Biomass Measurements from Space WIP DRAFT

A CEOS Information Paper for GFOI Countries

Goal. To accelerate the policy relevance and reporting benefits of planned biomass measurement missions through a 2-way dialogue with GFOI countries as to the data-stream capabilities and the country reporting needs.

Objectives:
1. To document the current and planned relevant missions
2. To support a layman's understanding of what these missions will actually provide by way of measurements, acquisition strategy, coverage, duration, resolution, accuracy etc.
3. To provide a clear narrative for the evolution of the data over time – and how the key characteristics might evolve.
4. To put the data in context of the constraints and features of the reporting imposed on countries by different frameworks and mechanisms, eg through IPCC methods, or for results-based payments.
5. To provide a foundation for the proposed dialogue and the main substance therein.

Draft contents
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Planning notes:

Questions:

Contacts:
- CEOS LPV Biomass - John Armston Mat Disney and Laura Duncanson

More contacts in LPVE presentation: TLS, good practices for AGB field estimates, airborne data scaled to space, models to maps, some policy.

Notes and quotes

Analysis of the global carbon cycle shows that the annual emissions of carbon from fossil fuels and land-use change are larger than the annual accumulations of carbon in the atmosphere and oceans. This suggests a largely unknown terrestrial sink for carbon, which has never been measured.
NOAA - Vegetation biomass is a crucial ecological variable for understanding the evolution and potential future changes of the climate system. Photosynthesis withdraws CO_2 *from the atmosphere and stores carbon in vegetation in an amount comparable to that of atmospheric carbon. Currently, biomass is a net sink of carbon with a net flux to the land of 2.6 ± 1.2 Pg C yr −1, partially offset by changes in the amount of biomass due to deforestation and other land-cover changes acting as a net source of carbon of 1.1 ± 0.8 Pg C yr −1 (values from IPCC, 2013). Thus, biomass changes provide a net sink of about 1.5 Pg C yr −1, which is equivalent to approximately 20 % of* CO_2 *emissions from fossil fuels. Vegetation systems have the potential either to sequester more carbon in the future or to contribute as an even larger source. Depending on the quantity of biomass, vegetation cover can have a direct influence on local, regional and even global climate, particularly on air temperature and water vapour. Therefore, a global assessment of biomass and its dynamics is an essential input to climate models and mitigation and adaptation strategies. The non-climate applications of biomass information are legion, as forest biomass is a major source of energy and materials across the planet, as well as being related to issues such as biodiversity, water quality and soil erosion.*

Biomass, for the purposes of CEOS LPV, is defined as the above ground standing dry mass of live or dead matter from tree or shrub (woody plant) life forms, expressed as a mass or mass per unit area. We are not considering below ground, woody debris or non-woody biomass, although we acknowledge these are also important components of the carbon cycle. Below ground biomass is not directly detectable from Earth Observing satellites, and non-woody and woody debris biomass are outside the scope of our protocol.

***Relevant Units**:*

Above Ground Biomass (AGB) is expressed as a mass, typically kg (kilogram), Mg (megagram or metric tonne) or Pg (petagram, or 10^9 *tonnes).*

Above Ground Biomass Density (AGBD) is expressed as a mass per unit area, typically Mg/ha

Introduction

Above ground biomass refers to woody vegetation on the Earth's surface, and is a key component to the biosphere, the Carbon cycle, and climate variability. Understanding the size and distribution of these vital Carbon stores, as well as their change over time, is important to our understanding of the Earth as a system. Mapping of biomass both spatially and temporally can enable governments and organisations to determine forest stock, monitor logging, land use and clearing, and can assist reporting efforts for programs such as REDD+.

A combination of improvements in techniques and technology and the increasing importance of these measurements has prompted several dedicated satellite missions to measure Above Ground Biomass. Each mission will provide a unique data product, with various implementations of Synthetic Aperture Radar and LiDAR instruments across the upcoming satellites. A common goal of these missions is to *quantify the role of terrestrial biomass in the terrestrial carbon sink to constrain climate and Earth system modeling and improve understanding of changes through time.*

Ground based forest mapping is routine practice for nations around the world, and recent satellite technology has allowed sustained, systematic and global mapping and classification of surface cover. These measurements have been used to create forest maps from satellite data in a standardised manner that allows comparison between the extent and type of forest plots around the world. However, these previous satellite missions have only determined the type of cover, and have not sought to determine the size and shape of the vegetation cover. Combining new satellite based measurements of size and shape with knowledge of tree properties such as species and age can be used to determine the weight, and therefore magnitude of Carbon sequestration of forest plots.

Ground and airborne investigations in measuring the size and shape, or the *allometric* properties of vegetation have been ongoing for several years in order to refine measurement and analytical techniques and to prepare validation sites. These investigations can be used to prepare an understanding of the measurement process, while also maturing the instruments and methods to be used by upcoming satellite missions.

Preserving and increasing existing forests is understood to be vital in combating Carbon emissions and sustaining our planets diverse biosphere. International policy has been implemented to incentivize the preservation of forests, such as the UNFCCC REDD+ program, and the importance of ongoing forest monitoring is identified in the United Nations Sustainable Development Goals 13 and 15. Satellite Earth Observations aim to enable monitoring, reporting and verification of forest cover and change.

This information paper will provide an overview of the data-stream capabilities of Biomass measurements, and how these can be used to support country reporting requirements. This paper will also detail current and future missions returning Biomass data, review the technology onboard each satellite, and summarise their expected performance. It will also describe the expected evolution of these missions and their data products over time. By reviewing the expectations of these Biomass missions, it is hoped this paper can support making informed decisions by countries for forest monitoring efforts.

Policy context of biomass measurements

UNFCCC (United Nations Framework Convention on Climate Change) identified biomass as an essential climate variable

The lack of accurate spatial forest biomass data was recognised as one of the greatest uncertainties in the global carbon budget by the Intergovernmental Panel on Climate Change, IPCC.

REDD+ Reducing Emissions from Deforestation and Forest Degradation

SDG Sustainable development goals

- *tropical forests are the focus of current forest conservation and management programmes and initiatives driven by the United Nations Framework Convention on Climate Change (UNFCCC), such as UN-REDD, the Forest Carbon Partnership Facility and the Global Forest Observations Initiative.*

Why biomass measurements are needed

Country requirements now and in future

Instrument technology

SAR

Synthetic Aperture Radar are a class of active microwave instrument that can be used for imaging the Earth's surface. As an active instrument, they require substantial power to operate, often with low duty cycles. However, active instruments of this type are unimpeded by cloud and smoke, and are capable of sensing at night.

One important differentiator of SAR instruments is the electromagnetic frequency used for acquisitions. The wavelengths used in SAR are the P-band (0.3-1 GHz), L-band (1-2 GHz), S-band (2-4 GHz), C-band (4-8 GHz), and X-band (8-12.5 GHz). Important applications exist for measurements in each of these bands, and continuity also varies across SAR wavelengths. In general, SAR instruments are sensitive to objects of the same size as the radar wavelength, and larger. Objects smaller than the wavelength gradually become transparent/invisible to the radar as they decrease in size.

For all radio waves, frequency is inversely proportional to wavelength - that is higher frequency waves have shorter wavelengths. The terms can be used interchangeably when describing an instrument. Band refers to the part of the radio spectrum the instrument is sensitive to.

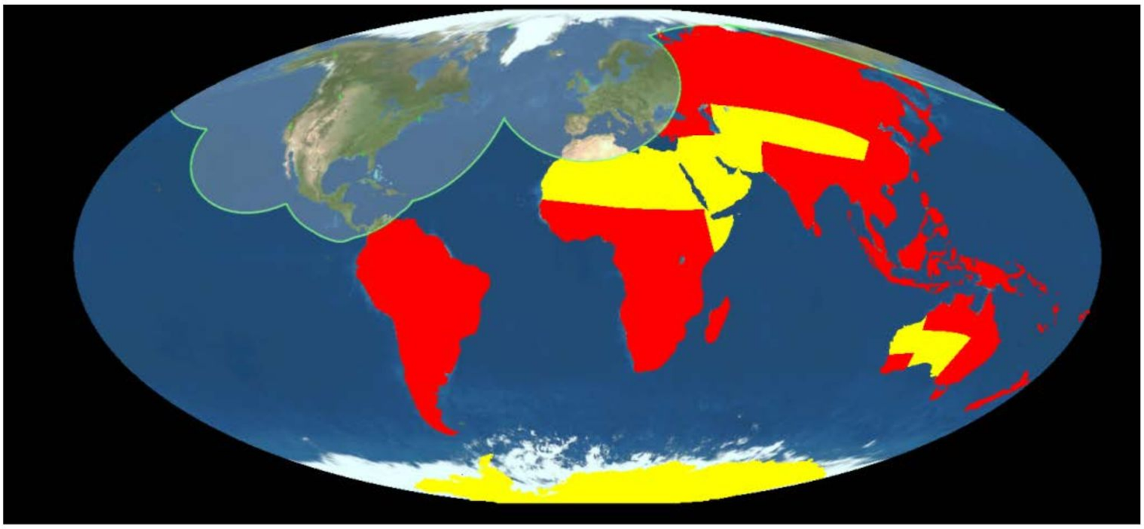
The wavelength of a wave dictates the kind of material that will interact with it, with shorter wavelengths having lower penetrative ability than longer wavelengths.

