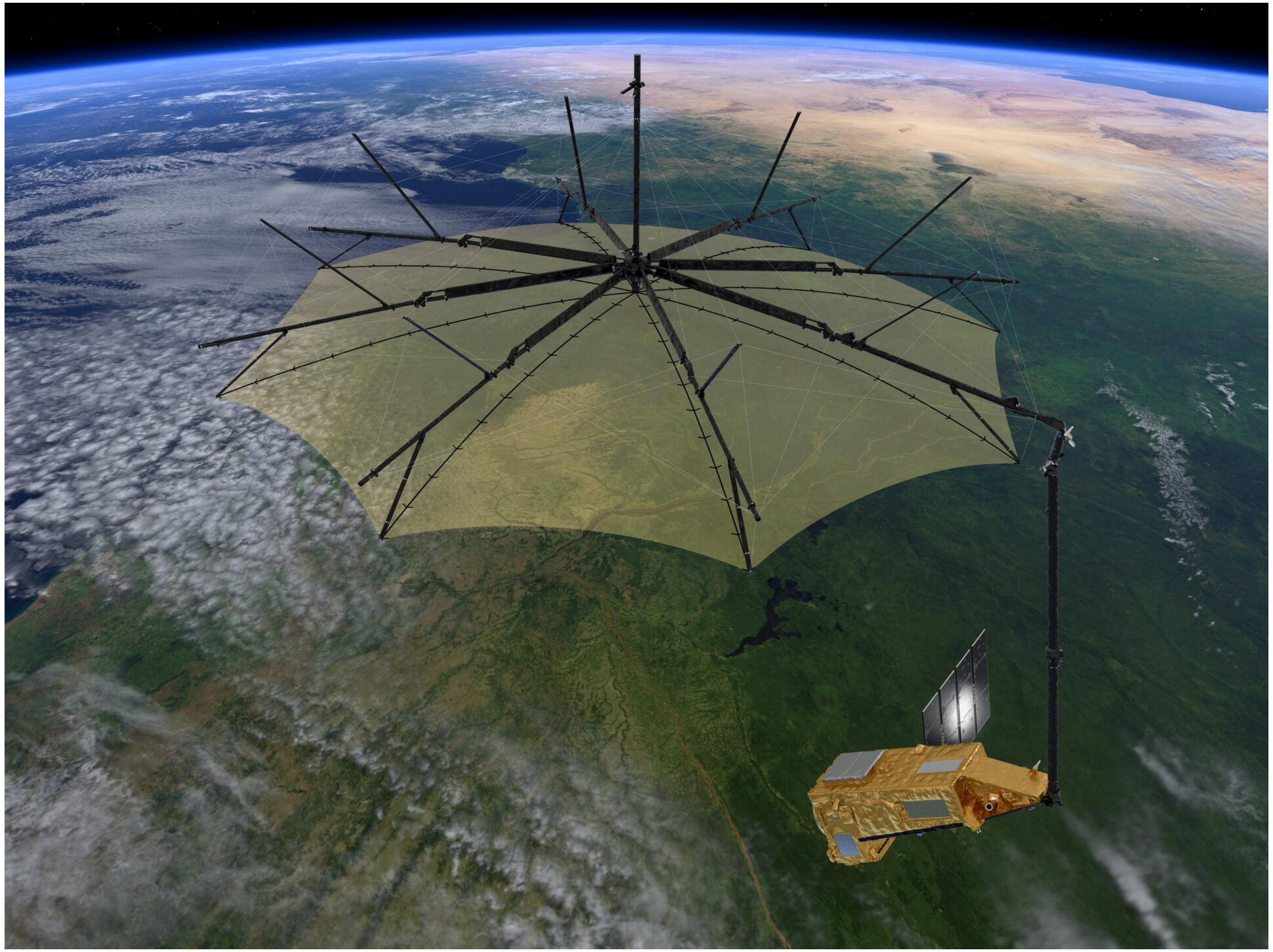
The Cal/Val Strategy for ESA's Biomass Mission

Björn Rommen, Philip Willemsen, Tristan Simon, Antonio Leanza, Sérgio Brás, Michael Fehringer

CEOS SAR Cal/Val Workshop 2024, Space Applications Centre, Ahmedabad, India
Session 2, 12 November 2024

