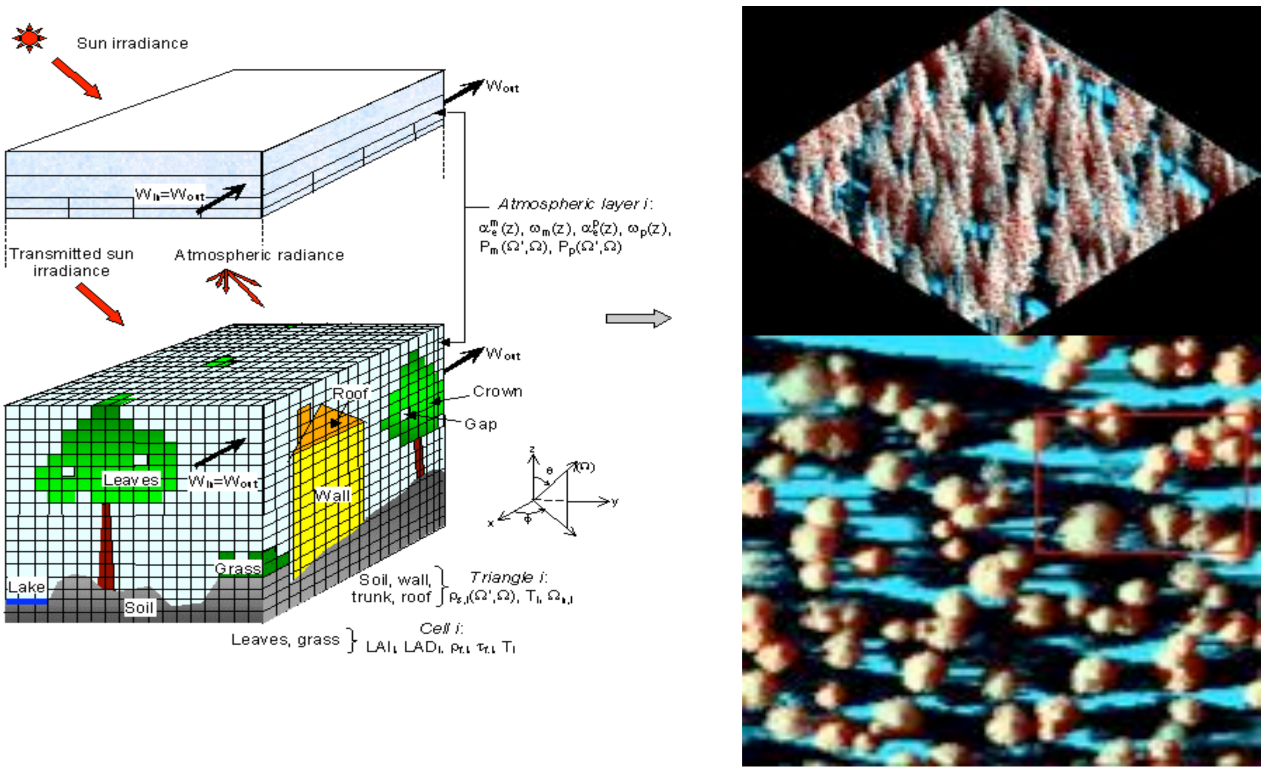


Figure 8. Usage of DART to simulate norway spruce stands; DART's scene representation (left), simulated images (right). From Malenovsky et al., 2008a.

Radiometric Simulation

To mitigate the risk associated with limiting to a single radiative transfer code within the 3DVegLab tool, and also because different models may have slightly different capabilities and limitations and trade-offs, we chose to distribute the modelling component of the toolbox to two partners, UCL and CESBIO. CESBIO's DART model is well established set of RT code building upon a voxelised representation of the vegetation canopy (and thus 3D capabable), while UCL's librat code offers the additional possibility to use vectorised characterisations of single trees in a canopy. The latter enables the explicit modelling of multiple scattering within single shoots, as shoots detail is prescribed down to the needle level. However, it is much harder to obtain the vegetation information needed for this detailed description; this can be done through usage of tree growth models (e.g. Treegrow, Disney et. al, 2006 or Morsdorf et al. 2009)), parametric sturctural models (e.g. OnyxTREE, Disney et al., 2009, 2010) or by using tree reconstructions based on TLS. Depending on site and species, such tree models might not be available and would thus constrain the approach unnecessarily. The voxelised approach offered by DART, on the other hand, offers the possibility of the implementation of a robust, portable processing scheme for ALS and TLS data that should work on any site, without prior knowledge of species and species properties. Further, demonstrating two rather different approaches to 3D radiative transport (using models that we know to be able to produce similar results in the context of a subset of the RAMI/ROMC experiments) is of great value in demonstrating the flexibility of a tool such as this. Also, one of the scientific aims of this project is to find out how large the trade off between the explicit and the voxel-based approach is in respect to simulation accuracy of image data. In the following, the two model tasks contributing to the toolbox are described in more detail.

DART Radiometric Simulation *(CESBIO)***:**

The first action item within this task is to remove the present DART code (more than 300 000 lines of code C/C++, Java, Java3D) from the modules (atmosphere radiative transfer, thermal infrared radiative transfer, LiDAR, etc.) that are not required by the proposed project[5]. Whilst the code needs separation to be practical, we should aim not to decouple the 3DVegLab implementation too much from the mainstream DART code so that further functionality might be added at a later date. This will lead to a model with a number of modules/functionalities that are listed below:

• Discrete direction set creation
• Computation and management of optical properties
• Scene generation as the juxtaposition of turbid cells and translucent triangles, with topography
• 3D radiative transfer calculations
•-Run of sequences of DART simulations with the selection of the parameters that vary
• Creation and display of reflectance LUTs
• Creation of scene spectra and space sensors broadbands

Additionally, the format of input parameters and output parameters will be adapted and the accuracy and robustness of this simplified code will be assessed. Furthermore, an interface with Netcetera will be established that accomplishes "the modelling tool" as required by the SoW. The required modules that will be provided by CESBIO to comprise the modelling tool are detailed below:

1) Creation of discrete directions
This module determines the discrete directions (and associated solid angles) used for simulating the radiative transfer. It determines also the angular sectors that contain these directions, for managing multiple scattering.

2) Computation/Management of optical properties
This module computes a set of optical properties that are used to characterize the optical properties of DART scene elements. Optical properties are computed through interpolation on data bases (text files) adapted to 2D surfaces (Lambertian, Lambertian + specular, Hapke + specular) or 3D turbid medium (Lambertian upper and lower reflectance and transmittance + LAD). Spectral multiplicative factors can be used for generating reflectance LUTs.

3) Computation of optical properties
This module (C language) simulates foliar optical properties, using foliar physiological information such as water and chlorophyll content. It is based on the well known and widely used PROSPECT model (Jacquemoud and Baret, 1990, Feret at al., 2008).

4) Scene simulation
DART radiative transfer works on scenes that can have different origins:
Scene created by DART. Indeed, DART can simulate directly scene elements (agricultural plots, houses, trees, lakes, etc).

[5] Although, as we describe later on, the ability to simulate lidar data at least may be of value to this tool, even though not a formal requirement.

Scene imported by DART from a land cover map. Useful for simulating large scenes where each surface (pixel) is described as a vertical column of cells with a given LAI and specific optical properties.

Direct importation of 3D objects (formats wrl, obj and x3D) of a "triangle scene". These objects cannot be edited in the DART environment. However, translations, homotheties and rotations are possible. It is also possible to simulate a field / forest of 3D objects: one or several 3D objects are duplicated and specific geometric transformations (rotation, etc.) are applied to each duplicated element (i.e. cloning, as described above). This is likely to be the main 'common' interface to the model within the tool.

Turbid (voxelised) scenes based on parsing a "triangle (vectorised) scene". This possibility was first used in the RAMI experiment. This powerful approach is required in order to avoid tremendous computation times as soon as one works with exact 3D vegetation scenes. In fact, this function forms one of the 'scene analysis' functions described above and could be separated for that purpose.

For any DART scene, it is possible to import a Digital Elevation Model (DEM, as raster image). A specific module can be used for automatic resampling if cell/scene dimensions are changed, thus the effects of scaling can be easily studied using DART.

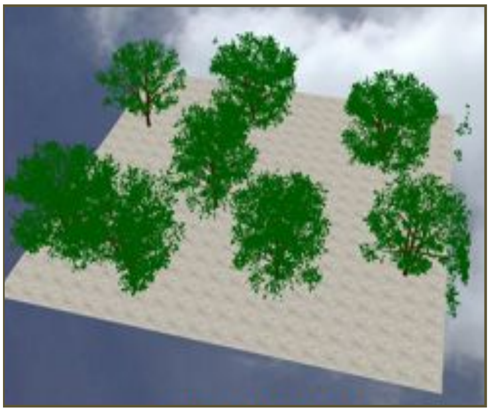
5) Radiative transfer simulation

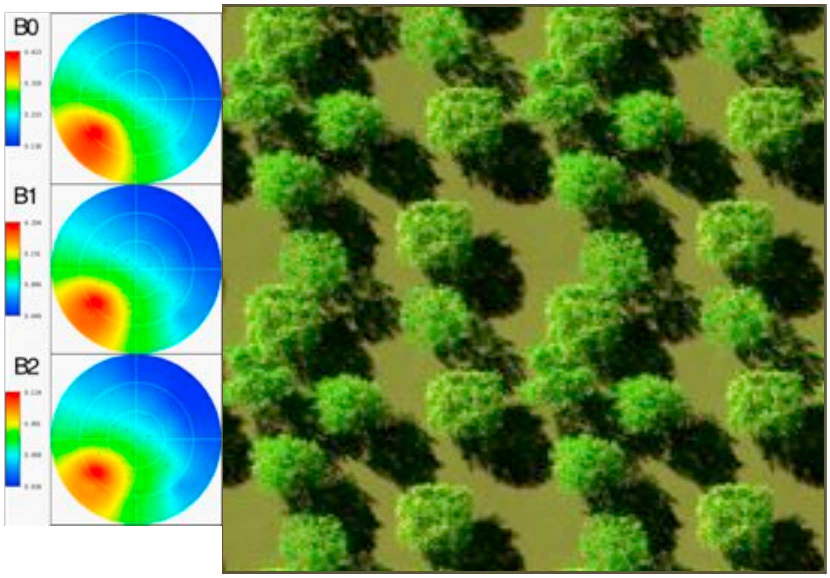
Ray tracing and directional reflectance
Monte Carlo and directional reflectance
Ray tracing and 3D radiation budget
Monte Carlo and 3D radiation budget

6) LUT creation and display.

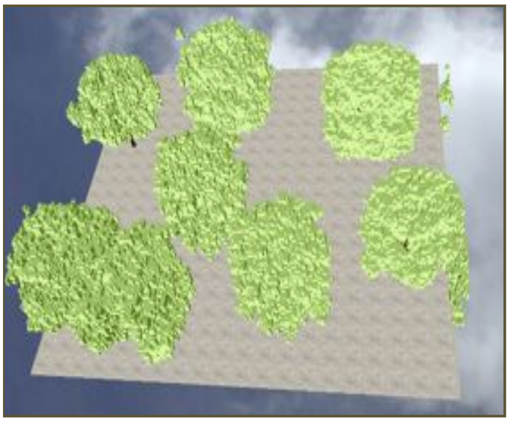
This module "sequencer" is necessary for running automatically a set of simulations (with no limitation except the computer memory and the time it will take to run the sequence) where a few parameters vary with a given range and with a given step. This module will create LUTs (Look Up Tables) starting from the results of the simulations run with the "Sequencer".

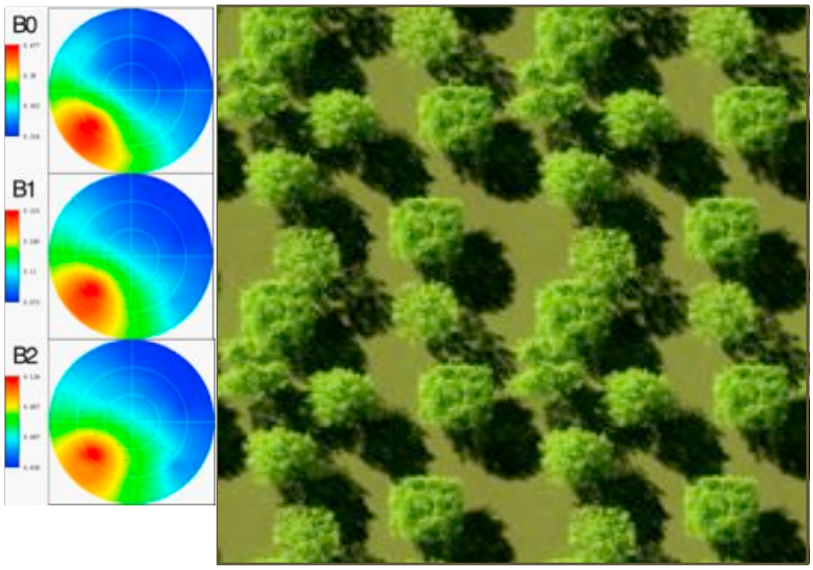
Most DART input parameters are provided as XML files:
direction angles: sun and view directions, hot spot sampling, additional view directions, etc.
optical properties: data base names, multiplicative factors (useful for LUT creation), etc.
scene and scene element (houses, turbid trees, agricultural plots, etc.) dimensions and positions,
types of products, etc.





a) Tree triangle scene. DART simulation: directional reflectance (b) and RGB color composite (c).





d) Turbid scene derived from the triangle scene (a). DART simulation: directional reflectance (e) and RGB color composite (f).