This means a short wavelength SAR signal will be reflected by leaves, while long wavelength SAR can penetrate the canopy, to be reflected by trunks and the ground.

P-band SAR

P-band has a wavelength of around 70 cm, which will make it the longest microwave wavelength in space when the Biomass mission launches. Despite having no history of measurements from space, P-band SAR has extensive airborne experience with the recent NASA AirMOSS project investigations of the subcanopy and subsurface. With its long wavelength, P-band SAR penetrates through the foliage and returns information on large forest structure, and soil moisture.

P-band will not be allowed to operate over the US/UK/etc (diagram) due to the ITU regulations on P-band operations within line of site of registered Space Object Tracking Radar ground stations, located in the North America and Europe.


(Red = Primary objective coverage mask, Yellow = Secondary objective coverage mask)

L-band SAR

L-band (23.5 cm wavelength) is currently the longest wavelength used in spaceborne SAR. It penetrates leaves and foliage, providing information about forest structural parameters such as branches and stems. Applications include distinguishing between forest and non-forest, direct detection of above-ground (dry) biomass up to 100-150 tons/ha, and forest cover change detection using time series. L-band is unique in its capacity to detect inundation in flooded forests even below a closed canopy, and is used for the mapping of ice in combination with other SAR wavelengths which are sensitive to different layers of ice. Other applications include rice paddy monitoring, mapping of paleo-geology in arid deserts, and to a lesser extent ocean applications.

S-band SAR

S-band (12 cm) has had very limited application in Satellite Earth Observations. It is reasonable to predict it will return observations similar to C-band and L-band observations, due to its wavelength. A recent paper investigated airborne backscatter S-band SAR for recovering forest biophysical properties, with reference to the upcoming NovaSAR-S mission. Findings from this investigation were:

Notes from Ningthoujam, R.K., Balzter, H., Tansey, K., Morrison, K., Johnson, S., Gerard, F., George, C., Malhi, Y., Burbidge, G., Doody, S. and Veck, N., 2016. Airborne S-band SAR for forest biophysical retrieval in temperate mixed forests of the UK. Remote Sensing, 8(7), p.609.

- *Studied airborne (AirSAR) S-band* ***backscatter*** *in anticipation of NovaSAR-S, across mixed temperate forest in the UK.*
- *"S-band backscatter was found to have high sensitivity to the forest canopy characteristics across all polarisations and incidence angles. This sensitivity originates from ground/trunk interaction as the dominant scattering mechanism related to broadleaved species for co-polarised mode and specific incidence angles." … "The conclusion is that S-band SAR data such as from NovaSAR-S is suitable for monitoring*

forest aboveground biomass less than 100 t/ha at 25 m resolution in low to medium incidence angle range."

- *In all forest types, microwaves emitted at longer SAR wavelengths (L- and P-band) are more sensitive to forest AGB (due to sampling woody vs leaves). This has been largely related to the cross-polarised channels (HV or VH) which have comparatively lower returns but generally increase asymptotically to the amount of woody biomass.*
- *SAR signals at shorter wavelengths (C- and X-bands) are known to saturate rapidly with forest biomass due to lower canopy penetration. Further, sensitivities of forest biomass levels from multi-frequency SAR data (C-, L- and P-band) have also been reported from different forest types, e.g., coniferous (Les Landes and Duke) and broadleaved evergreen (Hawaii) achieving around 20 t/ha, 40 t/ha and 100 t/ha saturation levels respectively.*
- *"For coniferous stands, simulated total S-band radar backscatter is lower than for a broadleaved canopy, being dominated by the total crown (direct) component across the incidence angle range for both co- and cross-polarisations. This demonstrates that the S-band radar signal is unsuitable for penetration within the conifer canopy, possibly due to the randomised diffuse scattering from needles and small branches and hence lower volume scattering."*
- *Comparing all polarisations, it is seen that S-band co-polarised backscatter data is better suited for biomass estimation than the cross-polarisation backscatter.*
- *"The results show that S-band SAR data from NovaSAR-S will likely be suitable for deriving forest structure information including aboveground woody biomass for temperate mixed forest…"*

C-band SAR

The main C–band (5.6 cm wavelength) applications are in ocean and ice monitoring, however it does have use for AGB. The C-band wavelength does not penetrate a closed forest canopy and therefore provides limited information about forest structure, however it provides more information in open forest environments such as woodlands where the signal can interact with the ground, stems and branches. Rice paddy monitoring is also an established C-band application. Very short repeat C-band observations (~3 days) are useful for the monitoring of deformation caused by earthquakes and volcanoes, while longer time series (1-2 month baseline) have proven useful for detection of deforestation and logging roads.

X-band SAR

The characteristics and usage of X-band (3.1cm wavelength) are similar to C-band – however it provides higher spatial resolution due to its shorter wavelength. This has proven useful for the detection of selective logging and forest degradation. X-band SAR is also frequently used for military applications, and has a rapidly growing commercial interest.

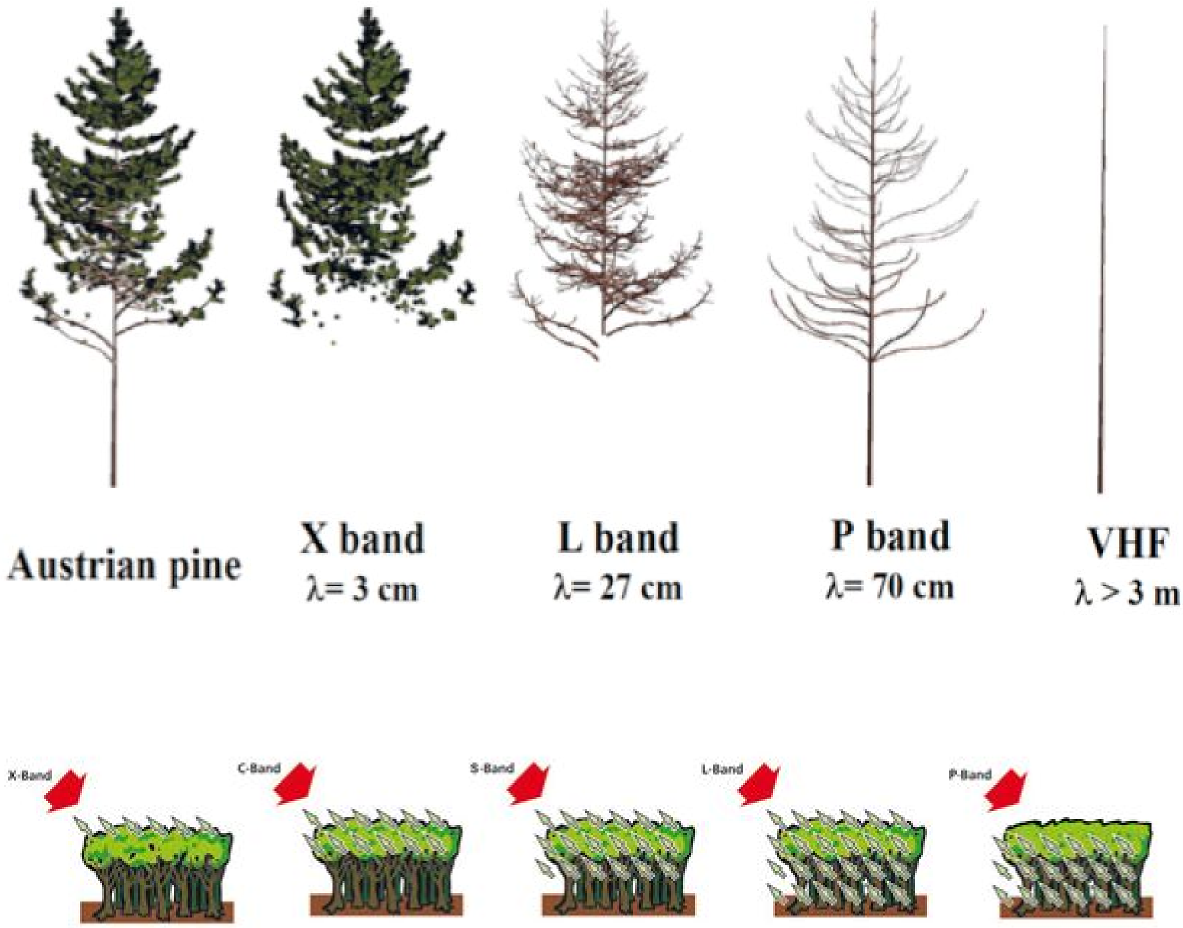


Figure 1 – Scattering Centre of the different layers of vegetation for Microwave SAR bands.