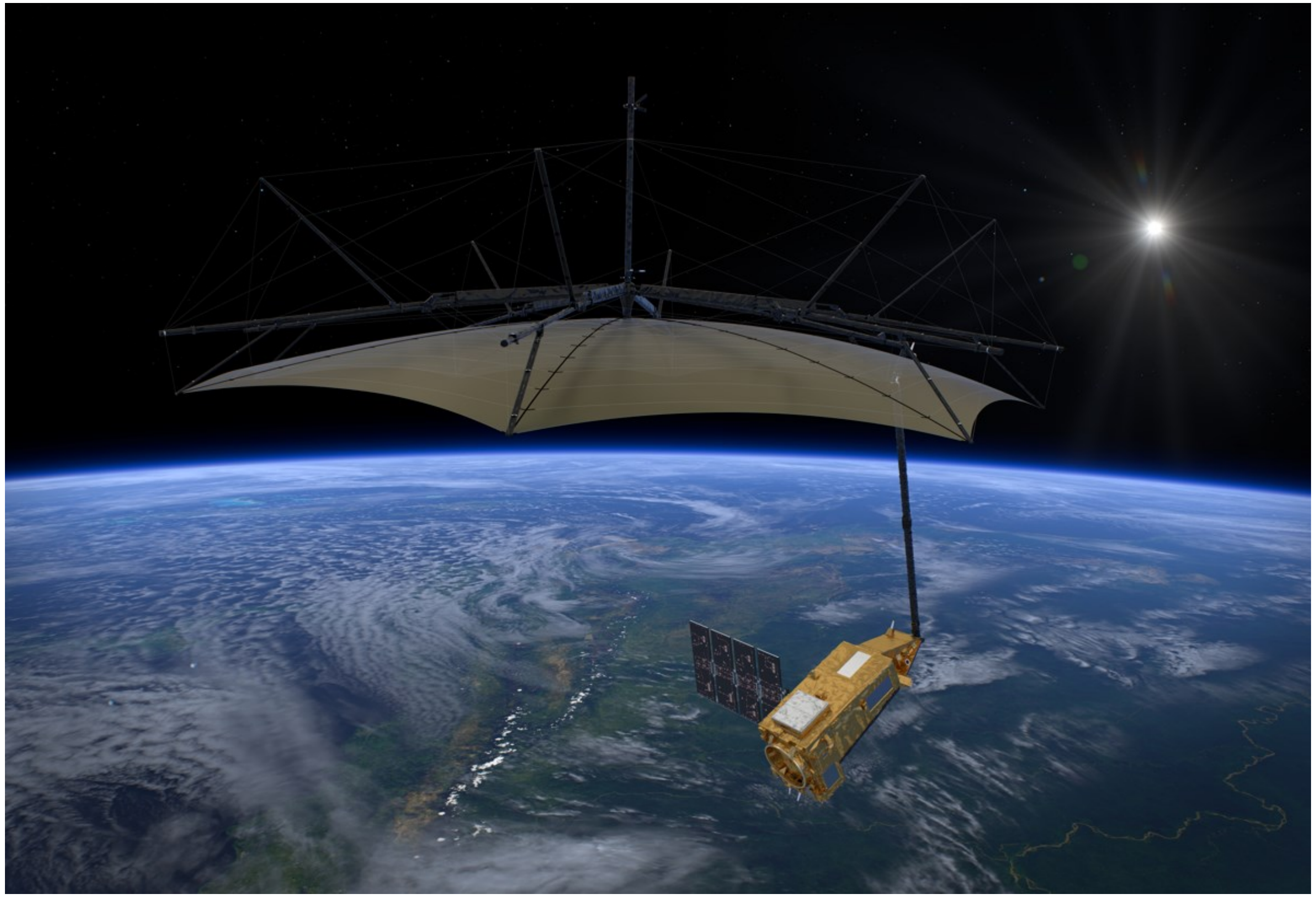
Overview

- Biomass mission objectives
- Key mission requirements
- Mission operations concept
- Biomass IOC planning
- Validation approach
- Current status & outlook
- ESA-ISRO arrangement



Biomass mission summary

"to take stock of the biomass in the world's forests and to monitor its evolution"



Primary objectives: determination of

- forest biomass
- forest height
- vegetation disturbances and re-growth

Secondary objectives:

- imaging of sub-surface geology in deserts
- mapping the topography under dense vegetation
- measurements of glacier and ice sheet velocities

From forest biomass to carbon to CO_2 :

- ➢ ~50% of dried woody biomass is carbon
- ➢ Carbon fraction in CO_2: atomic mass C = 12u and O = 16u ➔ $\frac{12}{12+16+16} = 0.27$

What information will we get from Biomass

Above-ground biomass (tons / hectare)

- 200 m resolution
- 1 map every ~9 months during INT phase
- global coverage of forested areas outside SOTR areas
- accuracy of 20%, or 10 t ha^{-1} for biomass < 50 t ha^{-1}

Upper canopy height (meter)