Figure 8. DART simulations of a citrus field from the RAMI experiment. Sun zenith angle 50° and sun azimuth angle 45° Triangle scene (top) : 381759 triangles, 280000 cells. Turbid scene (bottom): 8317 triangles, 1320000 cells. Scene dimensions: 10m x 10m x 3.5m. Horizontal layer: 40000 pixels (pixel size: 0.05*0.05m)

The DART release that would be provided would be the latest DART 4.x version (DART 4.3.4 was released in mid October 2010). The DART 5 version that is being developed since November 2009 by 4 full time computer scientists will not be provided in the course of the project because it is not yet completed. It will improve a lot DART in terms of code maintenance and computer time, as it uses object-oriented C++ code only and no more procedural C code. Moreover, it will include some new functionalities (continuous topography, etc.) and the possibility to handle triangle scenes with any number of triangles.

Librat Radiometric Simulation *(UCL)***:**

Figure 9. Scots pines tree based on modified Treegrow output for ages 5, 10, 20, 30, 40, 50 years (left to right). The scene reflectance was simulated with the drat optical model at a wavelength of 850 nm. From Disney et al., 2006.

UCL will provide a modelling module that is capable on using explicit 3D data, which will be based on the scope and specification of the explicit 3D model system to be defined in the RB. In addition, the generation of a core set of 3D scene models at the 300m x 300m scale from tree-level surveys either based on field measurements or on ALS data will be a focus. Alternatively, plot-level tree size classes and density distributions could be used if deemed necessary, it is generally agreed within the consortium that at least an *actual* distribution of trees should be used in the context of the project. The scene generation functionality described above allows for both explicit scene generation and randomised scenes (according to a given distribution). The explicit scenes will cover two forest types capable of being ingested into the 3D system, that means that either a model such as Treegrow, or OnyxTREE (www.onyx.com) can be parameterised from field measurements, and/or or TLS based single-tree reconstruction will be able to deliver the needed parameters (at least for some model trees, which are then cloned). Individual plant models will form a library, as described above, that can also be converted to voxel representations to check consistency with DART representations and simulations. This could as well include a deciduous site, where the multi-temporal aspect could be modelled by using leaf-on and leaf-off data. For two of the proposed sites, this information would be readily available, e.g. Lägeren and Järvselja. By building suitable tools in the scene analysis module, we will also be able to convert DART voxel representation (or voxel-based TLS tree measurements) to explicit 3D facet representations and so ensure further consistency between the modelling efforts.

Librat is a Monte Carlo ray tracing (MCRT) library developed from the *ararat* model of Lewis (1999). The general operation of the library and some of the existing tools are described below. One manifestation of the tools underlying the library is the ray tracing model *drat*. Whilst it is not straightforward to validate such a model, the series of RAMI (radiative transfer model inter-comparison) exercises (Pinty et al., 2004, Widlowski et al., 2007) allow for some confidence to be given to simulations from *drat* and derived tools as simulations are mostly found to agree very closely with other numerical solutions to radiative transport. Indeed the *drat* model is one of a small suite of models used in the RAMI online model-checking (ROMC) tool which is now used totest and benchmark other radiative transfer codes (Widlowski et al., 2008). Comparisons with airborne and spaceborne data are presented in Disney et al. (2006, 2009).

There are two main ways in which Monte Carlo ray tracing can be conducted, depending on the problem at hand. To simulate BRDF data (an infinitesimal solid angle) or data (such as EO data) over limited but finite fields of view, it is more convenient to use *librat* as a reverse ray tracer (Disney et al., 2000), i.e. simulation proceeds by firing a sample set of primary rays from the sensor into the world scene and then 'importance sampling' the illumination source.

Plants and other scene objects are described by sets of 3D geometric primitives. Those used in these simulations include triangular facets (mainly for leaf blades, but also for detailed trunk and branch), cylinders (for stems, branches etc.), and disks. The ground is often to be a flat plane. For most plant modelling, the core clustering of primitives is the plant level, i.e. a group of geometric primitives are associated with a tag that defines them as belonging to that group. An oct-tree spatial hierarchy is then imposed on this group to create an efficient mechanism for intersection testing by defining (axis-aligned) bounding boxes (see Lewis (1999) for details of intersection tests and other efficiencies). In the models here the original definition of each plant is made 'virtual', i.e. it does not directly appear in the scene. Instances of each virtual plant are then placed in the scene (with corresponding layers of bounding boxes) as 'clones' – copies of the virtual plants that are randomly rotated in azimuth. In this way, an attempt at simulating 'natural' variability is achieved using a set of 'full' plant descriptions (see above).

A special TRANSPARENT material exists within *librat*. The primary use of this is to mask sections of material maps, which can be used e.g. to simply model complex leaf form. A material map is a spatial look-up table (image) defining a spatial mapping of different material types over a local coordinate system on a primitive. When a ray intersects a material map the TRANSPARENT material allows rays to simply pass through, where other materials are used to define the local scattering (reflectance and transmittance) properties of that particular object. The leaves used in the *Combretum*, *Sclerocarya* and shrub models used in Lewis et al. (2010) have leaves defined by two triangles (allowing for some small leaf curvature). On top of this is mapped a high resolution leaf "shape" image with the image DN coded for TRANSPARENT to create details of leaf edges. Such effects are probably of limited impact when considering radiance at the canopy scale, but are included because the cost of implementation is very low. Note that although there is surface texture on these leaves (spatial variations of surface normal, veins, ribs etc.) that could be mapped through to the *librat* simulations, this is (slightly) more computationally expensive for very little benefit, so the leaf maps are used for the shape rather than texture. Figure 11 shows examples of the leaves used in the simulations here. Figure 141shows the impact of using the leaf maps compared with simple triangular facets.

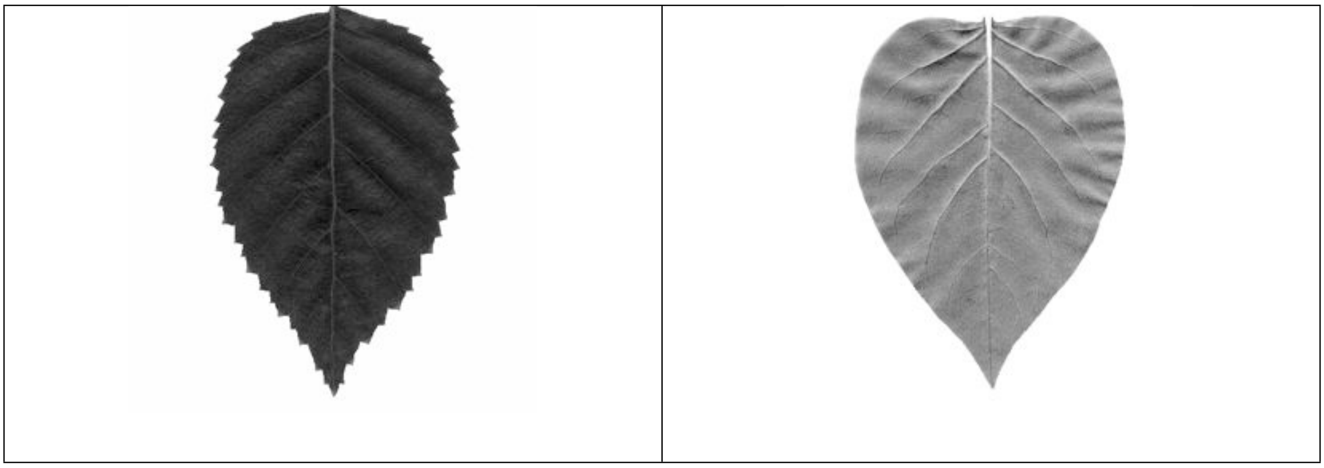


Figure 11. Examples of the leaf maps used in the tree and shrub 3D model simulations.

librat 'generic' mode

A feature of the *librat* model (not included in previous versions) is the ability to carry out simulations in 'generic' mode. In this mode, the number (and order) of scattering interactions with the various materials in the scene is recorded and written out, as opposed to calculating the attenuation of radiation at each interaction. The scattering information is then generic for that particular combination of canopy structure and view/illumination conditions. Any radiometric information (reflectance, transmittance) can then be used *a posteriori* to generate spectral reflectance values. This allows multiple radiometric combinations to be tried for any given structural/illumination configuration, with no extra cost. The use of this mode of operation means that it is trivial to vary the canopy spectral reflectance, without the need to repeat the (somewhat computationally expensive) Monte Carlo sampling. The use of this mode of operation is practically limited to cases when the total number of different types of materials (e.g. soil reflectance, leaf reflectance, leaf transmittance etc.) is quite small (e.g. 5 in total). The use of this form of operation is discussed further in Lewis and Disney (2010b), showing how it can also be used to operate with truncated ray depth sampling based on concepts of canopy spectral invariants.

Scattering information and other functionality of librat

Further information other than just the total integrated spectral or angular scattering (reflectance) can be obtained from the 3D model simulations. In particular, the scattering behaviour as a function of scattering order can be calculated. This provides information on how closely the scattering behaviour of the scenes can to be approximated from simpler radiative transfer models which tend to consider perhaps only the first order of scattering analytically, while approximating higher order scattering in some way. The rate of decay of the contributions to total scattering as a function of scattering order is determined by the structural arrangement of the canopy, and is described by the so-called recollision probability theory. There has been considerable recent work on exploiting this theory. Huang et al. (2007) provide a review of the fundamental theory; Lewis and Disney (2007) show an application of the theory to modelling leaf scattering behaviour.

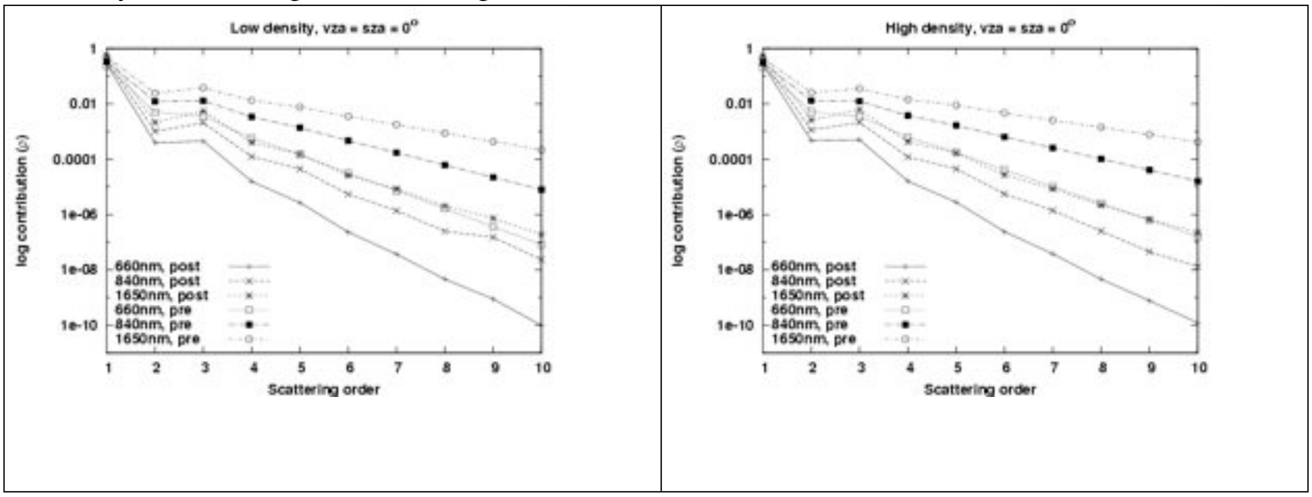
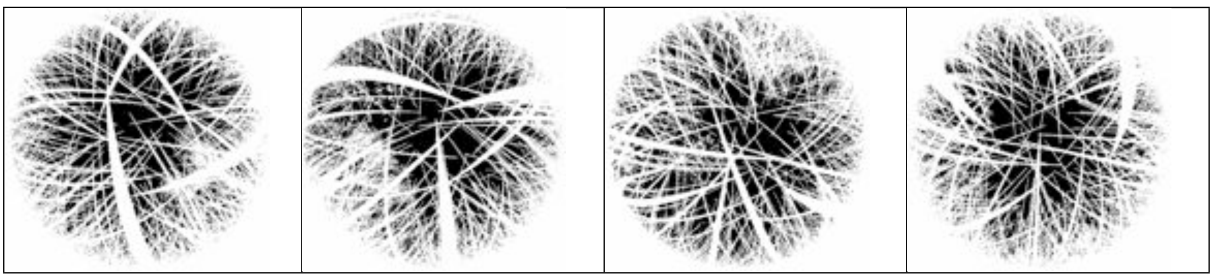


Figure 12. Contributions to total scattering as a function of scattering order for the low (left) and high (right) density savanna canopies. Wavebands 660, 840 and 1650nm are shown in each case for the pre- and post-burn scenarios (from Lewis et al., 2010a).

Figure 12 shows the variation of the scattering behaviour as a function of scattering order for the high and low density savanna canopy cases. It can be seen that the scattering contributions drop off very rapidly, with 99% of the total scattering in the first two scattering orders in the 660nm band, and 98% in the first two scattering orders in the 1650nm band. Ignoring the scattering contributions less that $1x10^{-6}$ where rounding errors and noise in the simulations comes into play, we see that this point is reached after quite different numbers of scattering interactions. In the post burn cases, the decay is much more rapid, while for the pre-burn cases, notably for the 1650nm, this decay is much slower. A key advantage of the 3D modelling tools is this ability to allow us to deconstruct the canopy scattering signal in great detail.

Other functions of librat include the ability to simulate hemispherical photography (and also directly calculate gap probability) from inside or outside the canopy. This is illustrated in Figure 13 for a savanna canopy.