LIDAR

LIDAR, or Light Detection and Ranging, is a type of active instrument that uses Laser emitters to sample the distance to an object. These instruments are able to return very accurate distances and have been used for many years, for example in the GLAS and ICESat missions. For biomass, the laser will sample the distance to each scattering centre – leaves, branches, trunks and the ground, as the laser can pass through gaps in each layer. This makes it possible to return information about structure of these layers, however it is not an imager, and analysis of a response curve will be required to generate AGB maps.

Hyperspectral classification

It is important to note that while *vegetation information* can be returned by hyperspectral and multispectral imagery, it cannot be used to return *Above Ground Biomass measurements*. It may however become an important constraint in combining satellite data to refine Biomass models. Spectral measurements can be used to classify cover type, such as grass, different forest types, etc. This may then inform models regarding expected types of vegetation, and densities, etc? eg, pine forest vs eucalypt, etc? Will research if this is done.

Measurement techniques

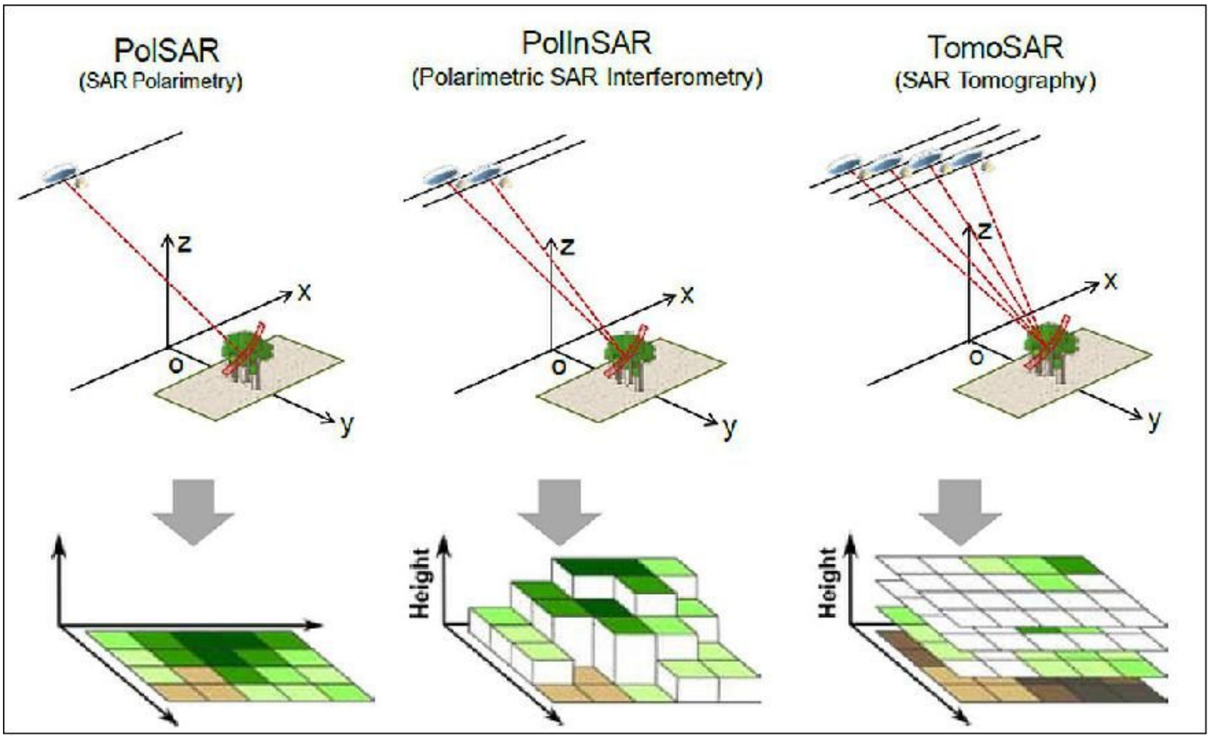
This section will introduce each characteristic that will be mentioned in the satellite mission section, and explain its relevance. An understanding developed here will help analyse each mission. Try to keep this section general and don't cloud with numbers and comparisons.

- *Backscatter*
  - *saturation*

LIDAR

DEM derived - eg last year the forest was 7 m high, now it's 8 m, the new volume is ___ m3

Simple comparisons Footprint - make a nice comparative figure for footprint sizes AND repeat frequency. Sample rate, coverage (P band issue), mission duration/continuity. What next? Data access? Accuracy?



1) ***Horizontal mapping:*** *In polarimetric mode, after calibration and correction for ionospheric effects, each BIOMASS pixel measures the scattering matrix, from which the* ***backscattering intensity*** *will be derived in each of the linear polarization combinations, i.e.* ***HH, VV, HV & VH****, where H and V stand for horizontal and vertical transmitted and received signals. For a forest canopy, the P-band radar waves penetrate deep into the canopy, and their interaction with the structure of the forest (through volume scattering, surface scattering or double bounce scattering mechanisms) differs between polarizations. P-band SAR is particularly sensitive to large forest constituents, such as the trunk and large*

branches, where most of the biomass resides, and polarizations can be chosen to minimize the contribution from the ground and effects arising from topographic and soil moisture variation. ***Hence P-band polarimetric measurements can be used to map AGB (Above Ground Biomass****), as demonstrated from airborne data for temperate & boreal forests and tropical forest.*

2) ***Height mapping****: Using repeat revisits to the same location with controlled inter-track distances, the BIOMASS SAR system will measure the* ***polarimetric complex interferometric correlation*** *between image pairs, from which it is possible to estimate the height of scattering in the forest canopy as a function of polarization (****PolInSAR)****.This allows canopy height to be derived, assuming a model for the vertical structure of scatterers in the forest. Numerous airborne experiments over temperate, boreal and tropical test sites have shown that forest height can be mapped with accuracy comparable to that of airborne lidar. A crucial factor here is that at the* ***long wavelength used by BIOMASS, temporal coherence is preserved over much longer timescales than, for example, at L-band****. This is because BIOMASS is sensitive to* ***larger structures in the canopy, which more are more stable****; in addition, the longer wavelength makes the phase less sensitive to small motions of the dominant scatterers. BIOMASS will be first spaceborne radar sensor providing large scale height maps using PolInSAR, although application of the technique from space has been demonstrated using Shuttle Imaging Radar (SIR-C) L-band data.*

3) ***3-D mapping****: The P-band frequency used by BIOMASS is low enough to ensure penetration through the entire canopy, even in dense tropical forests. As a consequence, resolution of the vertical structure of the forest will be possible using tomographic methods from the multi-baseline acquisitions to be made by BIOMASS. This is the concept of* ***SAR tomography****, which has been implemented with airborne systems and will be available for the first time using space with the BIOMASS mission. When the vertical resolution is less than half the forest height, it is possible to split the vertical distribution of the backscatter intensity into a number of layers, without assuming any prior knowledge about the forest vertical structure. As expected, the bottom layer contains mainly ground scattering and the backscatter from this layer is very weakly correlated with AGB. However, in two different tropical forest sites in French Guiana, the backscatter from a layer at about 30 m above the ground was found to be strongly correlated with AGB, up to biomass densities of 450-500 t/ha, allowing the production of wide area biomass maps. Findings from airborne data are expected to carry across to BIOMASS, despite the coarser spatial and vertical resolution available in BIOMASS tomography.*

Above ground biomass (AGB) the total biomass (living matter) of all growing trees per unit area. The measurement of AGB relies upon two properties, the volume and density. Satellite instruments will return the volume by measuring the dimensions of trees within a forest plot. Density will rely upon a priori information developed from ground studies. While the expected accuracy of the resulting biomass measurement is relatively low (TANDEM-L expects 20%), this will be a vast improvement on the current limited understanding of the global distribution of biomass and a step towards operational biomass monitoring.