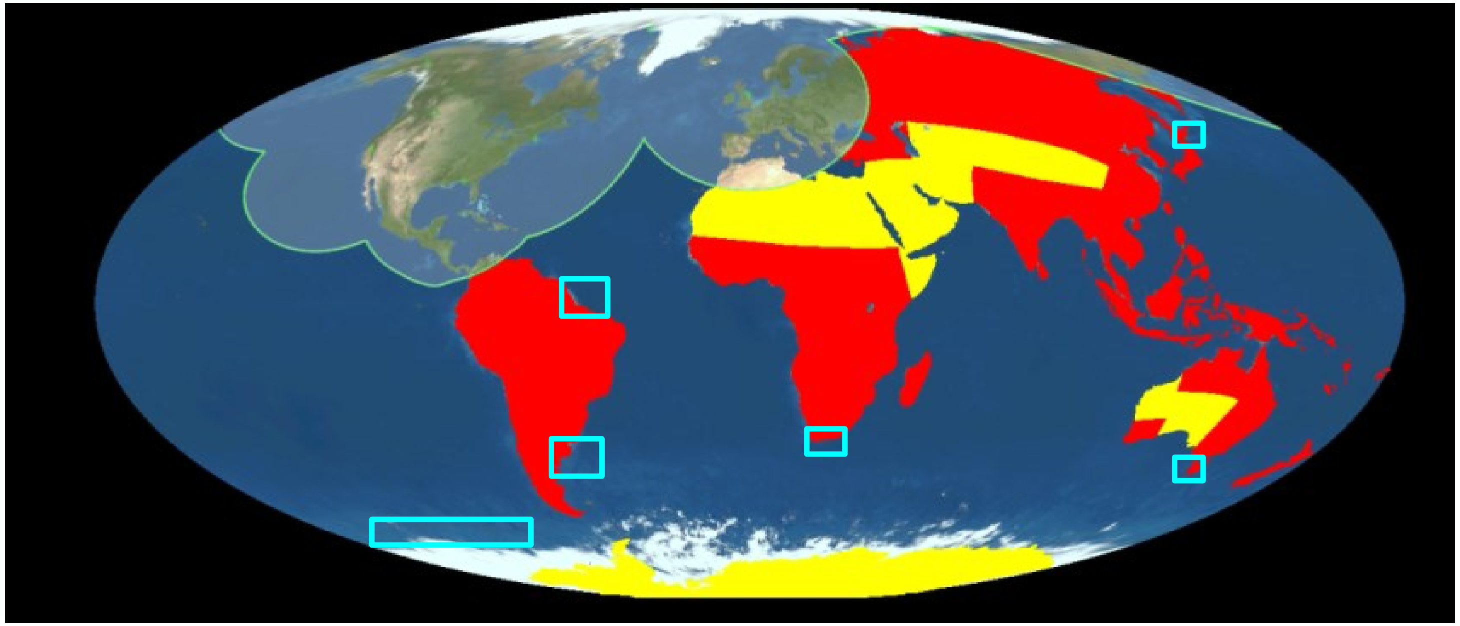
- 200 m resolution
- 1 map every ~9 months during INT phase
- global coverage of forested areas outside SOTR areas
- accuracy of 20-30%

Areas of forest clearing (hectare)

- 50 m resolution
- 1 map every ~9 months for 4 years
- global coverage of forested areas outside SOTR areas
- 90% classification accuracy

Coverage

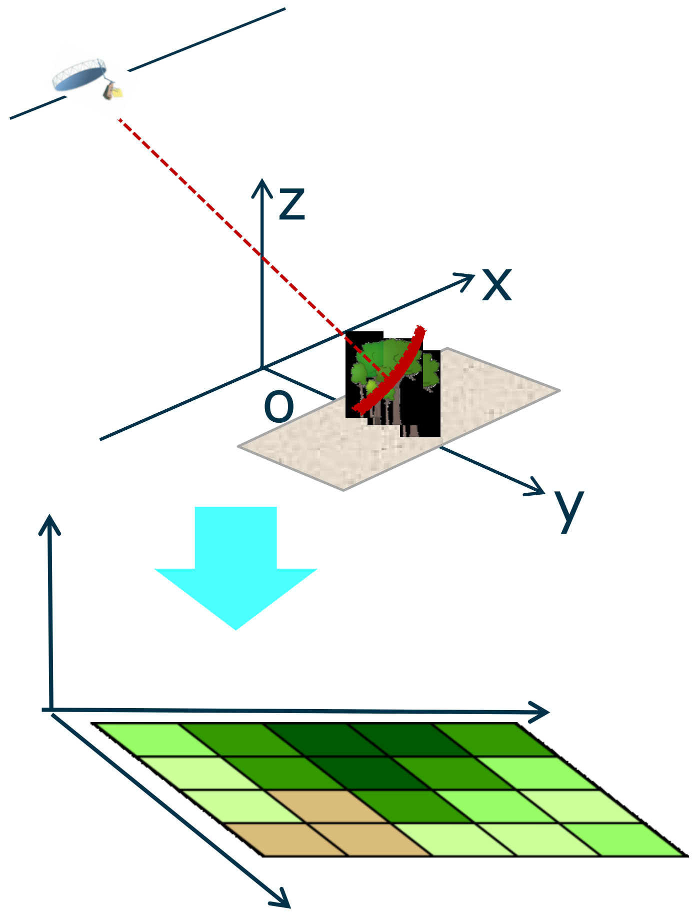
- Systematic Acquisitions for forested land (red area)
- Global coverage in 9 months (INT phase) and 17 months (TOM phase)
- Best effort acquisitions for non forested areas (yellow + ocean/sea ice ROIs)
- Acquisition mask restricted by US Space Objects Tracking Radar (SOTR)