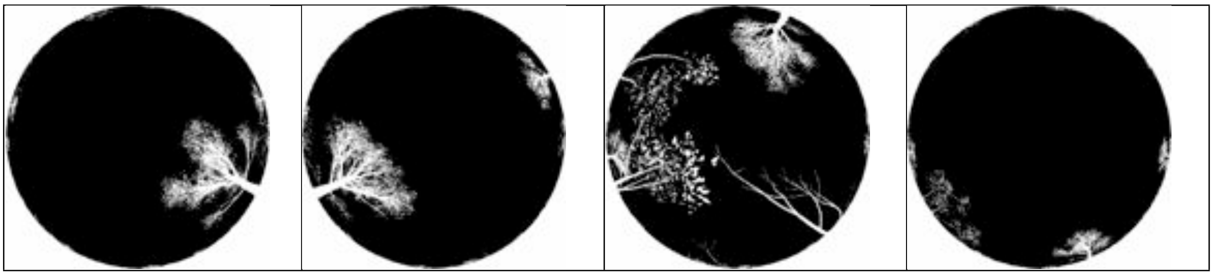


Figure 13. Example simulated gap fraction images of the high density, savanna canopy with a grass and tree layer. Images in top row are from 0.2m above the ground (i.e. including grass and tree canopy), in the right column 1.7m above the ground (i.e. above grass canopy but from same location).

```
camera {
 camera.name = "simple camera";
# geometry
 geometry.perspective = TRUE;
 geometry.idealArea = 100000
 geometry.azimuth = 0.0;
 geometry.zenith = 0.0;
 geometry.twist = 0.0;
 geometry.lookAt = 0, 0, 0;
 geometry.boomLength = 10000.;
 samplingCharacteristics.nPixels=262144;
 samplingCharacteristics.rpp = 64;
 result.samplingImage="cameraImage.hips"
 result.integral.mode="scattering order"
 result.integral = "results.dat"
}
```

```
camera {
 camera.name = "simple illumination";

# geometry
 geometry.perspective = TRUE;
 geometry.idealArea = 100000
 geometry.azimuth = 0.0;
 geometry.zenith = 0.0;
 geometry.twist = 0.0;
 geometry.lookAt = 0, 0, 0;
 geometry.boomLength = 10000.;
}
```

Figure 14. Example camera and light source control files.

Operation of librat

Although *librat* is written as a library, an example interface code is included in the current distribution that has much of the typical functionality required for remote sensing simulations, known as *start*. The library is written in the C programming language. Because of the library form of the model, it will not be a complex task to design interfaces with the 3DVegLab components. However, some existing components of the *start* interface will likely prove useful for 3DVegLab. Of particular interest here is the generic description that can be used for definition of the 'camera' and 'light source' objects. These are ASCII text files (although a GUI interface would be useful in 3DVegLab) that define, for instance: whether the object is orthographic (e.g. for BRDF simulations) or of a finite field of view; the location and MTF of the object (if required), sampling characteristics to be used etc. Using this interface, simulation involves specifying a file containing the world scene (as described above), the sensor wavebands of interest, and one or more camera and light sources to achieve a radiometric simulation set. Data are produced as images (if required) but more generally as integrals over the sensor IFOV. Information is maintained on radiance or reflectance as a function of scattering order, as described above. If no sensor wavebands are provided, the generic mode of output (above) is used. An example camera and light source file are shown in Figure 14. In this case, both the camera and light source are at nadir, viewing and illuminating an area of 10000 x 10000 real world model linear units (e.g. mm). Both camera and light source are defined here to be a 10000 linear units distant from the origin (the lookAt point). There are several ways in which these geometries can be specified.

camera {
 camera.name = "lidar camera";
# geometry 	
 geometry.perspective = TRUE;
 geometry.idealArea = 100000
 geometry.azimuth = 0.0;
 geometry.zenith = 0.0;
 geometry.twist = 0.0;
 geometry.lookAt = 0, 0, 0;
 geometry.boomLength = 10000.;
 samplingCharacteristics.nPixels=262144;
 samplingCharacteristics.rpp = 64;
 result.integral.mode = "distance"
 result.integral = "results_lidar.dat"
 lidar.nBins = 150
 lidar.binStart = 14000
 lidar.binStep = 1000
}
	camera {
	 camera.name = "simple illumination";
	
	# geometry
	 geometry.perspective = TRUE;
	 geometry.idealArea = 100000
	 geometry.azimuth = 0.0;
	 geometry.zenith = 0.0;
	 geometry.twist = 0.0;
	 geometry.lookAt = 0, 0, 0;
	 geometry.boomLength = 10000.;
	 lidar.pulseStart = 5000;
	 lidar.pulseForm = "gaussian";
	 lidar.pulseLength = 10000.0;
	}

Figure 15. Example lidar camera and light source specification.

Further, simply by setting a flag giving the lidar pulse length and associated lidar control information[6], a lidar simulation can be performed. Whilst there is no requirement for this in the SoW, it seems pointless not to provide this functionality. Clearly, because of the workload in the study however, we cannot put the same efforts into testing and validation of this component, and suggest that it is included as an 'experimental' component. Figure 15 shows an example of a lidar specification. In the camera, the sampling characteristics are specified (number of samples, start of sampling, sampling step (in linear distance units)). The lidar pulse characteristics are defined in the light source file. Here, we have a Gaussian pulse of length 10000 units. This simulation model has been used to simulate discrete return lidar signals (Disney et al., 2010) as well as various other studies with lidar, including (multispectral) waveform lidar (Hancock et al., 2008a,b).

[6] http://www2.geog.ucl.ac.uk/~plewis/bpms/src/start/tests/lidar/lidar0.html

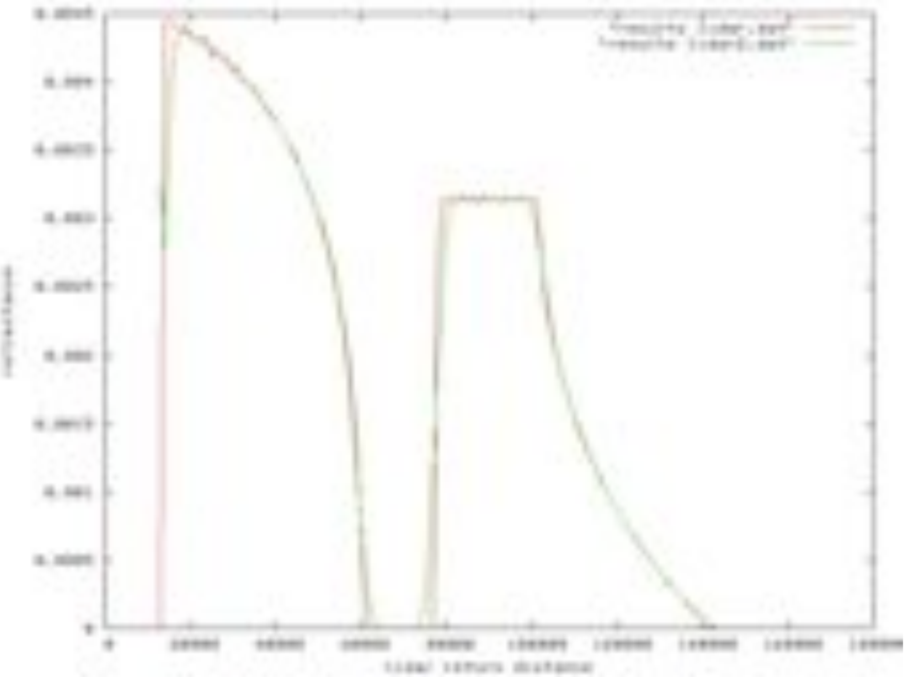


Figure 16. Example lidar waveforms over a simple geometric test scene (sphere on a flat surface) for an infintessimal lidar pulse length (red) and a finite pulse length (green).

Scene element radiometric models

For most simulations within librat, Lambertian scattering is assumed. However, other element radiometric models are available, currently including an MRPV model (Rahman et al., 1993; Engelsen et al., 1996). The interface designed to implement that non-Lambertian model can be adapted to incorporate other surface interaction models as necessary in this tool. The scope of this will be defined in generating the TS.

Librat within 3DVegLab

The model component of UCL will comprise the following modules and capabilities:

- a simulation tool for simulating directional radiance or reflectance (in various forms, from BRDF, through BRF, DHRF etc., plus lidar reflectivity if required) for arbitrary IFOV (or infinitesimal IFOV), view, illuminations, spectral bands and spatial sampling;
- a set of additional ‘tools’ for generating and analysing the canopy models;
- it will produce TOC reflectance suitable for comparison to processed atmospherically corrected EO data, or, through incorporation of an atmospheric model in 3DVegLab, TOA signals;
- Interface of the existing codes to the 3DVegLab design, enforcing as far as possible agreed direct compatibilities with DART (e.g. on formats and driver files);
- demonstrations and tests for the modelling tools and interfaces, mainly comprising demonstration of capability of simulating observed signal, and suite of simulations for existing and forthcoming ESA sensors;

In addition, since the module of UCL can model explicit 3D scenes to the finest (needle) detail, this module will as well be used to test whether the voxel approach, which is used to parameterise a simplified 3D scene model from TLS in conjunction with ALS based information (e.g. tree locations and crown characteristics, dbh, height, as well as drivers from statistical averages of these) to test what level of representation is sufficient to meet the aims of 3DVegLab.

UCL will study the impact this parameterisation has on the signal compared to the equivalent full 3D simulations, and will make suggestions for how reconstruction approaches should be developed to be structurally and radiometrically in line for simulating *actual* EO data.

The source code for librat is provided through e-licensing[7] through UCL (this is currently being set up) with a zero licensing fee for all academic/research users (so zero fee for this project). If this is not acceptable to ESA, this can be straightforwardly negotiated. Any new code and interfaces generated under this project will be under whatever licensing agreements are set up with ESA. Librat is written entirely in C and has been run and compiled on a wide range of unix/linux operating systems with a variety of compilers. It is, in that sense, platform independent, although it has not been tested on PCs running windows.

Analysis

As indicated above, the analysis module would fit well into the BEAM environment. This should be designed to enable the tool to exploit the range of functions within BEAM, for instance, atmospheric correction and various data analysis methods. Other than writing the analysis modules in Java, the other main requirement will be ensure the synthetic data output format is compatible with BEAM. The main internal BEAM format is a form of flat binary data files and a header file derived from the commonly used ENVI format and should present no technical difficulties. The SoW suggests that output formats are in HDF5 or net CDF, which again will not prove a difficulty, either through format translation filters from any internal formats generated by the tool or by re-coding the output routines.

The range of the analysis functions to be implemented will be selected from the options put forward elsewhere in this document. These include options, for instance, to run a data assimilation method being developed for another ESA project (EOLDAS). The code for this is written in Fortran, so design interfaces will need to be specified to the Java codes of BEAM. Similar interface issues are likely to apply for other analysis modules. As well as the synthetic satellite data being in a BEAM-compatible format, the format for 3dVegLab-generated scene characteristics will also need to be considered in this light.

Once the specific analysis methods have been decided on (in agreement with ESA) the TS can be generated for these, leading to the DDF.

The analysis module will provide functionality for sensitivity studies and benchmarking of instruments or EO products.

2.6.4. Deliverables

The outputs of this task are the TS of the toolbox and the DDF. The TS document generated will contain a precise and coherent definition of all the functions, required modules and performance expectations for the toolbox. This will be expressed in a modular fashion, according to the

[7] http://www.uclb-elicensing.com/

organisation of the toolbox modules presented above. The technical specifications for interfaces and outputs, including data formats and metadata, will be documented in the TS. Space Engineering Software Standards will be adhered to while specifying and designing the toolbox. This process will be guided and checked by our software developers, Netcetera.

Design of the toolbox: Based on the *Technical Specifications* a *Design Definition File (DDF)* shall be developed containing the description of the final algorithms and processing chain. The toolbox shall follow a modular structure, which will allow for its efficient extension and development in the future. Specifically the canopy and atmosphere RTM shall be considered as independent modules, which can be exchanged. For the atmospheric RTM the LibRadtran [RD-7| model shall be considered and employed if possible. The
during Task 2 all the software engineering process as required in the ECSS-40B and adequate Tailoring). This standard shall be followed up to the Qualification and Acceptance Test Review.software shall be developed as Open Source code and as an operation system independent platform. More specifically it is intended to develop this toolbox as a plug-in within the BEAM Toolbox in order to capitalise of the already available functionality as well as to facilitate the integration with EO data, if the consortium identifies no major obstacles. The design of the toolbox as a BEAM plug-in shall thus follow the BEAM architecture [RD-8] and ensure compatibility with the BEAM developer environment. While the toolbox itself shall be Open Source code the RTM module might be included as proprietary code as long as the toolbox as a whole can be distributed freely. The import module of the toolbox shall be designed to allow for variable input data. At the end of this step a *Critical Design Review (CDR)* shall be carried out in order to approve the proposed design.

D1.4: Technical Specification (TS) of the toolbox
D1.5: Design Definition File (DDF) of the toolbox

2.7. TASK 4 (T4): <u>DATA COLLECTION</u>

(Responsible person: Dr. Z. Malenovský, RSL, *Switzerland,* with contributions from TU Wien and the two site contractors)

2.7.1. Problem & Inputs

The objective of Task 4 (T4) is to collect ground measurements (Activity 1) and EO data (Activity 2) of two study test sites (selected during project kick-off meeting), which are required for: i) RTM parameterization of the 3DVegLab toolbox, ii) quality verification of acquired EO image data, iii) retrieval of biophysical variables of interest, and iv) accuracy validation of obtained EO products.
Inputs to T4 are Field Protocols (FP) and Site and Dataset Specifications (SDS) produced as deliverables of T2 (D1.2 and D1.3).