Canopy Height

- Lidar
- PolInSAR (Polarimetric InSAR)
- Interferometric SAR (single polarization) – requires bare earth DEM

3-D Canopy Structure (stand density, canopy layers)

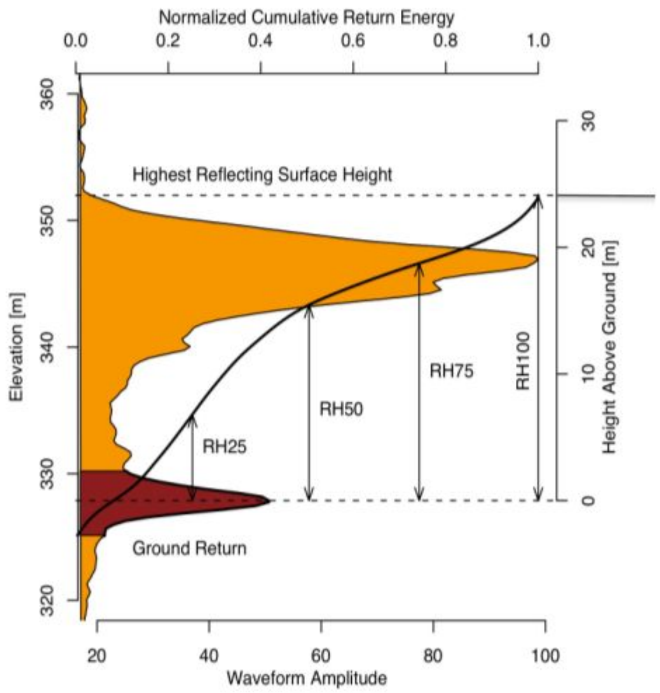
- Lidar – RH measures
- SAR Tomography (Bistatic SAR, Repeat pass InSAR)

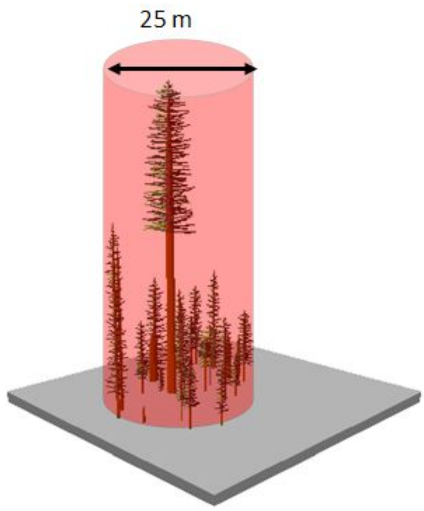
Biomass

- Correlation with SAR backscatter
- Correlation with Lidar RH measures
- Correlation with canopy height (InSAR, PolInSAR)
- Correlation with canopy structure (SAR tomography)

Below Ground Biomass - relevant?

- Allometry





- Figure 2 – LIDAR response curve. The height of a tree can be inferred from the distance between the first reflecting surface – the canopy, and the last – the ground.
- *We cannot weigh trees in forest plots Instead, we measure stem diameters and heights, and apply **allometric equations** to estimate biomass*
-
- *The determination of forest biomass is performed indirectly via the measurement of the vertical forest structure. A decisive structure parameter is thereby the forest height. In order to record the forest height globally one has to use*
- *- a long wavelength radar signal that penetrates the forest down to the ground,and*
- *- polarimetric SAR interferometry for determining the height.*
- *The method is based on a simplified forest model and on the fact that with SAR polarimetry the ground, trunk and canopy can be resolved separately. With aid of SAR interferometry the scattering as a function of height can be determined. From these, the forest height can be computed with great accuracy (10%). Allometric equations then used for biomass calculation (20%)*
-

Ground measurements and validation

Ground based lidar, classification, etc.

Terrestrial Laser Scanning (TLS) is an emerging technique for more accurate estimates of in situ biomass

Much work has been performed on the ground in this area, using ground based LIDAR, airborne instruments, validation site inspections, etc.

Satellite missions

Objectives:

- *To document the current and planned relevant missions*
- *To provide a clear narrative for the evolution of the data over time – and **how the key characteristics might evolve.***

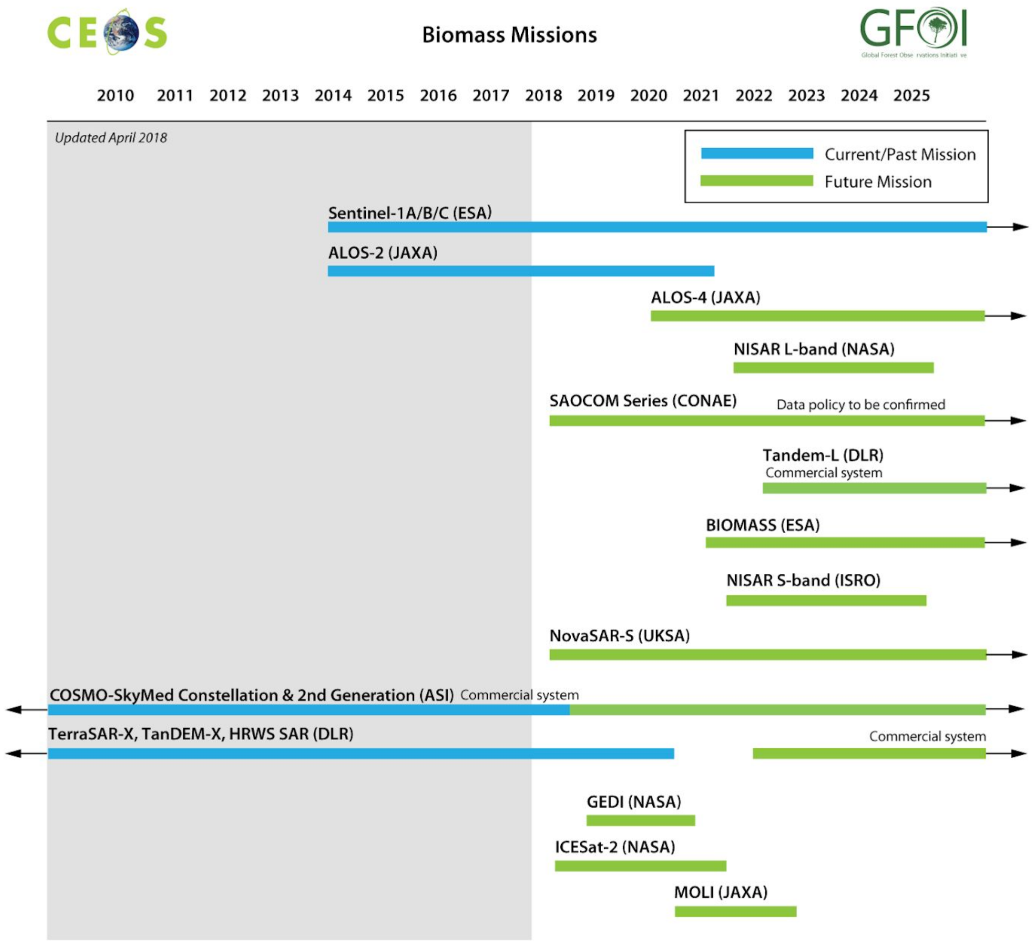
Terrestrial Ecosystem Structure is an “Earth System explorer” category in the 2017 decadal survey. 3D structure of terrestrial ecosystem including forest canopy and above ground biomass and changes in above ground carbon stock from processes such as deforestation and forest degradation. Note pg 369 of survey

Utilise biomass section from JAXA EO doc. Try to mention how and why and if data will improve with newer satellites. ensure logical time order to mission listings

eg satellites: http://www.gfoi.org/space-data/phasing/

[Relevant Missions]()

Mission	Sensor Type	Dates	Biomass Focus	Limitations
Tandem-X (DLR)	X-band, Bistatic, Polarimetric SAR	2010-20??	Mature forests	Limited ground coverage
ALOS PALSAR-2 (JAXA)	L-band, Polarimetric SAR	2014-20??	All ecosystems with AWB < 100 t/ha	Limited data availability as JAXA does not have open data policy, soil moisture impacts
SAOCOM A/B (CONAE)	L-band, Polarimetric SAR	2017-2022	All ecosystems with AWB < 100 t/ha	Limited data availability to be negotiated with CONAE, soil moisture impacts
IceSAT-2 (NASA)	Waveform Lidar	2018(?)-2021	Mature and regrowing forests, woodlands	Because of its 3 m height resolution, limited to taller forests, 1000 m grid
GEDI (NASA)	Waveform Lidar	2019-2021	Mature and regrowing forests, woodlands	Limited to the area between 60 N to 60 S, 500 m grid
SAOCOM-CS (ESA)	L-band, Bistatic, Polarimetric SAR	2019 to 2022	Boreal forest mission, but also all ecosystems with AWB < 100 t/ha	Data availability TBD, soil moisture impacts
Biomass (ESA)	P-band, Polarimetric SAR	2019-2022	Tropical forest mission, but also all ecosystems with AWB > 100 t/ha	Cannot collect data over HNL regions with UHF transmission restrictions, soil moisture impacts
NISAR (NASA)	S- and L-band, Polarimetric SARs	2021-2024	All ecosystems with AWB < 100 t/ha	Soil moisture impacts



Heritage and 2018 status

Historical missions, etc

- *What sensors have been flown in space? (Instrument and algorithm maturity)*
- *What data are currently available? (Data policy, date ranges, science outcomes/understanding)*
- *What resolution is typical, what do we expect in the future?*
- *What are some existing applications? (Ongoing programs, cal/val?*

Measurements with the ability to generate Biomass products have been available for some time. A brief overview of these missions is presented.