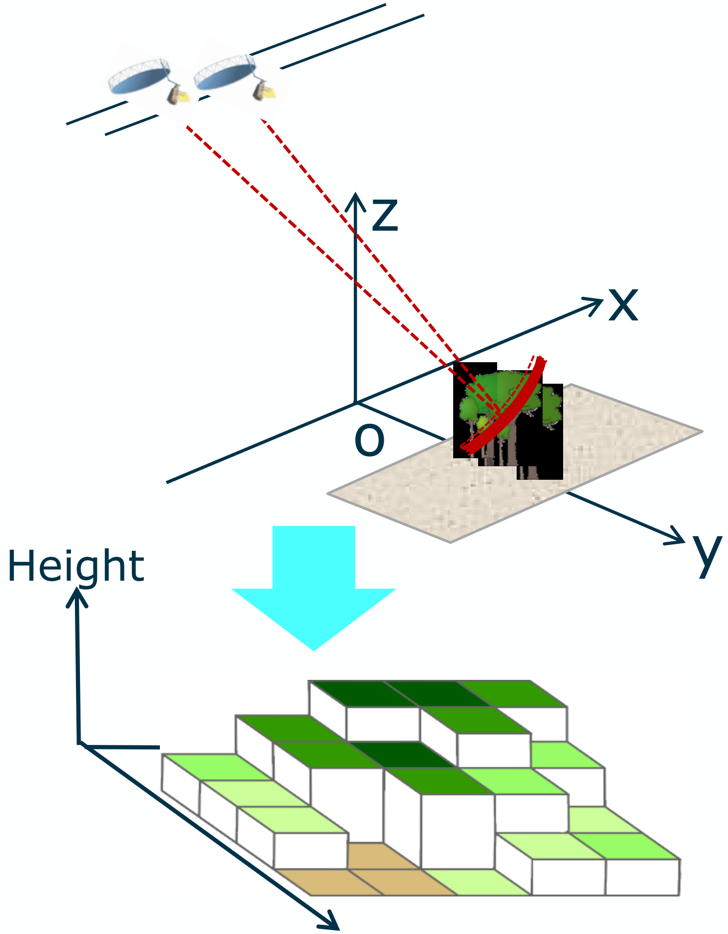
(Red = Primary objective coverage mask, Yellow = Secondary objective coverage mask)

Biomass SAR observation capability

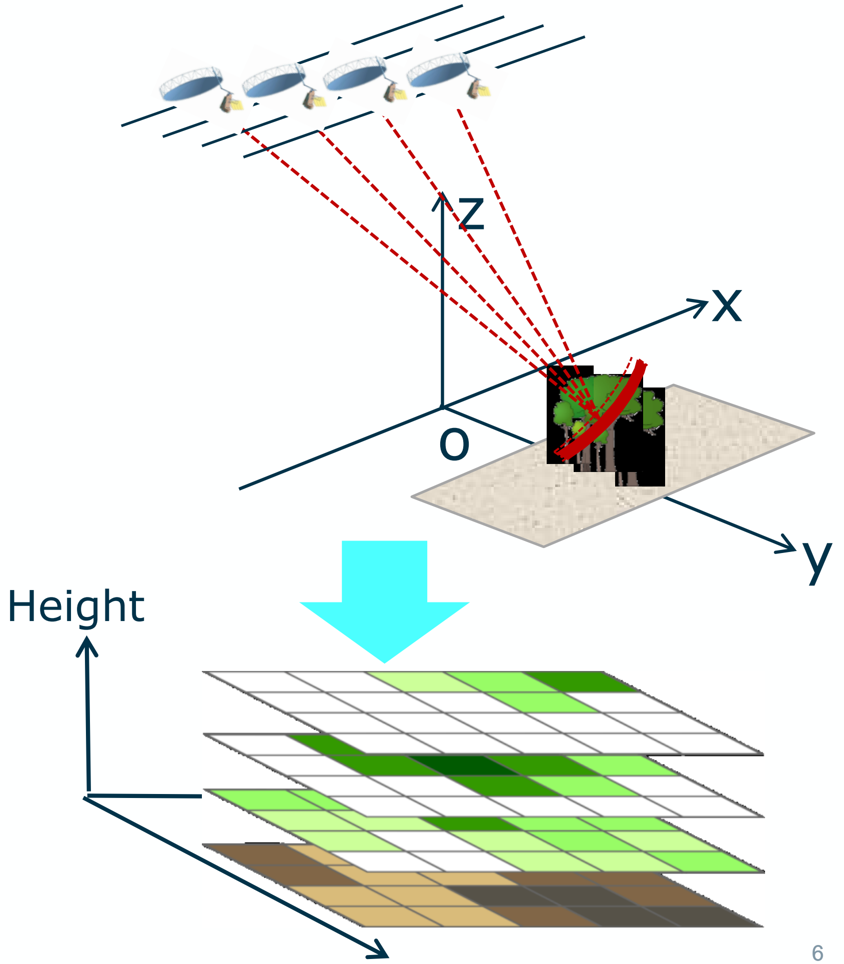
PolSAR
(SAR Polarimetry)



PolInSAR
(Polarimetric SAR Interferometry)



TomoSAR
(SAR Tomography)