2.7.2. Approach & Activities

The data collection activities will be conducted within dedicated ground/flight campaigns. In case that the selected study tests sites will be suitable, the 3DVegLab campaigns will join the already planned

ESA campaigns (e.g., GMES Sentinel-2 and/or FLEX space-demonstrator campaigns planned for vegetation season of 2011) or campaigns of the other scientific projects sponsored from national or European resources. If applicable, existing datasets of the test sites will be used (e.g., locations of trees and spectral properties of understory). Non-exiting datasets will be additionally collected either once per season, if not being strongly dependent on phenological cycle (e.g., tree height and fractional cover, leaf optical and biochemical properties and EO image data), or in a multi-temporal fashion, if being phenologically dependent and better reachable in different season (e.g., 3D woody skeleton architecture of deciduous trees in winter).

Activity 1: Collection of Earth Observation Datasets (EOD)
Outputs of Activity 1 will result in project deliverable D2.1 (EOD).

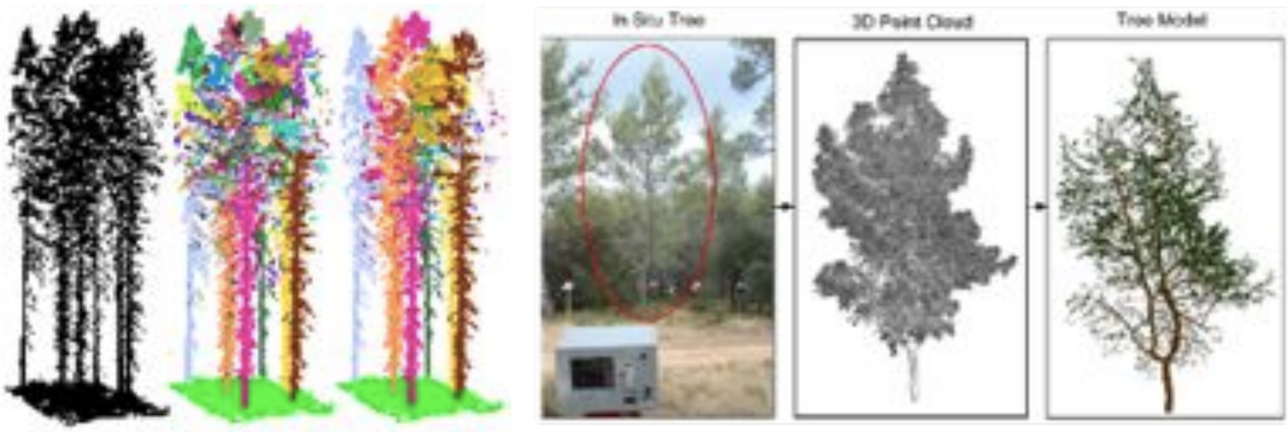


Figure 17. Two approaches for tree reconstruction from TLS data. A voxel based method (left, from A. Bienert et al., 2010) and a tree structure reconstruction based on L-systems with separation of woody and leafy canopy elements (J.-F. Cote et al., 2009).

Subtask T4.1: Airborne laser scanning (ALS) EO observations
ALS flight campaign will take place as close as possible or simultaneously with the airborne spectral campaign. In case of deciduous forest study site, the campaigns will be carried out during leaf-off (winter) and leaf-on (summer) period in order to separate properly foliage and woody skeleton of trees.

Subtask T4.2: Airborne spectral EO observations
Airborne spectral observations will be used to simulate Sentinel 2 and 3 image data to test functionality of the 3DVegLab toolbox. One of the currently available airborne imaging spectroradiometer (e.g., ESA airborne spectrometer APEX) will be used to collect airborne data of the appropriate spatial and spectral resolution over two selected forest study sites. Flight campaign will be carried out during the high summer season, when the forest stands will be phenologically fully matured, and simultaneously with ALS flight campaign (if feasible). Data pre-processing (geometric, radiometric, and atmospheric correction) will result in geo-coded images of hemispherical-conical reflectance factors.

Subtask T4.3: Space spectral EO observations

Satellite EO data will be used to test the toolbox performance on a real space-borne images. Space spectral images of two satellite systems will be acquired simultaneously with the ground/flight campaign. Two proposed targeting space systems are: i) CHRIS on board of PROBA (as a high spectral and spatial resolution data) and ii) MERIS on board of ENVISAT (as a medium spatial resolution data). Image data of both sensors have been used for retrieval of biochemical-physical properties of vegetation canopy and are fully suitable to test the 3DVegLab toolbox functionality.

Activity 2: Collection of ground measured In-Situ Dataset (ISD)

Outputs of Activity 2 will result in project deliverable D2.1 (ISD).

Subtask T4.4: Terrestrial laser scanning (TLS) observations

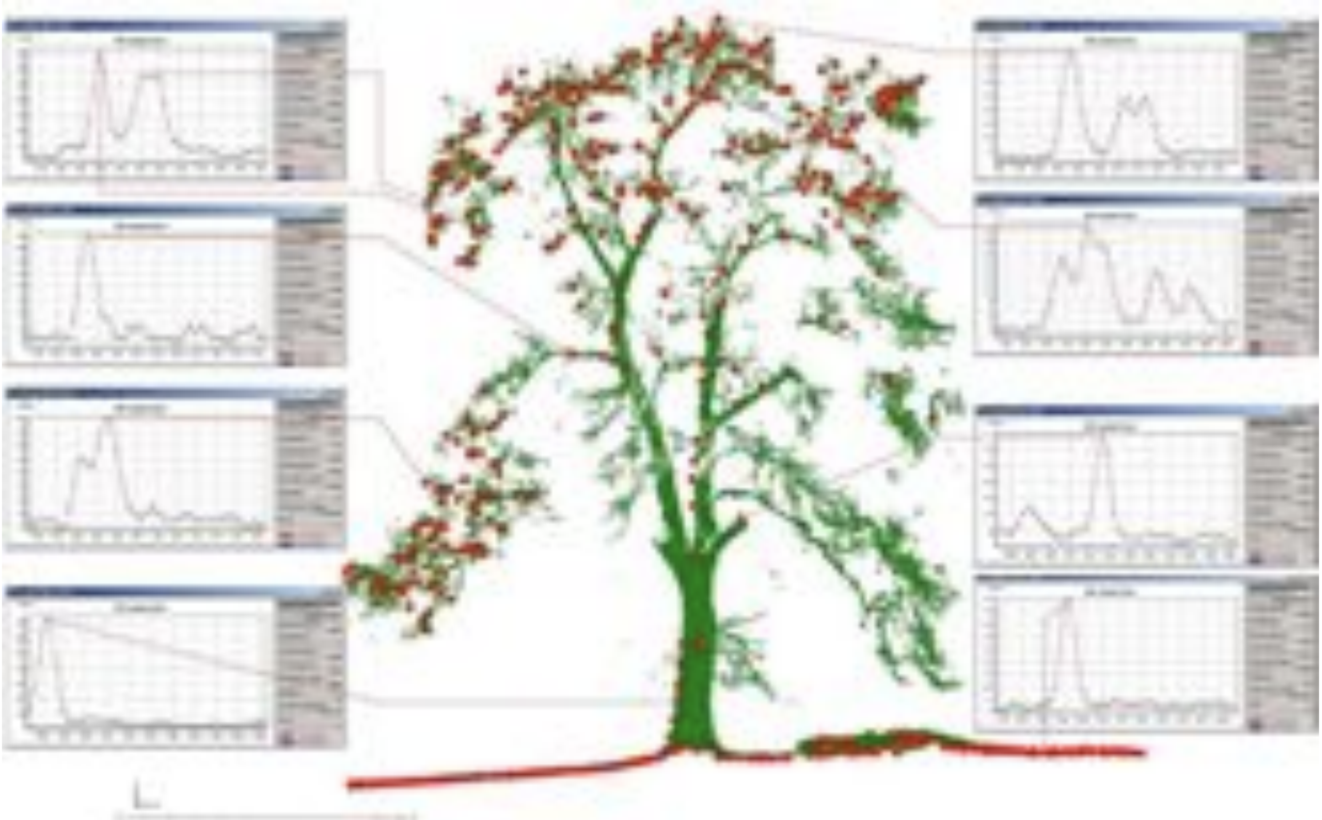


Figure 18. Simultaneously acquired Full Waveform ALS (red points and individual waveforms of selected points) and TLS (small green dots). Terrestrial scanner locations were not optimized for comprehensive branch structure reconstruction, taken from M. Doneus et al., 2010.

The aim of this task is the explicit and faithful modelling of the branching structure of trees and stochastic modelling of the finer twig and leaf structure of trees, both from TLS data. Additionally, ALS data will be used to assess the upper part of the canopies. The stochastic model will feature vegetation parameters (e.g. covered planimetric vegetation area, portion of leafs). The stochastic modelling of the finer canopy elements will require a tighter collaboration of TU Wien with UCL and CESBIO in order to develop models suitable for radiative transfer algorithms.

There is a trade-off between scanning effort (field work time, admissible environmental conditions, extra equipment for elevated scanning positions) and the ability for explicit modelling. ALS data will be used as well to complement the TLS data for both scale- and perspective-aspects. There is also an additional trade-off between efforts put in automating tree reconstruction and exploiting the experience and knowledge of humans in semi-automated tasks. The gaps in the point clouds along higher branches pose a severe challenge. Approaches for explicit modelling of branches do either provide a patchy reconstruction (Pfeifer et al., 2004) or are not fully automated (J.-F. Cote et al., 2009).

The methodology that has been developed in Task 2 will be deployed on the field sites using the following steps:

First, there is the collection of field data, for 100m x 100m an acquisition phase of 5 days for 3 people is foreseen, the site selection is subject to consultation with the project partners and will be handled at the CDR. The second and last step of method deployment is the application of the program on the new data, resulting in the branch model of trees and stochastic models for the finer elements

The reconstructed data will then be converted into the format defined in the technical specification (TS) of the toolbox.

Next to the tree locations, stem diameter as function of height (M. Thies et al., 2005), the main branching structure and bounds for the branch diameter, the distribution of the foliage will be the output of the tree reconstruction.

Subtask T4.5: Ground spectral measurements and optical properties

Ground spectral measurements will be collected to check quality of the air-borne data pre-processing (i.e., spectral quality after radiometric and atmospheric image corrections) and for parameterization of the radiative transfer models of 3DVegLab toolbox. Field reflectance measurements of several homogeneous near-Lambertian ground targets will be taken with numerical field spectroradiometer (ASD FieldSpec-3) during the over-flight of an airborne imaging spectroradiometer. Target locations will be recorded with a GNSS system. Targets located at the airborne images and field measurements will be cross-compared to assess a final quality of the airborne reflectance values.
The optical properties (reflectance and transmittance) of tree foliage, bark, woody elements and dominant understory features will be measured in integrating sphere coupled with the ASD FieldSpec-3 (Malenovsky et al., 2006). Specular and Lambertian part of leaf reflectance will be measured separately, whenever feasible. Optical properties of all the forest stand major surfaces are essential information to parameterize RTM for forward simulations the spectral Look-up tables (LUT).

Subtask T4.6: Biochemical-physical properties of canopy

The leaf samples collected for optical measurements will be analysed in laboratory for basic biochemical properties: content of chlorophylls (a+b), carotenoids (HPCL spectrometry), water, and dry matter. The laboratory analyses will be normalized by measured leaf area in order to be usable for validation of the complementary variables retrieved from Sentinel 2-3 simulated image data and also CHRIS and MERIS images.

Biophysical properties of canopy, leaf area index and canopy fraction, will be measured with ground optical devices: LiCor Plant Canopy Analyser LAI-2000 and digital hemispherical photography. Crown dimensions (height & diameter) and tree height and position can be measured with the FieldMap system, combining a laser telemeter with a digital compass. Biophysical measurements will be used to either parameterize the toolbox radiative transfer models (Malenovsky et al., 2008), or to validate accuracy of the retrieved EO products.

Subtask T4.7: Collection of auxiliary data
Auxiliary meteorological measurements (e.g., aerosol optical thickness) will be acquired during the airborne ground/flight campaigns with a sun-photometer in order to be able to perform atmospheric corrections of the imaging spectroscopy data.

2.7.3. Deliverables

D2.1: EO data set (EOD)
D2.2: In-situ data set (including the 3D canopy characterisation), (ISD)

2.8. TASK 5 (T5): TOOLBOX DEVELOPMENT

(Responsible person: Dr. J. Brazile, (Netcetera, Switzerland) with contributions from UCL and CESBIO)

2.8.1. Problem & Inputs

From the point of view of Task 5, the primary work is the specification coordination and integration of independently developed software components written in multiple platforms made to interoperate with each other from within the plugin architecture of a foreign framework (BEAM) operated on a foreign platform (Java). In general, the inputs consist of the specifications of the target plugin architecture and platform (BEAM), the input and output requirements of that plugin, and the internal integration interfaces (e.g. files, control scripts, etc) of the components contributing the shim plugin's core functionality (see Figure 19).

In general, the inputs consist of the specifications of the target plugin architecture and platform (BEAM), the input and output requirements of that plugin, and the internal integration interfaces (e.g. files, control scripts, etc) of the components contributing the shim plugin's core functionality.
Netcetera has successfully developed software using this approach in multiple Earth Observation projects including Fortran and IDL within Tcl (Dangel et al., 2005), C within IDL and Tcl (Brazile et al., 2003), IDL within C (Brazile et al., 2008), Fortran within Java (Brazile et al., 2007) and IDL within Matlab (Brazile et al., 2005).

2.8.2. Assumptions and preconditions

Two inter-related risks have been identified, associated with this task:
Best practice software development and integration processes, which are assumed to correlate with maximizing chances of successful software, are probably not the normal processes practiced by the

scientific developers doing the majority of (distributed) code development.

As responsible party for toolbox development (but in actuality, integrator of all external components), the most visible risk of project success appears to lie with the integration and validation tasks associated with this task - T5.