GLAS (NASA, 2003, LIDAR)

Geoscience Laser Altimeter System. continuous global observations of Earth

ALOS PALSAR (JAXA, 2006, L-band)

- The mapping of land areas (without the need for ground control points) for cartographic applications
- The monitoring of disasters on a global scale (as a complement to the capabilities of other spacecraft
- Resource surveying.
- QPol

EOL 2011.

ALOS-2 PALSAR-2 (JAXA, 2014, L-band)

EOL 2019

ALOS 2 is an L-band SAR mission by JAXA, currently in service and providing imagery on a commercial basis since 2014. ALOS-2 is regarded as the best SAR instrument flying currently, however the commercial access policy severely inhibits uptake and use. It has 3 operating modes, with a maximum resolution of 1x3 m at a swatch of 25 km, single polarisation, and a maximum swath at 490 km with a resolution of 100 m, dual polarisation. The three

- Spotlight mode
    - The most detailed observation mode with 1 by 3 meters resolution (observation width of 25 km), Single choice of Polarisation.
- Strip Map mode
    - A high-resolution mode with the choice of 3, 6 or 10 meters resolution (observation width of 50 or 70 km), Up to Dual Polarisation
- ScanSAR mode
    - A broad area observation mode with 100 m or 60 m resolution (observation width of 350 km or 490 km), up to Dual Pol.
- Quad Pol available at 6 m or 10 m resolution, observation width 40-50 km and 30 km.

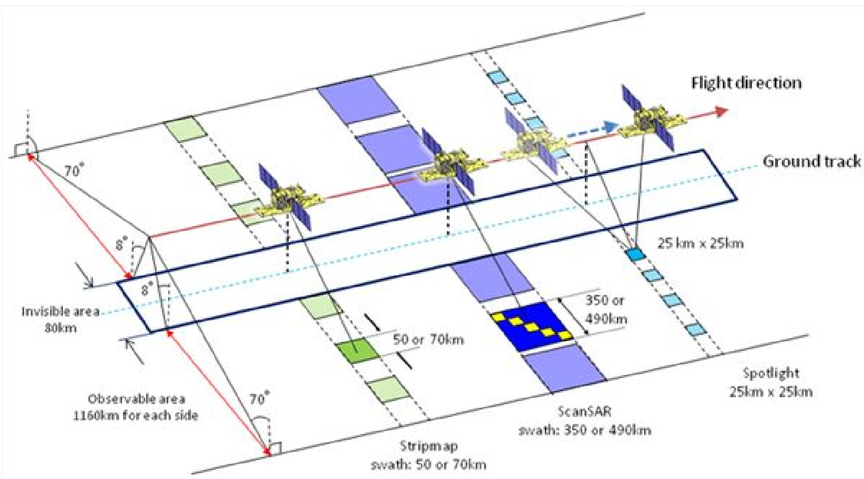


Figure 1 – eg ALOS-2 “nitty gritty” – note blind spot and example of gaps.?

ICESAT (NASA, 2003, LIDAR)

Laser lifetime issues, changed from continual measurement to several 30 day campaigns 2 to 3 times per year. EOL 2009

TanDEM-X (DLR, 2010, X-band)

EOL 2020

The primary objective of TanDEM-X was the generation of a highly accurate, global coverage DEM. The key feature of Tandem-X is the bistatic design of the mission, utilising the TerraSAR-X satellite in a tandem formation. This allows instantaneous, along-track interferometric measurement. Other than topographical maps, another noted application of TanDEM-X is the 3D surveying of forest structure, with the wavelength of X-band sensing the tree top foliage, which can be used for volume calculation.

TanDEM-X has a maximum resolution of 25 cm at 4 km swath, and a maximum swath of 270 km at 40 m. The global DEM product has a spatial resolution of 12 m.

- Staring SpotLight: up to 25 cm resolution (scene size depending on the incidence angle, e.g. 4 km (width) x 3.7km (length) at 60°
- SpotLight: up to 1 m resolution, 10 km (width) x 5 km (length)
- StripMap: up to 3 m resolution, 30 km (width) x 50 km (length)
- ScanSAR: up to 18.5 m resolution, 100 km (width) x 150 km (length)
- Wide ScanSAR: up to 40 m resolution (scene size up to 270 km (width) x 200 km (length)

Land Cover and Vegetation: ***High resolution radar interferometry allows the assessment of three dimensional canopy architectural descriptors*. *These descriptors, such as crown size statistics, vertical distribution of the crown layer, gap occurrence intensity, etc., allow forest degradation, regeneration stage mapping or natural regeneration mosaic mapping.*** *Information on the forest state is needed for land use planning, forest rehabilitation planning, forest protection, fire prevention and nature conservation. Better knowledge of the forest state is of importance for forest management and forest ecology (biodiversity). The TanDEM-X mission will provide a unique data set in terms of resolution and temporal consistency to satisfy these requirements. Requirement: High spatial resolution DEMs for forest state assessment (upper layer).*

Pol-InSAR*: DEM optimisation using polarisation diversity helps to minimise interferometric phase variance and hence to achieve high quality interferograms as well as high resolution DEMs over land surfaces.* ***Estimating the vegetation bias in X-band SAR interferometry and combining it with data from other sensors (L-band air and space borne SAR) is essential to extract maps of forest and agriculture vegetation structure parameters such as height, canopy layering etc.*** *These application products require a sensor capable of quasi single pass polarimetric SAR interferometry. The TanDEM-X mission provides such a novel sensor configuration and will deliver exemplarily first DEMs without a reduced vegetation height offset in forest areas and important crop parameters needed for an efficient agricultural management. Requirement: Demonstration of the estimation of volumetric biases and short vegetation parameters.*

Data Policy? - Seems science application limited - minor fee, but non-commercial use. "The processed TanDEM-X data may only be used for scientific, non-commercial purposes."

Note drawback: Need to shift satellite helix orbit to adjust for different acquisition modes. DEM is highest priority and individual scenes are lower priority.

In this paper we present the first global forest/non-forest classification map from TanDEM-X interferometric SAR data at X band, based on the exploitation of the coherence-derived volume correlation factor, which quantifies the amount of interferometric decorrelation caused by volume scattering phenomena.

- Polarimetric, Interferometric SAR
- Bi-static Mode
- Pursuit Mono-static Mode
- Along-track Interferometry, ATI Mode

COSMO-SkyMed (ASI, 2007, X-band)

The primary feature of COSMO SkyMed is it's 4 satellite constellation, with mean revisit times as low as 3 hours. Multiple satellites also enable interferometric products at low delay. Initially with a lifetime of 7 years, the constellation is still operational and providing X-band imagery on a commercial and scientific basis.

Sentinel 1A/1B

RADARSAT-1, (1995-2013) RADARSAT-2 (2007-)

Forestry (boreal and tropical): Detect clear cuts, update forest inventories, map depletions, map forest fires, assess regeneration, monitor land use changes

RADARSAT Constellation

Outlook and evolution

SAR is a rapidly growing field in Earth Observation, especially in commercial X-band provision. For biomass, L-band will see several dedicated missions, while S-band and P-band will see one each, on NISAR and BIOMASS respectively. LIDAR Biomass will also see two missions, with MOLI and GEDI. Satellite missions with relevance to Biomass are detailed here.