Key mission requirements

Fully polarimetric P-band SAR

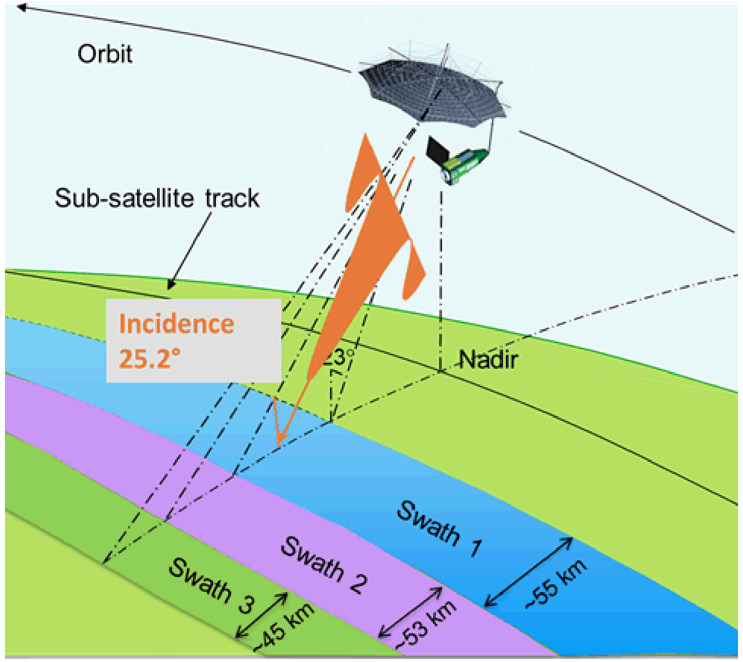
- Highest sensitivity to biomass compared to other wavelengths
- High temporal coherence over repeat passes
- P-band signals are highly susceptible to ionospheric distortions
- Large wavelength and large antenna diameter requires to rely on a dedicated antenna pattern characterisation in orbit (currently no test facilities which would allow satellite antenna E2E performance testing on ground)
  - Dedicated development: Biomass Calibration Transponder (BCT)
- To meet L2 product performances the system must comply to high accuracy polarimetric and radiometric requirements
- Quad-pol mode requires acquisition of the scattering coefficients in all linear polarisation combinations, i.e. HH, VV, HV & VH (in transmit and receive).

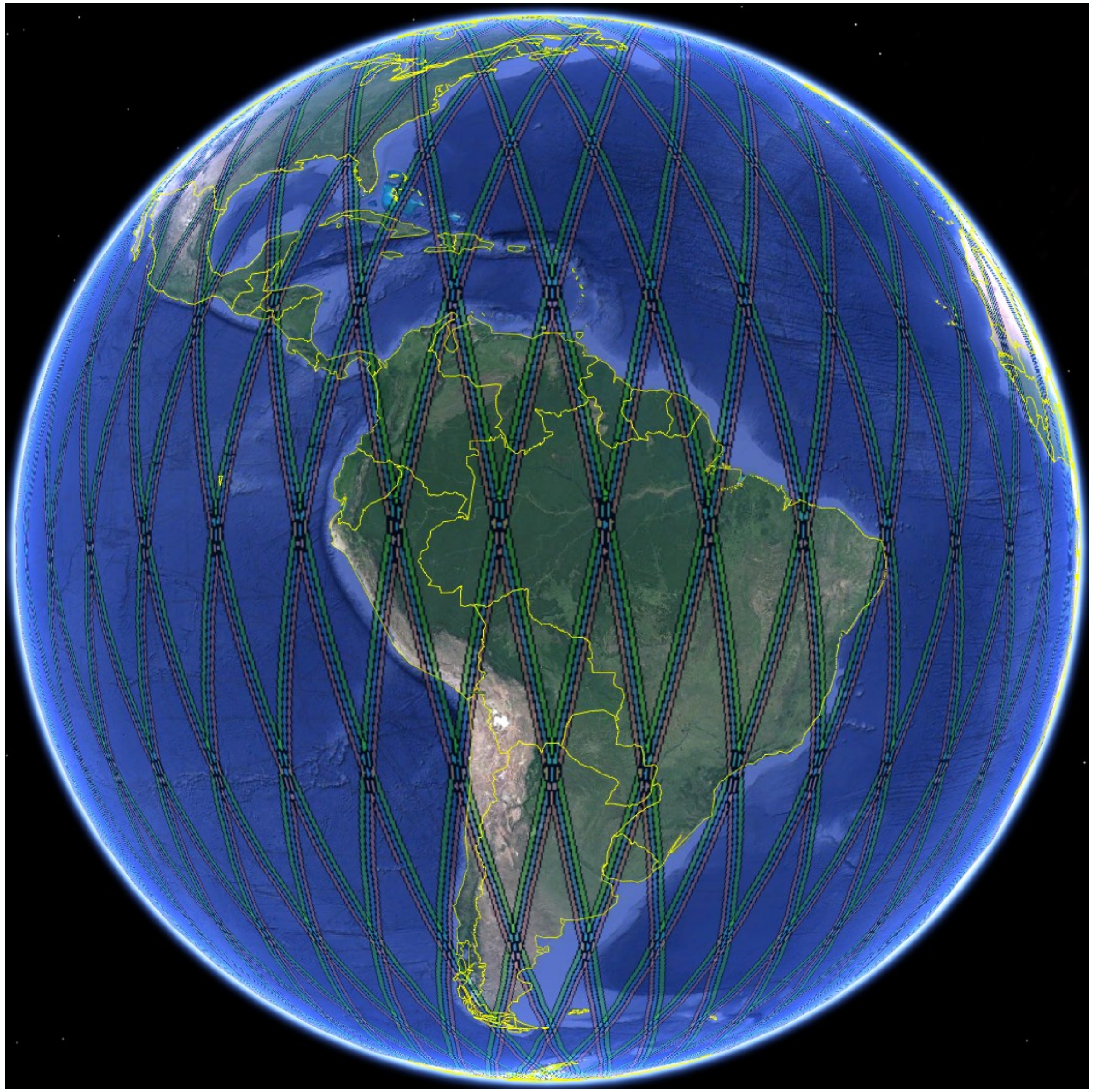
Two mission phases employing multi-pass interferometry