Therefore, the following assumptions and preconditions are identified to help address these challenges and manage all around expectations:

- Netcetera proposes milestones from a software development perspective, which should be controlled from the project management side to maximise chances of successful final integration. In exchange, Netcetera offers an always available development and integration platform, so that any consortium member at any time knows the current integration status.
- According to ITT 3.2.3 footnote, "contractor will be considered to be compliant with ECSS-40B by simply following the proposed work plan"
- No re-implementation (e.g. in Java) of consortium member code is foreseen
- "Operating System independent" requirement is met if 2 different platforms are demonstrated. At this time, these are foreseen as Linux and Mac OSX.
- Only one version of the BEAM interface (e.g. 4.8) needs to be supported
- The "user friendly graphical interface" is covered by BEAM standard functionality e.g. no separate GUI-specific interfaces to this plug-in need to be developed
- No integration with external interfaces are needed (e.g. authentication, authorization, database interfaces, etc)
- Either source code to one of the many available plug-ins will be made available, or timely access to e.g. Brockmann Consult resources will be made available.
- Netcetera will be given the opportunity to substantially affect the technical requirements and specifications given as toolbox development inputs, as well as acceptance criteria and conditions.

These are intended solely to limit expectations of Netcetera responsibility for e.g. scientific correctness, which may be negatively affected by any one module, as opposed to the technical correctness of properly setting up, executing and transferring input and output between those modules and back to BEAM through the shim plug-in.

2.8.3. Approach & Activities

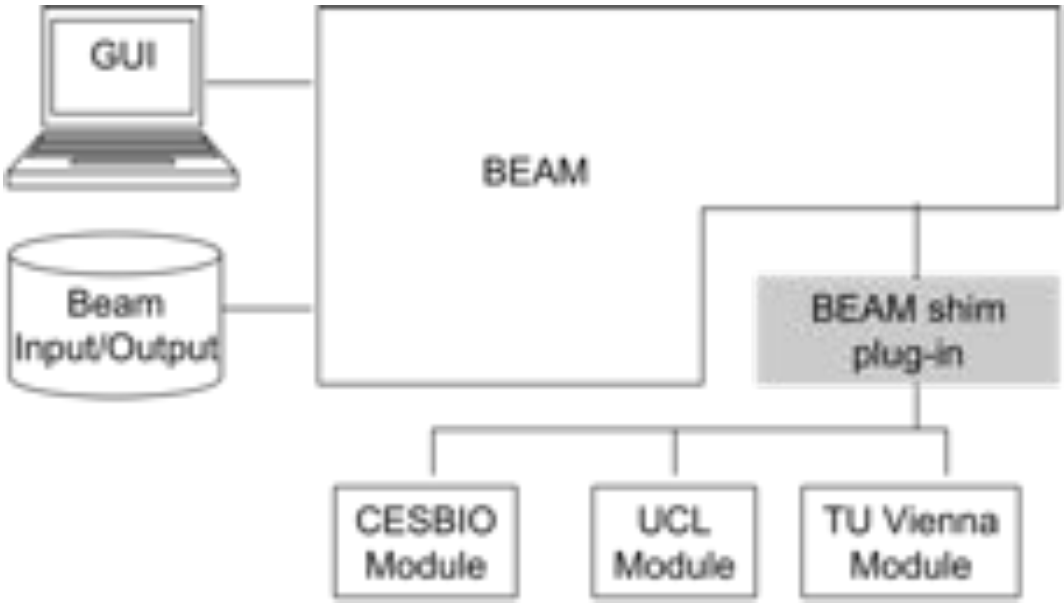


Figure 19. Toolbox as BEAM "shim" plug-in

The approach taken is first to validate the shim approach through development of a prototype proof of concept shim. The interface needs of this shim will then be provided to consortium partners for them to know about potential customizations they may need to make on their core components (e.g. being able to specify input file names or directories, logging and reporting needs and interfaces, failure modes, etc). This input is probably needed by PM1 for the Requirements Baseline (RB). In the proof of concept, dummy stub executables (e.g. standalone C programs or IDL runtime archives) will be used in place of the foreseen components so that consortium members know how and where their component is anticipated to fit into the plug-in.
At a later time, but as early as possible, (e.g. KO+4) a first integration trial run will be made with the BEAM shim and consortium components with dummy data to ensure that there aren't misunderstandings in the interfaces needed.
At a later time, but as early as possible, (e.g. PM2+1) an integration trial run will be made with the BEAM shim, consortium components and realistic data to ensure that there aren't misunderstandings in the interfaces needed. Certainly by this time if not sooner, plugin computed results will also be comparable with expected results to allow an automated way to run test cases and evaluate if computed results match expected results.
A final integration phase is foreseen whereby all validation runs are ensured to execute as expected - leading to the acceptance review (AR), where all final deliverables are made available.
The total number of days available for development is constrained by anticipated integration discussions, participation in onsite meetings, and the likely rework needed after milestone reviews, etc.

Subtask End to End testing (UCL)

Subtask end-to-end testing: end-to-end testing will provide an estimate of the toolbox capability to reproduce existing EOD, prior to demonstrating the scientific capability of the toolbox to simulate forthcoming sensor capabilities. This will comprise a complete test of the simulation toolbox ability to ingest 3D scene specifications developed from the ISD, and reproduce the EOD at a range of scales, both top-of-canopy (TOC) for airborne EOD, and top-of-atmosphere (TOA) for satellite EOD. In relation to the flow diagram above, the end-to-end testing requires that the world scene is consistent with the ISD, interfaces correctly with the 3D canopy and atmospheric models and presents a comparison of the synthetic EOD with the various EOD available to the project.

3.8.1. Problem & Inputs

Subtask end-to-end testing problem:

- To demonstrate the toolbox can ingest a specified set of test 3D model scenes;
- To demonstrate generate a set of simulated synthetic EOD from these scenes, both TOC and TOA simulations of specified samples of EOD at various scales, angles, bands;
- To provide a summary of the toolbox ability to ingest 3D canopy structure from the ISD and using this structure to simulate EOD;
- To provide an assessment of the toolbox performance.

Subtask end-to-end testing inputs:

3D scene specifications from the ISD over test sites (at least two, and for observed stages of phenology) suitable for ingestion into toolbox i.e. a consistent world scene. This comprises: specification of all 3D scene structural components (for librat) including tree locations, size, LAI, leaf/needle size, as well as equivalent DART scene parameterisations; radiometric properties of all scene components (understory, woody and leaf/needle material).

- Selection of EOD over test sites processed to TOA reflectance (via calibration, geometric correction an geo-registration with some estimate of errors), and TOC reflectance via RT atmospheric model-based correction.
- Specification of observation parameters for which scenes are to be simulated derived from EOD, including view and illumination angles; field-of-view (possibly PSF if defined); spectral bands (possibly band pass functions if defined).
- Simulation of TOA reflectance to compare to EOD will include path radiance from the atmospheric RT model (libradtran, Mayer & Killing 2005) requiring: latitude, longitude, date of observations; view and sun angle positions (for wide swath or scanning instruments); target altitude; atmospheric composition (O3, H20, CO2 mixing ratio) if known.
- Assessment of toolbox performance will be based on metrics (RMSE, etc.) TBD during the initial DDF phase of T1.

This sub-task depends on having the ISD processed to 3D scenes, EOD and toolbox development all in place before being carried out and completed. However, intermediate tests of the 3D model performance will be carried out during scene development and testing. This will comprise estimating the structural properties measured in the ISD i.e. canopy LAI and fractional cover, using the 3D models. A subset of LAI measurements made using the LAI2000 instrument and hemiphotos will be simulated using the 3D models and processed under the same assumptions as the field data. This will allow for consistent comparison of LAI and fractional cover between ISD and the 3D models, which will provide a check on the structural validity of the 3D scene models. An example of this approach is described above for a simulated savanna system)

Activities & Actions

Sub-task end-to-end testing:
The core RT models comprising the simulation toolbox, librat and DART, have been specifically developed for simulating canopy scattering for comparison to EOD. As a result, the implementation of the end-to-end simulation process is well-understood for both models and will primarily involve the specification of the required 3D canopy scenarios over which simulations will be carried out (derived from the ISD) and the definition of required simulation parameters (derived from the EOD). Following the flow diagram above, the end-to-end testing ensures the world scene (3D canopy representation) is consistent with ISD, compatible with the 3D canopy and atmospheric models, and that the resulting synthetic EOD are comparable to the measured EOD.

For each 3D scene and EOD configuration, simulations will be carried out using the toolbox to simulate TOC and TOA reflectance and the resulting values compared to the EOD. Clearly, for the EOD at spatial resolutions much higher than the sampling size of the ISD plots, simulations can be carried out on a per-pixel basis. As the EOD resolution approaches or exceeds the maximum extent of measured plot size (300m) this will not be possible. The 3D scenes could be replicated to cover larger areas, but spatial variance would be the same as for the smaller plots. Even for the higher resolution EOD however, geo-correction and registration uncertainty will introduce error into the observed EOD values. This uncertainty can be (partially) estimated in using the 3D model simulation tool if the spatial variability of the simulated scenes is assumed to match that observed. The spatial variation of the 3D model scenes will be tested at an intermediate stage during scene development via simulation of the spatial variation of LAI and gap fraction, and comparison to ISD. The end-to-end testing will comprise a limited set of simulations and comparisons to corresponding EOD, to be included with the software code and documentation. Comparisons between the synthetic and measured EOD will be carried out at-sensor i.e. TOA. This allows the uncertainty resulting from the atmospheric RT model to be characterised as this will be included in the forward modelling process.

2.8.4. Deliverables

D3.3: Project Website (PW)

D2.3: Toolbox software (TB)

D2.4: Summary of end-to-end testing results.

Milestone description	Schedule dates	Effort in %	Comment
Web site and Development Environment Setup	Starting at KO	4%	Development and collaboration environment needed from the start
Plugin-Prototype Development	by KO+2	30%	Important for providing critical input to module developers
First integration	Starting at PM1 + 1	10%	First data should be available
First real integration	Starting at PM2 + 1	20%	Final interfaces should be known
Finalization	by AR	36%	

Starting at KO [4% person days]

Input: none

Output: D3.4

Activity:

- Setup project wiki (D3.3 PW)
- general description of project
- intended products
- contact details
- password protected filesystem for sharing project deliverables (webdav)
- source code control (subversion)
- issue management system (e.g. Jira)
- continuously updated wiki w/project progress

by KO+2 [30% person days]

Input: buildable/runnable BEAM with example plugin source code

Output: BEAM plugin shim, with tech note input for D1.1, D1.4, D1.5

Activity:

- Prototype a BEAM plugin shim for inputs to D1.1(RB), D1.4(TS), D1.5(DDF)
- a BEAM plugin whose core functionality is in non-java langauges
- identify needed interfaces to BEAM (e.g. DIMAP file format, etc)
- identify non-java inter-component interfaces (files, scripts, etc)
- address "operating system independant" solution for non-java part (e.g. NestedVM, Cibyl, Axiomatic or runtime selection of pre-compiled binaries, etc)

Starting at PM1 + 1 (e.g. KO+4) [10% person days]

Input: consortium components (e.g. RT codes, etc), dummy data

Output: working BEAM shim with dummy data

Activity:

- First real integration attempt
- a non-trivial BEAM execution of real non-java components w/dummy data

Starting at PM2 + 1 (e.g. KO+10) [20% person days]

Input: consortium code components, real input data, expected output

Output: working BEAM shim with real data, calculated vs expected report

Activity:

- Integration with real EOD data

by AR (e.g. KO+15) [36% person days]

Input: final consortium components, validation input data set

Output: working BEAM shim with real data, calculated == expected (D2.3 TB)

Activity:

- Preparation of final delivery
- validated integration run
- BEAM shim documentation

2.9. TASK 6 (T6): SCIENTIFIC DEMONSTRATION STUDY

(Responsible person: Dr. M. Disney, UCL, *UK,* with contributions from CESBIO and RSL)

2.9.1. Problem & Inputs

Two different scientific demonstration studies are presented here, with the second being dependent on the completion of the first, but adding an inverse modelling component. The first is the demonstration of the toolbox for modelling changing LAI in a 3D canopy, constrained by EOD at two points (leaf on, leaf off) and with the transitions between these two states modelled to follow an approximate logistic green-up and senescence of a deciduous forest. The second demonstration would be to use the synthetic EOD covering this seasonal change to quantify the capability of Sentinel 2 & 3 data to derive estimates of LAI via an EO data assimilation scheme developed elsewhere.

2.9.2. Approach & Activities

Problem:

- To demonstrate the capabilities of the toolbox in generating a ‘trajectory’ of LAI in a 3D model canopy over a single seasonal cycle, constrained by ISD at two points and interpolated between these points. 3D model outputs of synthetic EOD at each stage, specifically Sentinel 2 & 3 configurations;
- To demonstrate the utility of the synthetic Sentinel 2 & 3 data in estimating LAI via

application of an EO land data assimilation scheme, including estimates of the uncertainty in retrieved LAI due to the observation characteristics.

Inputs:

- Set of 3D scenes covering a range of LAI between maximum and minimum observed states, based on a realistic expectation of the trajectory;
- Estimates of LAI (from ISD), at two points during the phonological cycle at which 3D models will be constrained;
- EOD at two points during the phonological cycle at which 3D models will be constrained;
- Prototype EO land data assimilation scheme (EO-LDAS), which can ingest a time series of EOD (synthetic Sentinel 2 & 3 in this case) with a range of spatial and spectral properties and error characteristics, and carry out a constrained optimisation of a simple RT model scheme to retrieve values of LAI plus uncertainties.

Sub-task: demonstrate the scientific capabilities of the toolbox to generate synthetic EOD covering a synthetic LAI trajectory over a phenological cycle in a deciduous forest, constrained to observed values at two key points, ideally maximum and minimum LAI, with realistic transition between these points.