SAOCOM series (CONAE, 2018-2024, L-band)

CONAE plans four (launch 2018, 2019, 2023, 2024) L-band SAR missions, which, when operating in pairs, will provide a revisit time of 8 days globally;

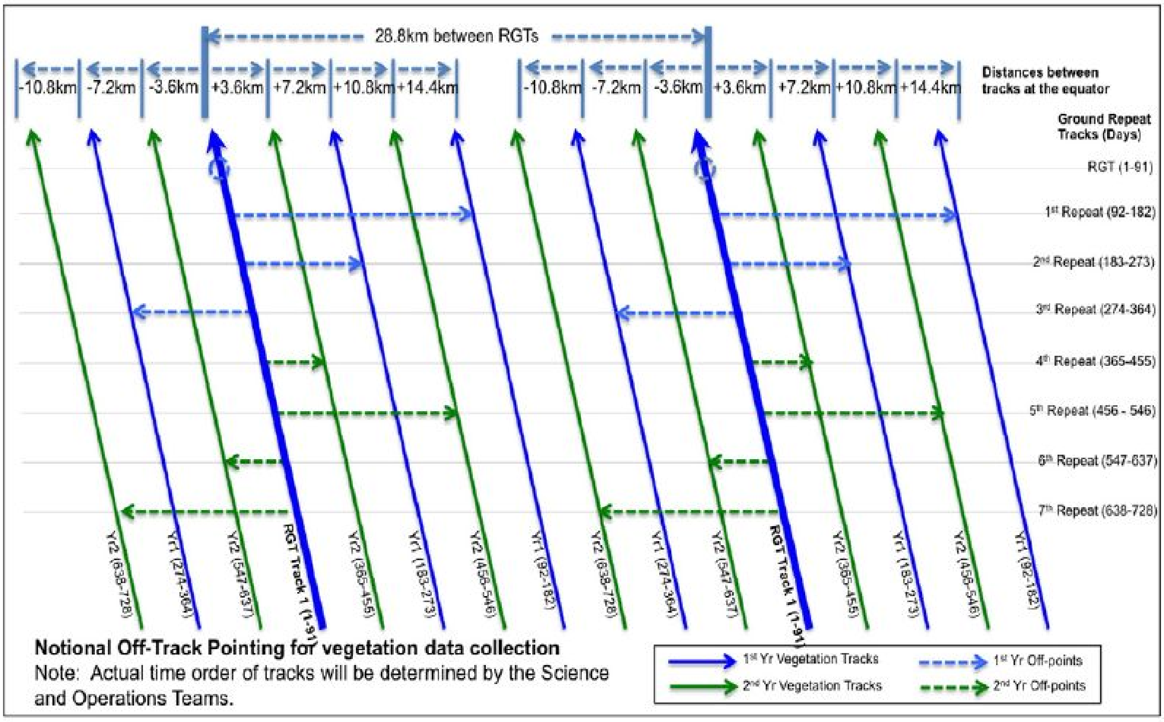
CSG Series (ASI, 2018, X-band)

Continuation of COSMO SkyMed.

ICESAT-2 (NASA, 2018, LIDAR)

Follow on from ICESAT, 5 year life. Primary measurement will be ice-sheets change. Biomass measurement will be Laser Altimetry based canopy depth.

- *Measure vegetation canopy height as a basis for estimating large-scale biomass and biomass change.* - This is the lowest importance measurement of ICESat-2.
- ICESat-2 shall produce elevation measurements, that enable independent determination of global vegetation height, with a ground track spacing of <2 km over a 2-year period. This requirement is deleted in the Threshold Requirement.
- Synergistic use of ICESat-2 data with other space-based mapping systems is suggested to extend the use of ICESat-2 data.
- This increased repetition rate will result in a 0.7 m separation for each laser pulse on the surface. This is ideal for rough and heterogeneous terrain such as glaciers or sea surface heights where the minimal gaps in along-track measurements will provide a higher fidelity of the topography.
- **For mid-latitudes operational off-nadir pointing at different angles will generate a dense grid of measurements over a two-year period. These operational maneuvers are in response to the requirement h) in Section 2 that requires a track density of 2 km over two years. At the equator this leads to the following ground track pattern for the first two years of the mission This will enable dense sampling of canopy height measurements and thus provide carbon inventory during the first two years of the mission.**



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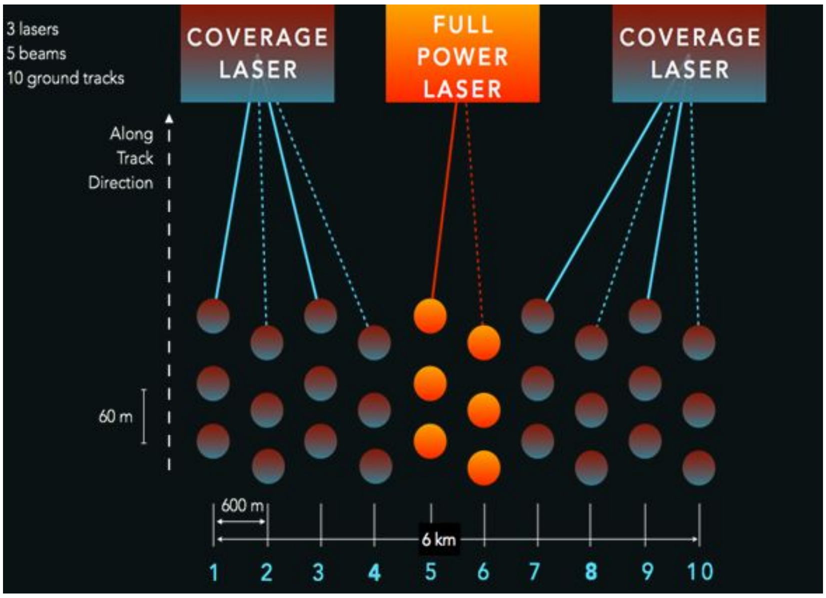
GEDI (NASA, 2019, LIDAR)

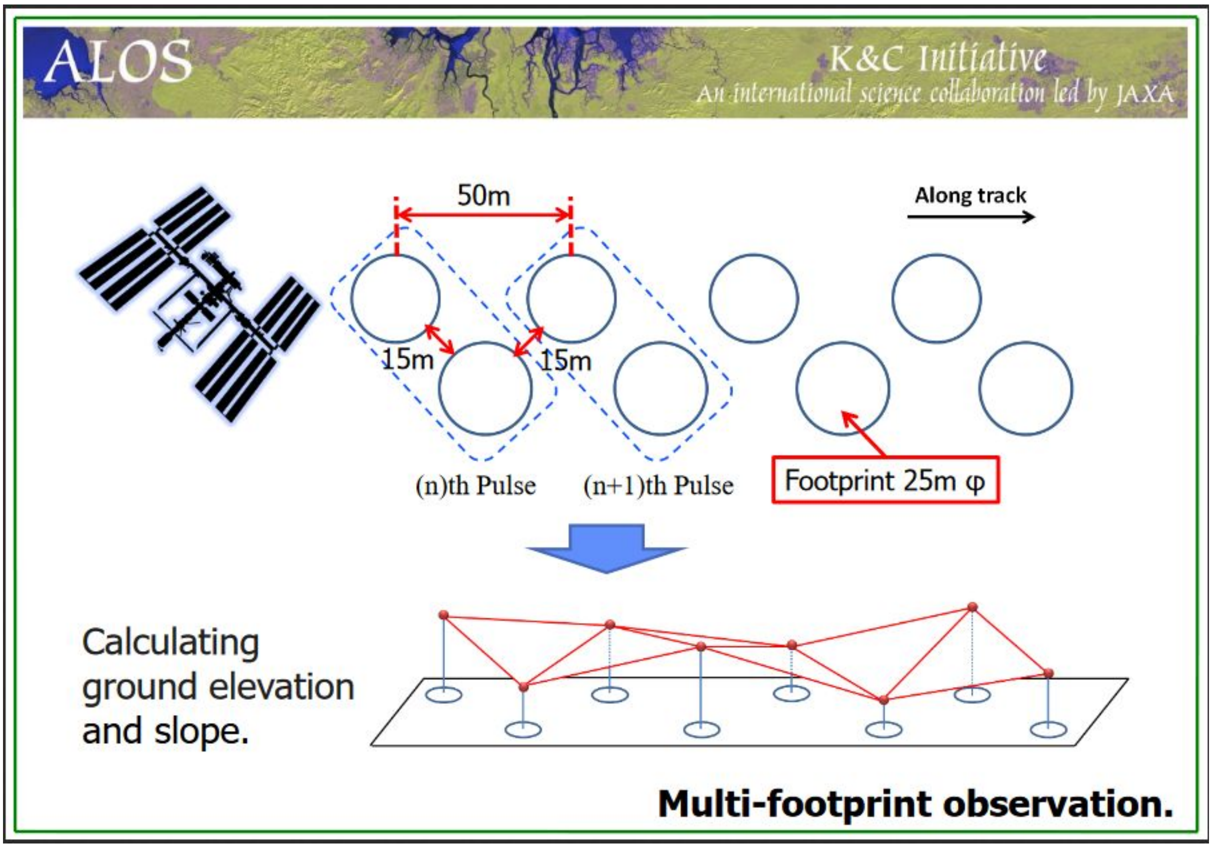
- *2 yr nominal on board ISS*

- *May 2019*
- *GEDI will acquire data only along transects or tracks, with between-track spacing of about 500 m*
- *limited by ISS orbit +- 51.5*
- 

- *Each footprint (column) provides complete vertical structure of the canopy.*
- *Gridded Biomass … ≤ 1 km resolution. At the end of two years after on-orbit checkout, at least 80% of the 1 km cells will meet an accuracy within 20% standard error, or 20 Mg/ha whichever is greater*
- *Transects of vertical profiles*
-

MOLI (JAXA, 2020, LIDAR)

MOLI



ALOS-4 (JAXA, 2020, L-band)

ALOS-4

BIOMASS (ESA, 2021, P-band)

BIOMASS was proposed for the Earth Explorer 7 core mission in 2005, and selected in 2013.