- controlled inter-orbit baselines between successive revisits to the same site
- Tomographic phase: observations with 6 3-day baselines (7 acquisitions)
- Interferometric phase: observations with 2 3-day baselines (3 acquisitions)

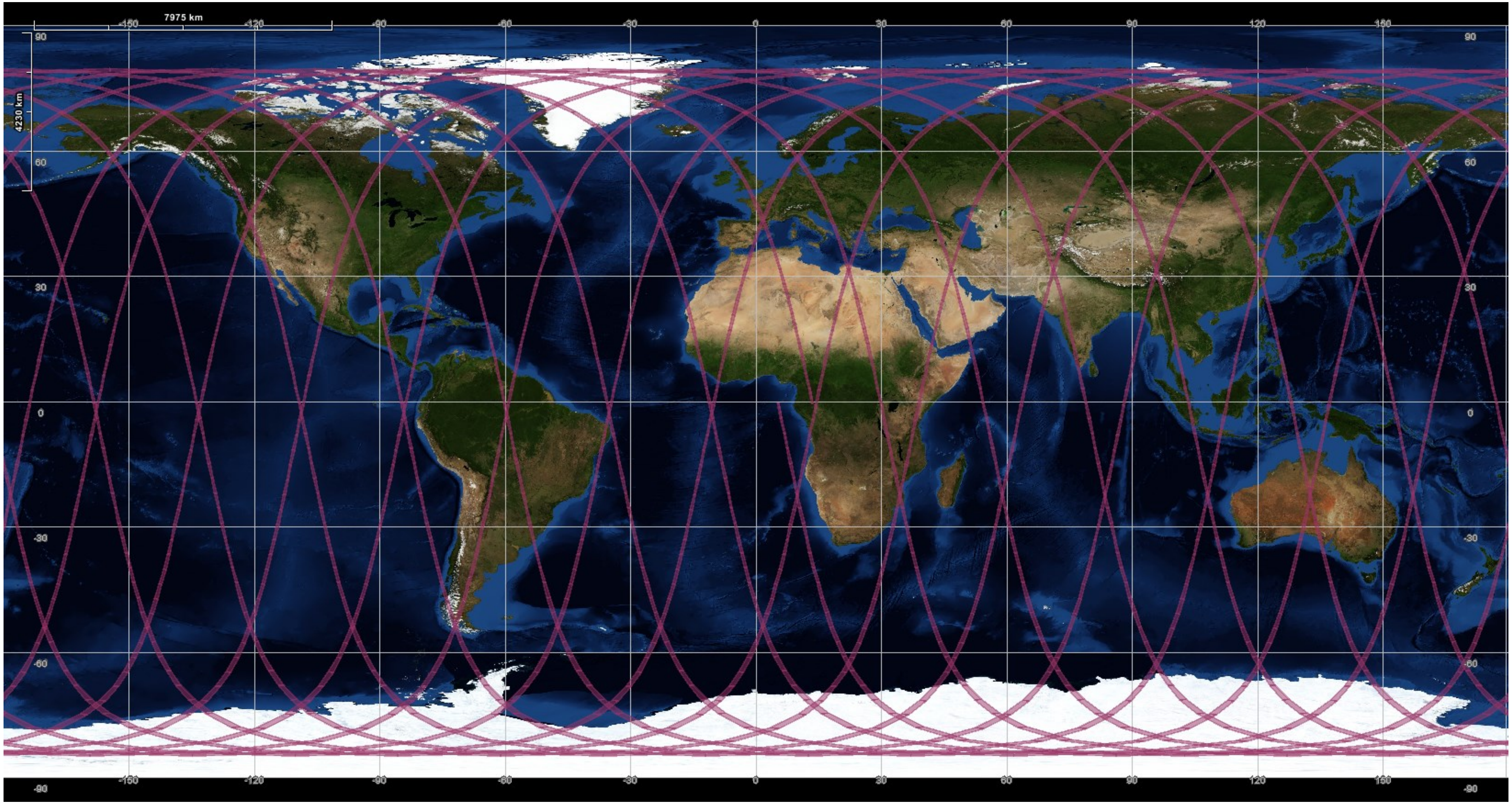
Key mission characteristics

- → Sun-synchronous 666 km dawn-dusk orbit
- → 3-day repeat / 44 orbits
- → Small East-West drift to implement baselines
- → Stripmap mode operation @6MHz bandwidth
- → Satellite roll for swath access (**left**-looking)
- → Satellite repositioning manoeuvre after each "major cycle"