This work would involve generating a series of 3D canopies from the 3D tree models produced from the ISD and from TLS where appropriate, covering a range of LAI values not seen in the ISD. The resulting canopies would vary only in terms of LAI, not trunk and branch structure, through changes in leaf size and number, along with some change of leaf optical properties particularly in senescence, by the generation of modelled leaf reflectance and transmittance with senescent materials using the PROSPECT leaf model (Feret et al., 2008). The models would be constrained to pass through the two known LAI stages represented by the ISD. Various options exist for representing the transitions between these points. A simple approach would be to use an approximate double logistic curve which has been proposed for deciduous broadleaf trees in particular (Zhang et al.,2004). The transition stages would not be intended to match particular measured ISD, as none would be available for those points, however if EOD were available, these could be used to test the 3D models against. The resulting 3D models would be used to simulate a series of synthetic Sentinel 2 & 3 observations over the LAI trajectory.

The resulting synthetic EOD would be a powerful demonstration of the toolbox to generate synthetic EOD, in particular Sentinel 2 & 3, over a range of canopy states. These data would also prove useful in the demonstrating the capabilities of new missions such as Sentinel 2 & 3 for estimating biophysical properties as they could be used in an inverse sense to invert a biophysical model. We discuss how this could be done below, if this task were to be selected.

Sub-task: using the forward modelled 3D-derived synthetic Sentinel 2 & 3 EOD in an EO land data assimilation scheme.

The EO-LDAS tool, developed under ESA Contract 22205/09-I-EC, is a prototype implementation of a system aimed at embedding Data Assimilation (DA) techniques in the routine production of EO based products characterizing the land surface. DA techniques have been widely used assimilation of observations into numerical weather prediction schemes but have been less well-used in EO applications related to the land surface (compared to atmospheric and ocean applications). This is partly as a result of the difficulty of providing an EO measurement that will constrain a land surface model directly or indirectly (lack of horizontal transport in such models can prevent constraint available to spatially dynamic models). These issues are reviewed by Mathieu & O'Neill (2008) and Wang et al. (2009). EO-derived products related to land surface properties such as C fluxes are often far-removed from TOA (or even TOC) radiance estimates, requiring process models to translate from one to the other. A DA scheme in this case requires some form of observation operator (OO) that provides a link between an observation of radiance from EO, to the model which uses this observation to drive development of some land surface process. Recent developments in this area have shown the power of this method as well as some of the difficulties (Quaife et al., 2008).

The EO-LDAS is designed to allow the ingestion of observations (TOC radiance, or, coupled to an atmospheric model, TOA radiance) with arbitrary view, illumination, spectral and spatial characteristics. These observations are used to update the state variables of the underlying canopy RT model, with the temporal link between model states being provided by a simple linear dynamics model. The prototype is built around the semi-discrete (1D) model of the canopy RT by Gobron et al., 1997 and a process model describing the state of the system under consideration. This allows prediction of the state of the system (represented by the process model) at some future time t_1, given values of the system state at some previous time(s). In the EOLDAS, a simple process model will be used of the form $x = \mathbf{A}\mathbf{x} + b$ where **x** is a vector containing all the unknown state variables at all times and locations, and **b** is independent of unknown values of **x**. Although this model is simple it allows various sorts of multi-temporal smoothing as well as allowing the usual model contribution to 3dVar assimilation (by taking **A** = **0** and setting **b** to be the background value predicted by a dynamic model applied to historic values of the state variables). By default, the model is set up to implement a first order difference temporal regulariser (i.e. no spatial model). In this case, **b** is set to the zero vector, and the model term A, which is of dimensions $(N_t?N_p)?(N_t?N_p)$ where N_t is the number of parameters per pixel and and N_p is the number of timesteps over which process model estimates are to be found, contains elements of 0 or 1, with:

$$
\begin{aligned}
A(i,j) &= 1 : j = i + N_p \\
&= 0 : j \neq i + N_p
\end{aligned}
$$

i.e. it is a model that predicts that the parameter value at the next time step will be the same as the current value (a zero-order process model), with an uncertainty in this specified through a covariance matrix Cv expressing the model and observation uncertainty. The assimilation process is a minimisation of a cost function *J(x)* against TOC reflectance observations on a per-pixel basis, where *J(x)* consists of three terms: (1) misfit of the state vector from a prior, $J_{pr}(x)$; (2) the misfit of the state vector to a prediction based on model dynamics, $J_m(x)$; and (3) the misfit of the predicted reflectance or radiance from that observed, $J_{pr}(x)$ i.e.

$$J(x) = J_{pr}(x) + J_{obs}(x) + J_m(x)$$

and the minimisation is constrained to keep model parameters within physically realisable limits. The underlying RT model parameters describe canopy (LAI, canopy height, leaf radius), leaf (biochemical absorption coefficients, leaf layers) and soil (reflectance) properties. The 1D RT model is a much simpler representation of canopy structure than that provided in the toolbox, so retrieved parameters will be ‘effective’ (1D equivalent) values (although the ‘true’ values will be known *a priori* as these will be the values in the 3D RT model simulations of synthetic EOD). However it has been shown that there is an equivalence between 1D (effective) and 3D canopy RT model parameters in practice (Pinty et al., 2004).

The code for the EO-LDAS prototype is available through UCL and is ideally-suited for an observation system simulation (OSSE)-type approach, as it quantifies the uncertainties arising from a particular choice of spectral, spatial (and temporal) sampling configuration, for constraining a simple process model in this case.

The figure below shows an example of the EO-LDAS being used to predict synthetic MERIS data over time (30 days) given estimates of the surface reflectance over the same time from another sensor (MODIS here), under the conditions of a changing surface state, a sine-varying LAI profile in this. MODIS ‘observations’ here are actually also synthetic, simulated using a canopy RT model with noise added (so that the ‘true’ values are known). These synthetic MODIS data are then used in the EO-LDAS to infer the underlying variation in the process model state, the change in LAI. The inferred LAI variation is then used to predict the MERIS observations (the original value of which is known from forward RT model simulations without added noise). The inferred LAI profile and resulting estimations of MERIS reflectance are the result of optimising 5 RT model parameters over 30 days i.e. 150 independent model parameters against 210 observations (30 days × 7 bands).

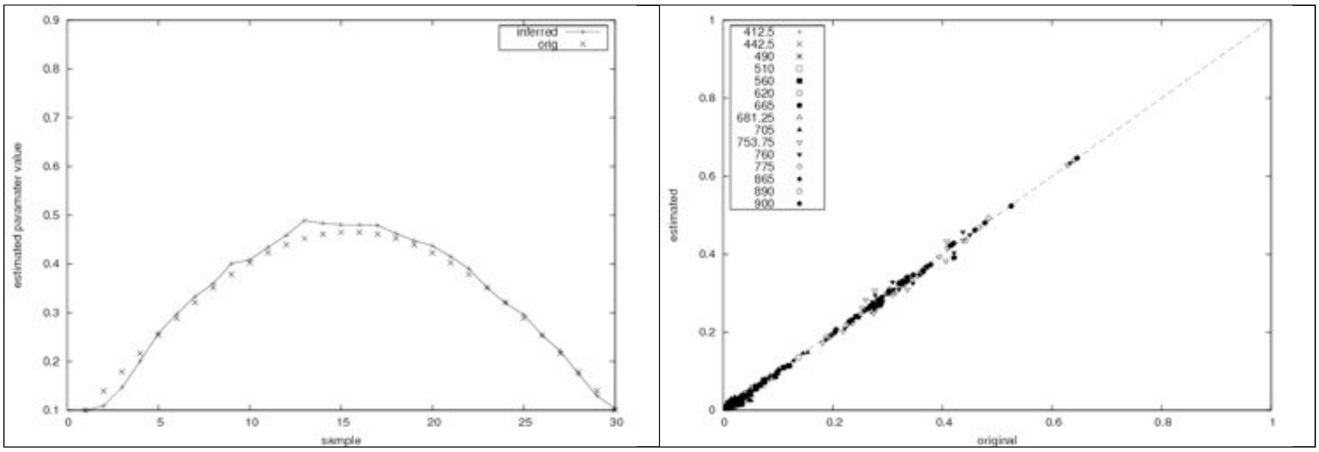


Figure 20. Left panel: inferred LAI from MODIS ‘observations’ assimilated into EO-LDAS over 30 days, with known LAI profile in green. Right panel: scatter plot of estimated MERIS observations over the same time period using the inferred LAI dynamics, against the original values.

Here, we will not have fully time-varying 3D model outputs from ISD, so we would use a subset of approximatel LAI states, interpolated between two known points as described above to generate a dataset of time-varying Sentinel 2 & 3 synthetic angular and spectral reflectance. These synthetic data will comprise simulations of MSI-like (13 bands from 0.44-2.19μm, varying 10, 20 and 60m spatial resolution, varying repeat, varying view and sun angle), OLCI-like (21 bands from 0.4-1.02μm, 300m pixels, varying repeat, varying view), and SLST-like (6 bands from 0.56-2.25μm, varying repeat, varying angle) data. These synthetic data will be used to retrieve LAI using the EO-LDAS, along with associated model and observation uncertainties.

We will discuss and quantify the performance of the various observation configurations in terms of their ability to retrieve LAI from the synthetic Sentinel data. The 3D toolbox potentially provides a very powerful method for developing and testing new EO product retrieval algorithms due to the capability for simulating observations with very realistic scene characteristics. In conjunction with a tool such as an EO-LDAS, this allows testing of the likely value of a wide range of forthcoming observations. We will discuss options and directions for using the toolbox for prototyping biophysical parameter retrieval algorithms more widely.

2.9.3. Deliverables

D3.1: Exploitation Report (ER) i.e. summary document detailing the comparisons across the test cases, showing how toolbox can be used, and providing guidance on how this might be developed further.
D3.2: Suite of 3D model scenes representing a range of test cases, plus simulations thereof for demo cases, plus indications as to how this can be extended.

2.10. TASK 7 (T7): PROMOTION

(Responsible person: Prof. Dr. M. E. Schaepman, RSL, *Switzerland*)

2.10.1. Problem & Input

In order for the toolbox to be successful, its availability and functionality needs to be advertised within the scientific community. We presume ESA to support the download of the toolbox from one of their websites beyond the duration of this project.

2.10.1. Approach & Activities

We will disseminate the toolbox and scientific demonstration studies using the following approach:

- A project webpage will be set up, enabling the communication within the consortium (since large data volumes will need to be exchanged) as well as the presentation of the project content to the outside world.The website will be set up by NCA at project start and maintained during the project by the consortium members. The site will additionally enable the communication with ESA in form of deliverables and reports, which will be stored in a restricted web repository.

- We suggest to organize a dedicated session at a large international conference (e.g. IGARS 2012) or - alternatively - during a specialized workshop (ISPRSMS and/or IWMMM-5, etc.), to demonstrate the scientific use of the toolbox, given personnal and financial resources are available past the formal end of project.
- We envisage journal publications following standard scientific practise in a high-ranked international journal (e.g. RSE, TGARS) to present either the toolbox, the scientific demonstration study or a combination of both.
- A final report of the findings of 3DVegLab will be prepared as part of the promotional package.

2.10.2. Deliverables

D3.3: Promotional package (PP) - final report
D3.4: Project Webpage (WP)

2.11. REFERENCES

Bienert, A., Queck, R., Schmidt, A., Bernhofer, C. & Maas, H.-G., VOXEL SPACE ANALYSIS OF TERRESTRIAL LASER SCANS IN FORESTS FOR WIND FIELD MODELING, International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVIII, Part 5 Commission V Symposium, Newcastle upon Tyne, UK., 2010.

Brazile, J., Kohler, P., and Hefti, S., A Software Architecture for In-flight Acquisition and Offline Scientific Post-Processing of Large Volume Hyperspectral Data, Proceedings of the 10th Tcl/Tk Conference (Tcl/2003), 2003.

Brazile, J. "Calling ENVI's Spectral Smoothing routine from within Matlab", RSL Technical Report, 2005.

Brazile, J., Low Fat Grid: A RESTful Grid Service for Non-Programmers, Jazoon '07 - The International Conference on Java Technology, 2007.

Bruniquel-Pinel, V. and Gastellu-Etchegorry, J.P. 1998. Sensitivity of texture of high resolution images of forest to biophysical and acquisition parameters. Remote Sensing of Environment, 65 (1), 61-85.

J. Brazile, R.A. Neville, K. Staenz, D. Schlaepfer, L. Sun, K. I. Itten, Cluster versus Grid for Operation Generation of ATCOR's MODTRAN-based Look Up Tables, Parallel Computing Systems and Applications, Elsevier, 2008, Vol 34, Issue 1, pp. 32-46.

Cote, J.-F., Widlowski, J.-L., Fournier, R.A. & Verstraete, M.M., The structural and radiative consistency of three-dimensional tree reconstructions from terrestrial lidar, Remote Sensing of Environment, 2009, Vol. 113(5), pp. 1067 - 1081.

Dangel, S., Petitcolin, F., Brazile, J., Miesch, C., Poutier, L., Jia, L., Moreno, J., Gloor, M., Kneubuehler, M., Schaepman, M., and Itten, K., SPECTRA end-to-end simulator : Final Report ESA, RSL, 2005, http://www.esa.int/esapub/bulletin/bulletin125/bul125_publicat.pdf

Disney, M., Kalogirou, V., Lewis, P., Prieto-Blanco, A., Hancock, S. & Pfeifer, M., Simulating the impact of discrete-return lidar system and survey characteristics over young conifer and broadleaf forests, Remote Sensing of Environment, 2010, Vol. 114(7), pp. 1546 - 1560.