- *BIOMASS was selected was especially built on its ability to measure AGB within dense tropical forests, which, despite having the highest total forest C stock values (and mean forest AGB density), have minimal coverage by ground data.*
- *Also does topographic mapping below forests, mapping ice sheets, glacier flow and structure analysis and mapping of subsurface geological features in arid areas*
- *69 cm wavelength, full polarisation, interferometric*
- *From a biomass-climate combination standpoint the SOTR exclusion zone has a minor impact in terms of loss in information content. The impact is most significant in regions that already benefit from intense regional observation networks*
- *SAR sensors operating in the L band frequency are unaffected by SOTR restrictions, so could be used to mitigate loss of coverage of forest areas in regions with AGB <100 Mg ha −1*
-

NovaSAR (USKA/SSTL, 2018, S-band)

Chinese Biomass (P-band)

RCM (C-band), CSA

RiSAT-1A/B (C-band), ISRO

NISAR (NASA/ISRO, 2021, L-Band and S-band)

The background L-band land observation strategy envisions 8x12m at HH-HV dual polarisation. NASA being in charge of the L-band SAR means that data will be free and open and extremely well managed and served; global biomass and forest disturbance products are foreseen annually at 100m resolution;

Tandem-L (DLR, 2024, L-band)

Tandem-L is a proposed DLR mission currently targeting a 2024 launch, after several years of pushbacks. The mission design takes experience from the previous Tandem-X SAR mission, utilising two satellites flying in formation, and will host an L-band synthetic aperture radar. The mission has several key mission goals, and aims to measure 7 identified Essential Climate Variables - including Biomass. The design life is 10 years, with provisions for 2 to 3 additional years. Tandem-L will make possible a global inventory of biomass with an accuracy of 20%, as well as measure seasonal and yearly variations.

The Tandem-L science team has formulated the requirements on a global digital terrain model with a spatial resolution of 50 m x 50 m and a relative vertical accuracy of ~4 m. With this resolution, the global digital terrain model generated by Tandem-L will be unique and the basis for uniform and universal map material.

- **polarimetric SAR interferometry** for measuring forest height, multi-pass coherence tomography for determining the vertical structure of vegetation and ice,
- global measurement of 3-D forest structure and biomass for a better understanding of ecosystem dynamics and the carbon cycle,
- Forests: Especially for forest applications Tandem-L has the potential to initialize a new era providing products that allows a systematic monitoring of natural and anthropogenic forest change processes:
    - Forest structure: Global forest 3-D mapping with a voxel size of 10 x 50 x 50 m3 twice a year in order to monitor annual and seasonal forest structure changes. Tandem-L will allow for the first time ever to map the vertical forest structure and to monitor seasonal and annual variation globally with a high spatial resolution. This will enable to map for the first time the (vertical) complexity and diversity of Earth's forest

ecosystems and to assess the extent and intensity of forest structural disturbances.

- Forest height: Annual global forest height mapping with accuracy better than 10% on a 50 x 50 m2 grid. An example of forest monitoring over a period of 10 years by means of forest height maps – of the same/similar specification as the ones expected from TanDEM-L
- Forest biomass: Annual global (above ground) forest biomass mapping with accuracy better than 20% (or better than 20 t/ha for biomass levels below 100 t/ha) on a 70 x 70 m2 grid. Tandem-L will measure biomass and its seasonal and yearly variation with unprecedented accuracy and spatial resolution on a global scale. This is a key contribution to the uncertainties in the terrestrial components of the carbon cycle.

TABLE 4. UNIQUENESS OF TANDEM-L PRODUCTS AND APPLICATIONS.

PRODUCT	TANDEM-L	AVAILABLE PRODUCTS (CURRENT, APPROVED OR PLANNED MISSIONS)
3-D Forest Height & Structure	◗ High spatial and vertical resolution • Height: 10% @ 30 x 30 m^2 • Structure: 10 x 50 x 50 m^3 voxel size ◗ Frequent monitoring for the assessment of seasonal and annual dynamics (2 global coverages/year)	◗ BIOMASS (approved): • Lower vertical and horizontal resolution (voxel size worse by a factor of 40) • No global coverage (SOTR restrictions in Europe, North America and parts of Asia) • No structure dynamics (single tomographic measurement dispersed over one year) ◗ GEDI (approved): • No seamless coverage (only lidar tracks) • No global coverage (lack of northern boreal forests) • poor performance for the assessment of seasonal and annual dynamics ◗ SAOCOM-CS (planned): • Mostly demonstration with reduced performance • No global coverage and no dynamics
Digital Elevation Model	◗ Terrain and surface models with high accuracy and resolution ◗ Seasonal and yearly updates	◗ TanDEM-X (current): • Provides only a digital surface model • No updates
3-D Deformation	◗ High resolution deformation maps on a global scale ◗ Systematic acquisition concept for the measurement of 3-D vector movements ◗ Low temporal decorrelation in L-band	◗ Sentinel-1 (current): • Increased susceptibility to temporal decorrelation due to four times shorter wavelength in C-band • Lower spatial resolution in TOPS mode • No dedicated acquisition plan and processing for 3-D vector movements ◗ ALOS-2 (current): • No systematic acquisition for large-scale deformations and no processing of image stacks • Conventional SAR with limited swath width and/or resolution ◗ TerraSAR-X/TanDEM-X (current): • Can only acquire one global acquisition/year • Strong temporal decorrelation in X-band
3-D Ice Structure	◗ High spatial and vertical resolution ◗ Monitoring of seasonal and annual dynamics	◗ No comparable spaceborne data available yet (currently only small-scale airborne and ground-based sounder/GPR data available).
Soil Moisture	◗ High spatial resolution (30 x 30 m^2) ◗ (Bi-)weekly acquisitions	◗ Spaceborne radiometers and scatterometers (SMOS, SMAP, …) provide only resolutions in the order of 10 km and more ◗ SAOCOM (approved) is a conventional SAR with significantly worse spatial and temporal resolution

Comparison of TanDEM-L products with contemporary products

OptiSAR (Commercial Canadian, ~2019/2020, X-band, L-band)

OptiSAR will be a large commercial venture with many tandem satellites – currently 8 pairs with both optical and SAR capability. Urthecast claim to blend 1 m X-band and 5 m L-band to return several novel products, including forest stand height, spectral classification to return species and stand density. They also claim to be able to use 30 fps video to develop a 3D surface model. These data will be fused to estimate AGB.

Comparison of upcoming missions

The accurate measurement of Above Ground Biomass will ultimately rely on the combination of data streams, with each SAR band informing on a structural layer of forests – short wavelengths for the canopy, and long wavelengths for the trunks and ground.

There remain however a number of benefits and drawbacks between each technique, and it will be important to understand these limitations when making informed decisions on data streams for monitoring and reporting.

A review and comparison of the expected performance of each mission is also called for.

This section will introduce each characteristic that will be mentioned in the satellite mission section, and explain its relevance. An understanding developed here will help analyse each mission. Try to keep this section concise and don't cloud with numbers and comparisons.

Footprint - make a nice comparative figure for footprint sizes AND repeat frequency.

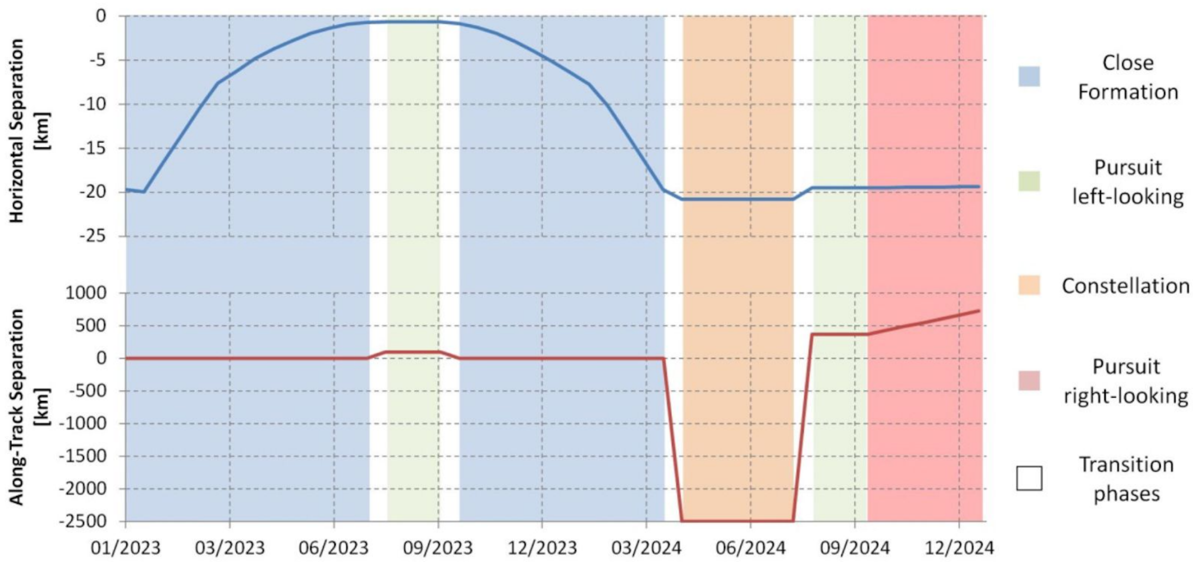
Sample rate, coverage (P-band issue), mission duration/continuity. What next? Weather/night operations? Data access? Accuracy? Duty cycle?