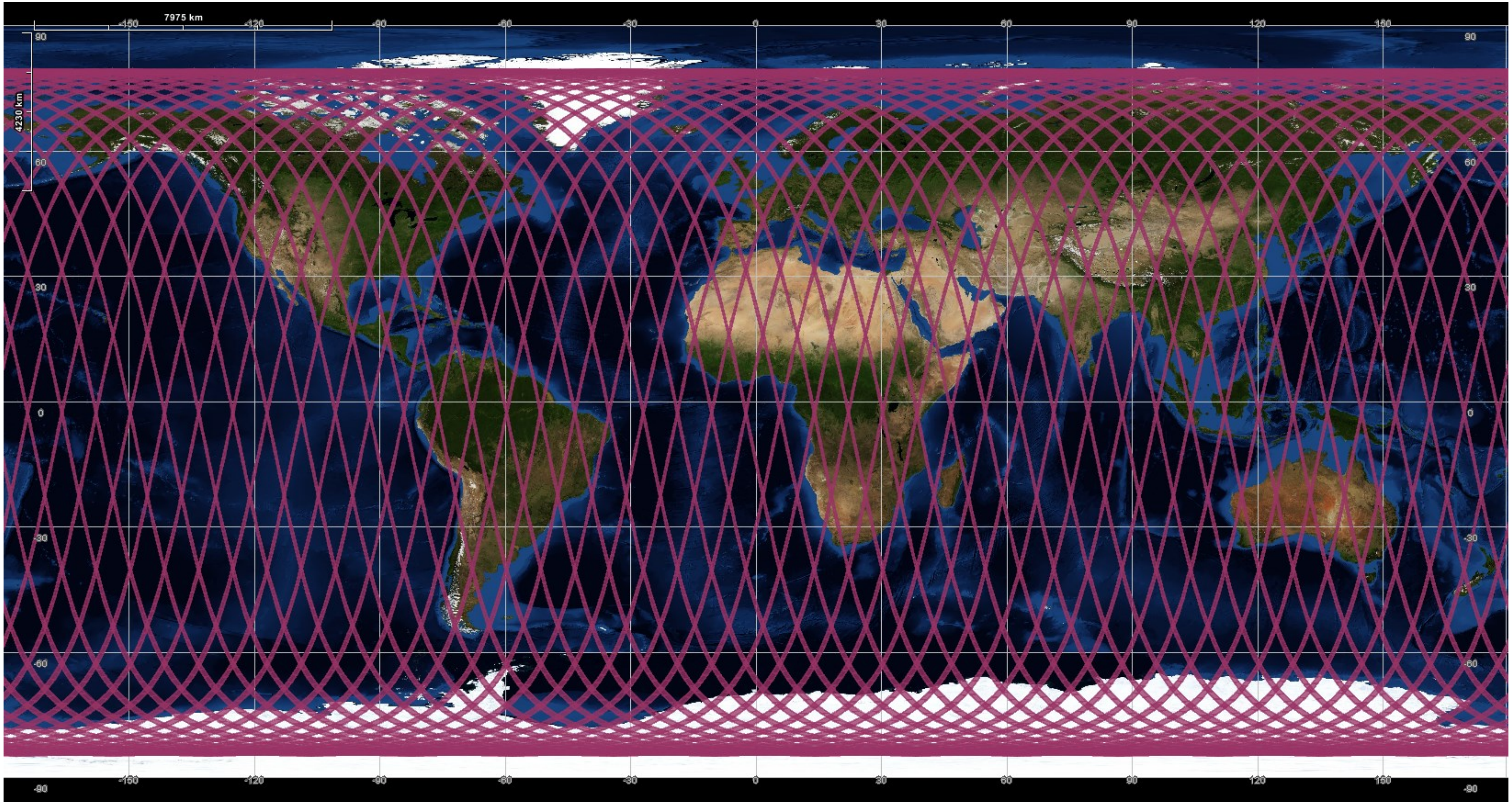




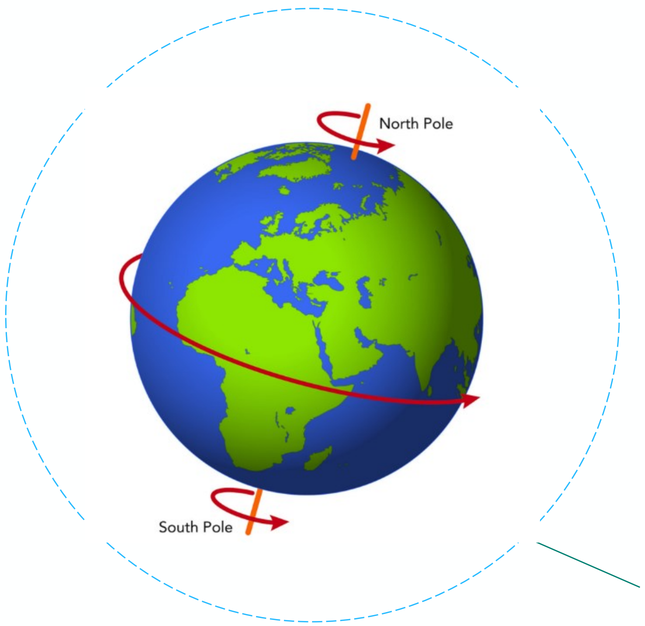
Observation geometry (1 day coverage)