Disney, M., Lewis, P. & Saich, P., 3D modelling of forest canopy structure for remote sensing simulations in the optical and microwave domains, Remote Sensing of Environment, 2006, Vol. 100(1), pp. 114-132.

Disney, M. I. and Lewis, P. (2007) Spectral invariant behaviour of a complex 3D forest canopy, in proc. 10th ISPMSRS meeting, Davos, Switzerland, 12-14 March 2007.

Disney, M. I., Lewis, P., Bouvet, M, Prieto-Blanco, A. & Hancock, S., Quantifying surface reflectivity for spaceborne lidar via two independent methods, IEEE Trans. Geosci. Rem. Sens., 2009, Vol. 47(10), 3262-3271.

Disney, M., Kalogirou, V., Lewis, P., Prieto-Blanco, A., Hancock, S. & Pfeifer, M., Simulating the impact of discrete-return lidar system and survey characteristics over young conifer and broadleaf forests, Remote Sensing of Environment, 2010, Vol. 114(7), pp. 1546 - 1560.

Disney, M. I., Lewis, P., Gomez-Dans, J., Roy, D., Wooster, M. & Lajas, D. (2010, submitted) 3D radiative transfer of a two-layer savanna system, Remote Sensing of Environment, submitted.

Doneus, M., Briese, C. & Studnicka, N., Analysis of Full-Waveform ALS data by simultaneously acquired TLS data: Towards an advanced DTM Generation in Wooded Areas, International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVII, Part 7B Commission VII Symposium, Vienna, Austria, 2010.

Engelsen, O., B. Pinty, M. M. Verstraete, and J. V. Martonchik (1996) Parametric Bidirectional Reflectance Factor Models: Evaluation, Improvements and Applications, EC Joint Research Centre, Technical Report No. EUR 16426 EN, 114 p.

Feret, J.-B., Francois, C., Asner, G.P., Gitelson, A.A., Martin, R.E., Bidel, L.P., Ustin, S.L., le Maire, G. & Jacquemoud, S., PROSPECT-4 and 5: Advances in the leaf optical properties model separating photosynthetic pigments, Remote Sensing of Environment, 2008, Vol. 112(6), pp. 3030-3043.

J.-P. Gastellu-Etchegorry, E. Martin and F. Gascon, DART: A 3D model for simulating satellite images and studying surface radiation budget, International Journal of Remote Sensing 25 (2004), pp. 73–96.

Gobron, N., B. Pinty, M. M. Verstraete, & Y. Govaerts, A semidiscrete model for the scattering of light by vegetation, J. Geophys. Res., 102, 1997, 9431–9446.

Goel, N.S., Models of vegetation canopy reflectance and their use in estimation of biophysical parameters from reflectance data, Rem. Sens. Rev., 1988, 4, 1-212.

N.S. Goel and R.L. Thompson, A snapshot of canopy reflectance models and a universal model for the radiation regime, Remote Sensing Reviews 18 (2000), pp. 197–206.

Y. Govaerts and M.M. Verstraete, Raytran: A Monte Carlo ray tracing model to compute light scattering in threedimensional heterogeneous media, IEEE Transactions on Geoscience and Remote Sensing 36 (1998), pp. 493–505.

S. Hancock, P. Lewis, Disney, M. I., M. Foster, J.-P. Muller (2008a) Assessing the accuracy of forest height estimation with long pulse waveform lidar through Monte-Carlo ray tracing, in proc. Silvilaser08, 17-19 September, Edinburgh, 2008

S. Hancock, Disney, M. I., P. Lewis, J.-P. Muller (2008b) Exploring the measurement of forests with full waveform lidar through Monte-Carlo ray tracing, in proc. IGARSS'08, 5-11 July, Boston, USA, 2008.

Hilker, T., van Leeuwen, M., Coops, N., Wulder, M., Newnham, G., Jupp, D. & Culvenor, D., Comparing canopy metrics derived from terrestrial and airborne laser scanning in a Douglas-fir dominated forest stand, Trees - Structure and Function, Springer Berlin / Heidelberg, 2010, Vol. 24, pp. 819-832.

Huang et al., 2008. Stochastic transport theory for investigating the three-dimensional canopy structure from space measurement, Remote Sensing of Environ., 112:35–50, 2008.

Izzawati, Lewis, P. and McMorrow, J., 1998. 3D model simulation of polarimetric radar backscatter and texture of oil-palm plantations. In: Geoscience and Remote Sensing Symposium proceedings, 1998: IGARSS '98. Vol. 3. IEEE, Piscataway, 1502-1504.

Jacquemoud, S. & Baret, F., PROSPECT: A model of leaf optical properties spectra, Remote Sensing of Environment, 1990, Vol. 34(2), pp. 75-91.

Kimes, D., Gastellu-Etchegorry, J. & Esteve, P., Recovery of forest canopy characteristics through inversion of a complex 3D model, Remote Sensing of Environment, 2002, Vol. 79(2-3), pp. 320-328.

Benjamin Koetz, Guoqing Sun, Felix Morsdorf, K.J. Ranson, Mathias Kneubuhler, Klaus Itten, Britta Allgower, Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization, Remote Sensing of Environment, Volume 106, Issue 4, 28 February 2007, Pages 449-459, ISSN 0034-4257, DOI: 10.1016/j.rse.2006.09.013.

Kuusk, A., Kuusk, J. & Lang, M., A dataset for the validation of reflectance models, Remote Sensing of Environment, 2009, Vol. 113(5), pp. 889 - 892.

Kuusk, A., Nilson, T., Kuusk, J. & Lang, M., Reflectance spectra of RAMI forest stands in Estonia: Simulations and measurements, Remote Sensing of Environment, 2010, Vol. 114(12), pp. 2962 - 2969.

Lewis, P., Disney, M.I. and Riedmann, M., 1999. Application of the Botanical Plant Modelling System

(BPMS) to the analysis of spatial information in remotely sensed imagery. In: Proceedings 25th Annual Remote Sensing Society Conference, 7-10th September 1999, Cardiff, U.K., 507-514.

P. Lewis, Three-dimensional plant modelling for remote sensing simulation studies using the botanical plant modelling system, Agronomie — Agriculture and Environment 19 (1999), pp. 185–210.

Lewis, P. & Disney, M.,Spectral invariants and scattering across multiple scales from within-leaf to canopy, Remote Sensing of Environment, 2007, Vol. 109(2), pp. 196-206.

P. Lewis (2007) Canopy modelling as a tool in remote sensing research, In: Vos, J., Marcelis, L.F.M., de Visser, P.H.B., Struik, P.C. and Evers, J.B. eds. Functional Structural Plant Modelling in Crop Production. Springer, Dordrecht, pp.219-229.

Lewis, P. E. and Disney, M. I. (2010) On canopy spectral invariants and hyperspectral ray tracing, 2nd Workshop on Hyperspectral Image Processing: Evolution in Remote Sensing (WHISPERS), 14-16 June, Reykjavik, Iceland. (PDF).

P. Lewis, M. Disney, J Gomez-Dans, M. Wooster, B. Pinty and D. Roy (2010) ESA final report: Radiative transfer modelling for the characterisation of natural burned surfaces: AO/1-5526/07/NL/HE.

Maas, H.G., Bienert, A., Scheller, S. & Keane, E., Automatic forest inventory parameter determination from terrestrial laser scanner data, International Journal of Remote Sensing, Taylor & Francis, 2008, Vol. 29(5), pp. 1579-1593.

Malenovsky, Z., Homolova, L., Hanus, J., Kaplan, V., Dolansky, T. & Yanez, L., Structural parametrization of Norway spruce trees in radiative transfer of high spatial resolution., Nordic Network on Physically based remote sensing of forests - PHYSENSE, University of Helsinky, Finland, 2008.

Malenovský Z., Albrechtová J., Lhotáková Z., Zurita-Milla R., Clevers J.G.P.W., Schaepman M.E., Cudlín P., 2006. Applicability of the PROSPECT model for Norway spruce needles. International Journal of Remote Sensing, 27(24), 5315-5340.

Malenovsky Z., Martin, E., Homolova, L., Gastellu-Etchegorry, J.-P., Zurita-Milla, R., Schaepman, M.E., Pokorny, R., Clevers, J.G. & Cudlan, P., Influence of woody elements of a Norway spruce canopy on nadir reflectance simulated by the DART model at very high spatial resolution, Remote Sensing of Environment, 2008, Vol. 112(1), pp. 1-18.

Mathieu, P. P. & O'Neill, A., Data assimilation: From photon counts to Earth System forecasts, Remote Sensing of Environment, Vol 112, 2008, 1258-1267.

Mayer, B. &Kylling, A., Technical note: The libRadtran software package for radiative transfer calculations - description and examples of use. Atmos. Chem. Phys., 2005, 5, 1855-1877.

Morsdorf, F., Meier, E., Kötz, B., Itten, K.I., Dobbertin, M. & Allgöwer, B.,LIDAR-based geometric reconstruction of boreal type forest stands at single tree level for forest and wildland fire management, Remote Sensing of Environment, 2004, Vol. 3(92), pp. 353-362.

Morsdorf, F., Mårell, A., Koetz, B., Cassagne, N., Pimont, F., Rigolot, E. & Allgöwer, B., Discrimination of vegetation strata in a multi-layered Mediterranean forest ecosystem using height and intensity information derived from airborne laser scanning, Remote Sensing of Environment, 2010, Vol. 114(7), pp. 1403 - 1415.

Morsdorf, F., Nichol, C., Malthus, T. & Woodhouse, I.H., Assessing forest structural and physiological information content of multi-spectral LiDAR waveforms by radiative transfer modelling, Remote Sensing of Environment, 2009, Vol. 113(10), pp. 2152- 2163.

P.R.J. North, Three-dimensional forest light interaction model using a Monte Carlo method, IEEE Transactions on Geoscience and Remote Sensing 34 (1996), pp. 946–956.

Pfeifer, N., Gorte, B., Winterhalder, D., Automatic Reconstruction of single trees from terrestrial laser scanner data, International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXV Part 5, Istanbul, Turkey, 2004.

Pinty, B., N. Gobron, J.-L. Widlowski, T. Lavergne, & M. M. Verstraete, Synergy between 1-D and 3-D radiation transfer models to retrieve vegetation canopy properties from remote sensing data, Journal of Geophysical Research, 2004, Vol. 109, D21205.

Prusinkiewicz, P. and Lindenmayer, A., 1990. The algorithmic beauty of plants. Springer-Verlag, New York.

Quaife, T., Lewis, P., De Kauwe, M., Williams, M., Law, B.E., Disney, M. & Bowyer, P., Assimilating canopy reflectance data into an ecosystem model with an Ensemble Kalman Filter, Remote Sensing Data Assimilation Special Issue, Remote Sensing of Environment, 2008, Vol. 112(4), pp. 1347-1364.

Rahman, H., B. Pinty, and M. M. Verstraete (1993) 'Coupled surface-atmosphere reflectance (CSAR) model. 2. Semi-empirical surface model usable with NOAA Advanced Very High Resolution Radiometer data', Journal of Geophysical Research, 98, 20,791-20,801.

Saich, P., Lewis, P. and Disney, M.I., 2003. Biophysical parameter retrieval from forest and crop canopies in the optical and microwave domains using 3D models of canopy structure. In: Geoscience and Remote Sensing Symposium, 2003: IGARSS '03: proceedings. Vol. 6. IEEE, Piscataway, 3546- 3548.

Schaepman, M.E., Ustin, S.L., Plaza, A.J., Painter, T.H., Verrelst, J. & Liang, S.,Earth system science related imaging spectroscopy--An assessment, Imaging Spectroscopy Special Issue, Remote Sensing of Environment, 2009, Vol. 113(Supplement 1), pp. S123-S137

S. Smolander and P. Stenberg, Simple parameterizations for the radiation budget of uniform broadleaved and coniferous canopies, Remote Sensing of Environment 94 (2005), pp. 355–363.

Thies, M., Pfeifer, N., Spiecker, H., Gorte, B., Three-dimensional reconstruction of stems for assessment of taper, sweep, lean based on laser scanning of trees, Scandinavian Journal of Forest Research, 2004, Vol. 19(6), pp. 571-581.

Verrelst, J., Schaepman, M., Koetz, B. & Kneubühler, M., Angular sensitivity analysis of vegetation indices derived from CHRIS/PROBA data, Earth Observations for Terrestrial Biodiversity and Ecosystems Special Issue, Remote Sensing of Environment, 2008, Vol. 112(5), pp. 2341-2353.

Verrelst, J., Schaepman, M.E., Malenovsky, Z. & Clevers, J.G.,Effects of woody elements on simulated canopy reflectance: Implications for forest chlorophyll content retrieval, Remote Sensing of Environment, 2010, Vol. 114(3), pp. 647-656.

J. Vos, L.F.M. Marcelis and J.B. Evers (2007) "Functional-Structural plant modelling in crop production: adding a dimension", In: Vos, J., Marcelis, L.F.M., de Visser, P.H.B., Struik, P.C. and Evers, J.B. eds. Functional Structural Plant Modelling in Crop Production. Springer, Dordrecht.

Wang, Y. P., Trudinger, C. M. & Enting, I. G., A review of applications of model–data fusion to studies of terrestrial carbon fluxes at different scales, Agricultural and Forest Meteorology, Vol 149, 2009, 1829-1842.

J.-L. Widlowski, T. Lavergne, B. Pinty, M.M. Verstraete and N. Gobron, Rayspread: A virtual laboratory for rapid BRF simulations over 3-D plant canopies. In: F. Graziani, Editor, Computational methods in transport, Lecture notes in computational science and engineering series Vol. 48, Springer Verlag, Berlin (2006), pp. 211–231 ISBN.10 3.540.28.122.3.