	Applications/Products	Coverage	Resolution	Accuracy	Repetition Rate
Biosphere	Forest Height	all forest areas	50 m (global) 20 m (regional) 10 m (local)	~ 10 %	every 16 days up to seasonal acquisitions and seasonal to annual product delivery
	Above Ground Biomass		100 m (global) 50 m (regional)	~ 20 % (or 20 t/ha)	
	Vertical Forest Structure		50 m (global) 30 m (regional)	3 layers	

Application/Products	Scale	Spatial Resolution	Accuracy
Upper Canopy Height	Global	50 x 50 m	20 %
	Regional	30 x 30 m	20 %
	Local	20 x 20 m	10 %
Upper Canopy Height Change	Global	50 x 50 m	1 m to 30 % of the change
	Regional	30 x 30 m	1 m to 30 % of the change
Forest Structure	Global	50 x 50 m	3 vertical layers 5 - 10 m
	Regional	30 x 30 m	3 vertical layers 5 - 10 m
Forest Structure Change	Global	50 x 50 m	-/+ 1 layer of the change
	Regional	30 x 30 m	-/+ 1 layer of the change

and also: Above Ground Biomass and Above Ground Biomass Change and others.

TanDEM-L Biosphere products



TanDEM-L observation timeline

Mission	**Agency**	**Launch (Duration)**	**LST**	**Main Modes**	**Revisit Time**	**Data Policy**
ALOS-4	JAXA	2020 (7)	12:00	*Spotlight*:1x3 m at 35x35 km *Stripmap*: 3/6/10 m at 100-200 km *ScanSAR*: 25 m at 700 km	14 Days	Free and Open
NISAR	NASA, ISRO	2021 (3.5)	6:00	*Land Ice*: 3x8 m, HH *Targeted areas*: 6x8 m, up to Quad pol *Background Land:* 12x8 m, HH/HV *Sea Ice:* 48x8 m, VV	12 Days	L-band: Free and Open S-band: Unknown, only measured over India
TANDEM-L	DLR	2022 (10-12)	18:00	*3-D Structure Mode*: 7 m at 175 km, Quad pol *Deformation Mode*: 7 m at 350 km, single/dual pol	16 Days, 8 in tandem Duty cycle: 30 min/ Orbit	Possibly limited release through the framework of the Helmholtz Alliance
SAOCOM 1A and 1B	CONAE	August 2018 (5)	6:00	*Stripmap*: <10 m at >40 km *TOPSAR Narrow*: <30 m at >150 km *TOPSAR Wide*: <50 m at >350 km NB: Several polarisation modes available for each mode, affecting specification	16 Days, 8 in tandem	Possibly limited release to Argentinian institutions

Lidar vs Sar (each band)

Is it better to use high resolution or highly frequent data? Can it be combined? Will there be a superior satellite to use?

What are some common issues with these data?

Reliance on allometric algorithms to determine mass from shape/size/density

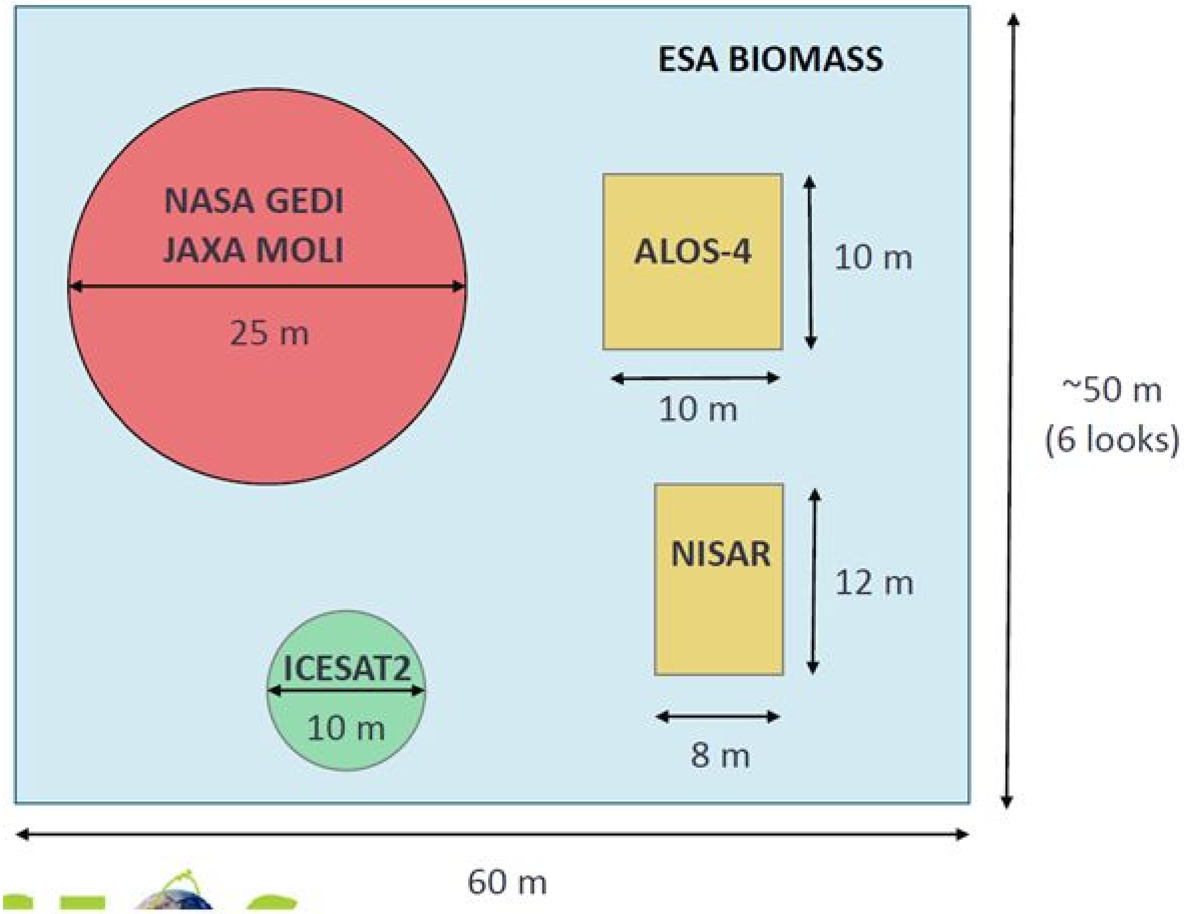
Re-read Lucas-J-Stars 2010 for a good list, including

- *In many open woodlands and woodlands, a proportion of the AGB is contained within the understorey and sub-canopy and similarly may not be of a size and density detectable by the SAR.*
- *Water - as noted by Ake - increases scattering (and therefore biomass estimations). especially in L-band HH, and particularly for non-remnant forests of lower AGB.*

Saturation:

Saturation - upper limit on sensitivity - saturation level of L-band radar at HV polarization on average remains >= 100 Mg ha1. Fresh water swamp forests have the lowest saturation with AGB at ~80 Mg ha-1, while needleleaf forests have the highest saturation at ~250 Mg ha-1. Swamp forests show a strong backscatter from the vegetation-surface specular reflection due to inundation that requires to be treated separately from those on terra firme. Our results demonstrate that L-Band backscatter relations to AGB can be significantly different depending on forest types and environmental effects, requiring multiple algorithms to map AGB from time series of satellite radar observations globally. (Yu and Saatchi (2016). Sensitivity of L-Band SAR Backscatter to Aboveground Biomass of Global Forests)

Many studies have reported saturation of SAR data when AGB exceeds approximately 60–100 Mg ha and 100–150 Mg ha for L-and P-band respectively, although reported levels vary considerably (Lucas et al., 2010)


ESA BIOMASS
NASA GEDI
JAXA MOLI
25 m
ALOS-4
10 m
10 m
NISAR
12 m
8 m
ICESAT2
10 m
~50 m
(6 looks)
60 m

Implications for GFOI

Include use-cases? eg biomass carbon, deforestation…?

Data Component & provider-user interaction

R&D programme topics

MGD

Capacity Building