Widlowski, J.-L., Robustelli, M., Disney, M., Gastellu-Etchegorry, J.-P., Lavergne, T., Lewis, P., North, P., Pinty, B., Thompson, R. & Verstraete, M. The RAMI On-line Model Checker (ROMC): A web-based benchmarking facility for canopy reflectance models, Remote Sensing of Environment, 2008, Vol. 112(3), pp. 1144-1150.

Zhang, X., Friedl, M. A., Schaaf, C. B. & Strahler, A. H., Climate controls on vegetation phenological patterns in northern mid- and high latitudes inferred from MODIS data, Global Change Biology, 2004, 10, 1133–1145.

2.12. ACRONYMS

AIMES Analysis, Integration and Modelling of the Earth System
ALS Airborne Laser Scanning
ATBD Algorithm Theoretical Basis Documents
Cal/ValCalibration/Validation
CEC Commission of European Communities
CEOS Committee on Earth Observation Satellites
CFSP Common Foreign and Security Policy
CLiC Climate and Cryosphere
CLIVAR Climate Variability and Predictability
COPES Coordinated Observation and Prediction of the Earth System
DIME Data Evaluation for Model Integration
DIVERSITAS International Programme of Biodiversity Science
DUE Data User Element
ESA European Space Agency
ESDP European Security and Defence Policy
ESSP Earth System Science Partnership
EU European Union
GACP Global Aerosol Climatology Project
GCP Global Carbon Project
GCOS Global Climate Observing System
GCSS GEWEX Cloud System Study
GECHH Global Environmental Change and Human Health
GEFACS Global Environmental Change and Food Systems
GEWEX Global Energy and Water Cycle Experiment
GLASS Global Land/Atmosphere System Study
GLOBEC Global Ocean Ecosystem Dynamics
GLP Global Land Project
GMES Global Monitoring for Environmental Security
GPCP Global Precipitation Climatology Project
GWSP Global Water System Project (GWSP
IGBP International Geosphere-Biosphere Program
IHDP International Human Dimensions Program on Global Environmental Change
iLEAPS Integrated Land Ecosystem-Atmosphere Processes Study
IMBER Integrated Marine Biogeochemistry and Ecosystem Research
ISCCP International Satellite Cloud Climatology Project
ITT Invitation To Tender
LOC Land-Ocean-Cryosphere products
LOICZ Land-Ocean Interactions in the Coastal Zone
LUCID Land-Use and Climate, Identification of robust impacts
MRD Mission Requirements Document
NPOESS National Polar-orbiting Operational Environmental Satellite System
SOLAS Surface Ocean–Lower Atmosphere Study
SPARC Stratospheric Processes And their Role in Climate
SRB Surface Radiation Budget Project
T Task

TLS	Terrestrial Laser Scanning
WCRP	World Climate Research Program
WP	Work Package

APPENDIX - SITE DESCRIPTIONS

Site “Tharandt” (DE)

Location: The site is located approximately 25 km southwest of Dresden, Germany (50°57’49’’N, 13°34’01’’E, 380 m a.s.l.).

Type of Forest: *The main canopy is composed of 87 % coniferous evergreen (72 % Picea abies, 15 % Pinus sylvestris) and 13 % deciduous (10 % Larix decidua, 1 % Betula spec. and 2 % others) around the clearing.*

Fluxtower: yes

Field data	
Tree locations (relative or absolute) & species discrimination	yes (partly) / planned
Tree dimensions (height, crown base height, crown diameter)	yes
Leaf optical properties & bark optical properties (spectrum)	planned
LAI & fractional cover (canopy density)	yes (LAI2000 + Fisheye photo + forest assessments + derived from terrestrial laser scans)
Terrestrial laser scanning (single scans, merged scans)	13 terrestrial laser scans (merged), including a scan position from the fluxtower (used instruments: Riegl LMS-Z 420i, Faro LS 880)
Remote Sensing Data	
Imaging Sensors (airborne/spaceborne)	Airborne: Orthophotos (RGB, CIR) and oriented aerial images (resolution: 0.20 m) Spaceborne: Landsat TM, ETM+
Airborne Laser Scanning (discrete return/ full-waveform)	ALS: first & last echos (instrument: LMS_Q560, recorded: 2006), full-waveform
Other information	
Atmospheric measurements	Wind, Temperature, Radiation, Humidity, Precipitation (all below and above the canopy), CO_2/H_2O-Fluxes
Soil moisture/land cover	Soil moisture: continuous measurements in 4 depths Land cover: forest assessments

Site “Loobos” (NL)

Location: Veluwe, the Netherlands
52°10’04.286 N, 05°44’38.252 E
http://www.climatexchange.nl/sites/loobos/index.htm
Type of Forest:
Pinus sylvestris (89%) – 90 years old forest
3.3% Corsican pine, 2.3% birch, 1.3% Douglas fir, 0.6% oak and 3.5% open area
Fluxtower: yes, 25 m height
Size: 100 m by 100 m

Field data	
Tree locations (relative or absolute) & species discrimination	Yes (at least representative sample, not every bush)
Tree dimensions (height, crown base height, crown diameter)	Yes (otherwise additions planned)
Leaf optical properties & bark optical properties (spectrum)	planned
LAI & fractional cover (canopy density)	yes
Terrestrial laser scanning (single scans, merged scans)	Riegl VZ-400 measurements performed in July 2010; more planned in the future.
Remote Sensing Data	
Imaging Sensors (airborne/spaceborne)	June 2010: AISA Eagle + Hawk flight
Airborne Laser Scanning (discrete return/ full-waveform)	June 2010: airborne ALS full-waveform flight
Other information	
Atmospheric measurements	Global radiation, net radiation, diffuse radiation, air temperature, pressure
Soil moisture/land cover	Soil temperature 5 cm, soil temperature 30 cm Land cover map available

Site “Bily Kriz” (CZ)

Location: Bily Kriz, N 49 ° 30´17 ´´, E 18° 32´28´´, 893 m a.s.l.,
Type of Forest:
Picea abies(L), Karst (99%), *Abies alba,* Mill. (1%), 33 years old
Fluxtower: yes
Size: 50m x 100m - detailed measurements.

Field data	
Tree locations (relative or absolute) & species discrimination	Yes
Tree dimensions (height, crown base height, crown diameter)	Yes
Leaf optical properties & bark optical properties (spectrum)	Yes
LAI & fractional cover (canopy density)	Yes
Terrestrial laser scanning (single scans, merged scans)	No
Remote Sensing Data	
Imaging Sensors (airborne/spaceborne)	Yes (AISA Eagle, HyMap, CHRIS-PROBA) Planned airborne (fluorescence and hyperspectral sensors – ESA FLEX 2011)
Airborne Laser Scanning (discrete return/ full-waveform)	Planned (2010, discrete return)
Other information	
Atmospheric measurements	atmo station, planned atmo LiDAR
Soil moisture/land cover	25% avg. / Coniferous temperate (montaine) forest

Site "Stitna" (CZ)

Location: Stitna, N 49°02'08" E 17°58'17´´, 559 m a.s.l
Type of Forest: *fagus sylvatica L. (97%), Larix decidua (3%)*
105 years old
Fluxtower: yes
Size: 70m x 70m - detailed measurements.

Field data	
Tree locations (relative or absolute) & species discrimination	planned
Tree dimensions (height, crown base height, crown diameter)	Yes
Leaf optical properties & bark optical properties (spectrum)	planned
LAI & fractional cover (canopy density)	Yes
Terrestrial laser scanning (single scans, merged scans)	planned (without leafs - 2010) hhsh
Remote Sensing Data	
Imaging Sensors (airborne/spaceborne)	Yes (AISA Eagle) planned (AISA Eagle 2011)
Airborne Laser Scanning (discrete return/ full-waveform)	planned (discrete return - 2010)
Other information	
Atmospheric measurements	Atmo station
Soil moisture/land cover	25% avg. / Deciduous temperate (montaine) forest

Site “Järvselja: Birch” (EST)

Location: Järvselja birch stand, Estonia (58○ 16’ 49.81"N, 27○ 19’ 51.53" E)
Type of Forest: *): 49 years; birch (Betula pendula) 57%, common alder (Alnus glutinosa) 29.5%, aspen (Populus tremula) 11%*
Fluxtower: no
Size: 100m x 100m

Field data	
Tree locations (relative or absolute) & species discrimination	Yes
Tree dimensions (height, crown base height, crown diameter)	Yes
Leaf optical properties & bark optical properties (spectrum)	Yes
LAI & fractional cover (canopy density)	Yes
Terrestrial laser scanning (single scans, merged scans)	no
Remote Sensing Data	
Imaging Sensors (airborne/spaceborne)	UAVSpec, CHRIS
Airborne Laser Scanning (discrete return/ full-waveform)	Yes (discrete return)
Other information	
Atmospheric measurements	-
Soil moisture/land cover	-

Site "Järvselja: Pine" (EST)

Location: Järvselja pine stand, Estonia (58○ 18' 41.19" N 27○ 17' 48.63" E)
Type of Forest: *124 years; Pine (Pinus sylvestris)*
Fluxtower: no
Size: 100m x 100m

Field data	
Tree locations (relative or absolute) & species discrimination	Yes
Tree dimensions (height, crown base height, crown diameter)	Yes
Leaf optical properties & bark optical properties (spectrum)	Yes (bundle of leaves)
LAI & fractional cover (canopy density)	Yes
Terrestrial laser scanning (single scans, merged scans)	no
Remote Sensing Data	
Imaging Sensors (airborne/spaceborne)	UAVSpec, CHRIS
Airborne Laser Scanning (discrete return/ full-waveform)	Yes (discrete return)
Other information	
Atmospheric measurements	-
Soil moisture/land cover	-

Site “Järvselja: Spruce” (EST)

Location: Järvselja spruce stand, Estonia (58○ 17’ 43.0" N 27○ 15’ 22.0" E)
Type of Forest: *59 years; Picea abies & Betula pendula*
Fluxtower: no
Size: 100m x 100m

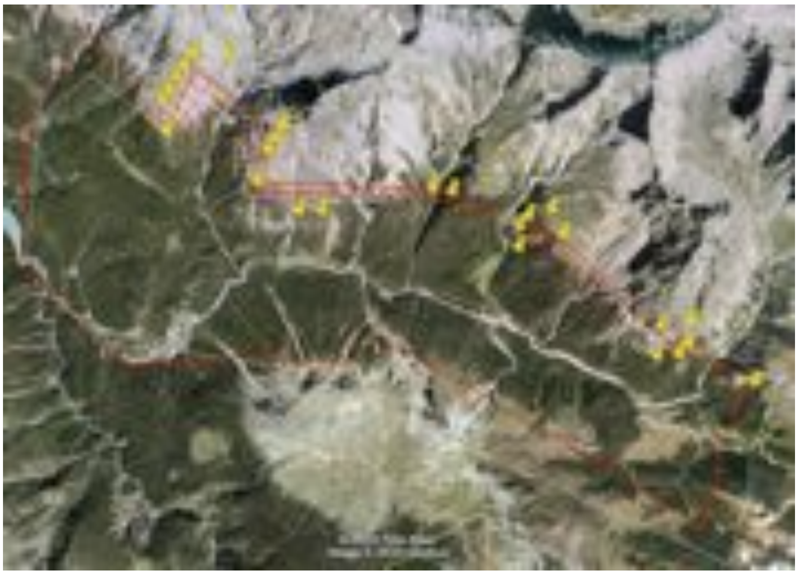
Field data	
Tree locations (relative or absolute) & species discrimination	Yes
Tree dimensions (height, crown base height, crown diameter)	Yes
Leaf optical properties & bark optical properties (spectrum)	Yes (bundle of leaves)
LAI & fractional cover (canopy density)	Yes
Terrestrial laser scanning (single scans, merged scans)	no
Remote Sensing Data	
Imaging Sensors (airborne/spaceborne)	UAVSpec, CHRIS
Airborne Laser Scanning (discrete return/ full-waveform)	Yes (discrete return)
Other information	
Atmospheric measurements	-
Soil moisture/land cover	-

Site "Lägeren" (CH)

Location: Lägeren, Switzerland (47.478260 N, 8.364289 E)
Type of Forest: *Nature-closed, non-managed, mixed forest (broadleaf and conifer)*
Fluxtower: yes
Size: 300 m x 300 m

Field data	
Tree locations	no (planned to be derived from ALS)
Tree dimensions (h,cbh,crown diameter)	no (planned to be derived from ALS)
Leaf optical properties (reflectance/ transmittance)	yes
Bark optical properties (reflectance)	yes
Terrestrial laser Scans (single scans, merged scans)	yes, 6 plots with 5 scans each
Remote Sensing Data	
Imaging Sensors (airborne/spaceborne)	APEX, Chris Proba
Airborne Laser Scanning (discrete return/ full-waveform)	yes, Riegl LMS Q560 full-waveform, both leaf-on and Leaf-off
Other information	
Atmospheric measurements	Sun-Photometer
Soil moisture/land cover	-

Site “Ofenpass” (CH)



Location: Swiss National Park, Switzerland (46.660470 N, 10.221450 E)
Type of Forest: *Coniferous, Pinus Montana, Pinus Cembra 90-120y*
Fluxtower: no
Size: 200 m x 200 m

Field data	
Tree locations	yes
Tree dimensions (h,cbh,crown diameter)	yes
Leaf optical properties (reflectance/ transmittance)	yes
Bark optical properties (reflectance)	yes
Terrestrial laser Scans (single scans, merged scans)	no
Remote Sensing Data	
Imaging Sensors (airborne/spaceborne)	APEX, Chris Proba
Airborne Laser Scanning (discrete return/ full-waveform)	yes, Riegl LMS Q560 full-waveform (2010) and Toposys Falcon II (first/last, 2002)
Other information	
Atmospheric measurements	Sun-Photometer
Soil moisture/land cover	-