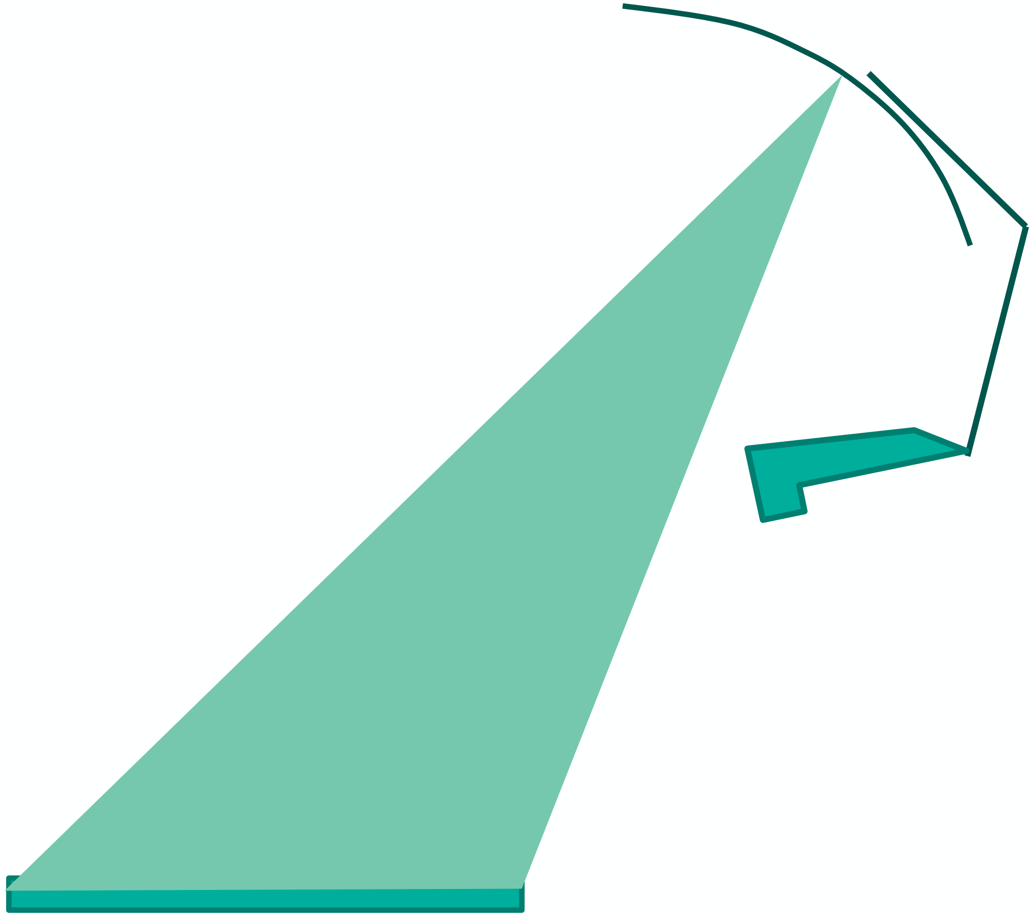
Observation geometry (3 days coverage)



A spacecraft in an orbit with a pure 3 days / 44 orbits, observes exactly same area every 3 days.



3 days / 44 orbits

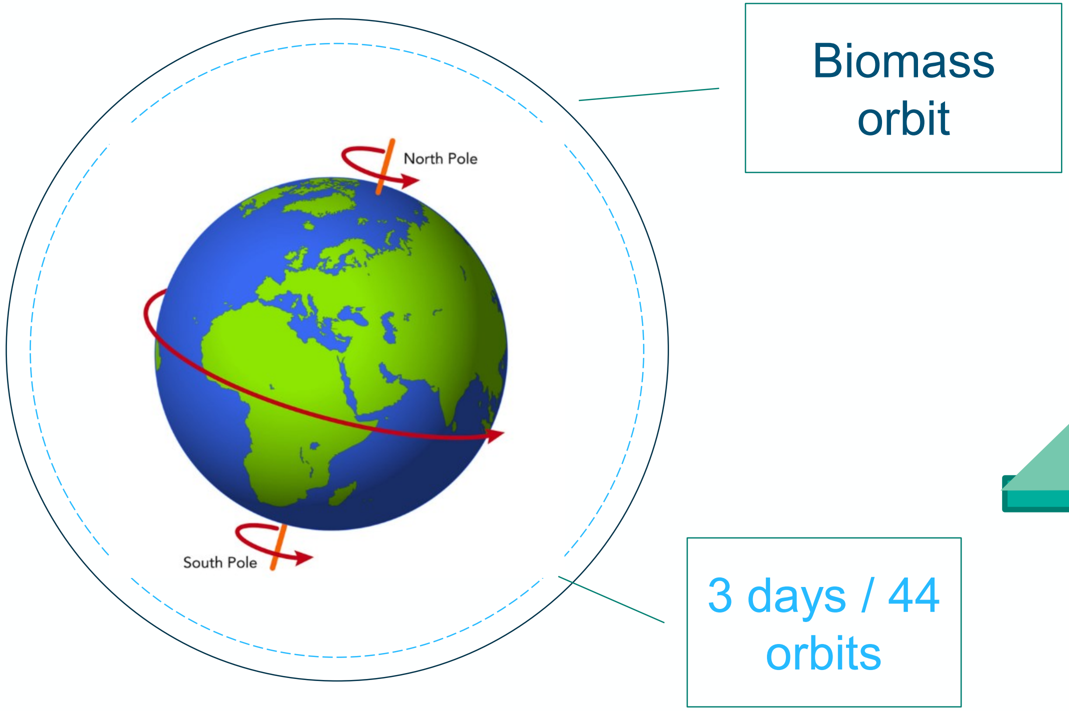


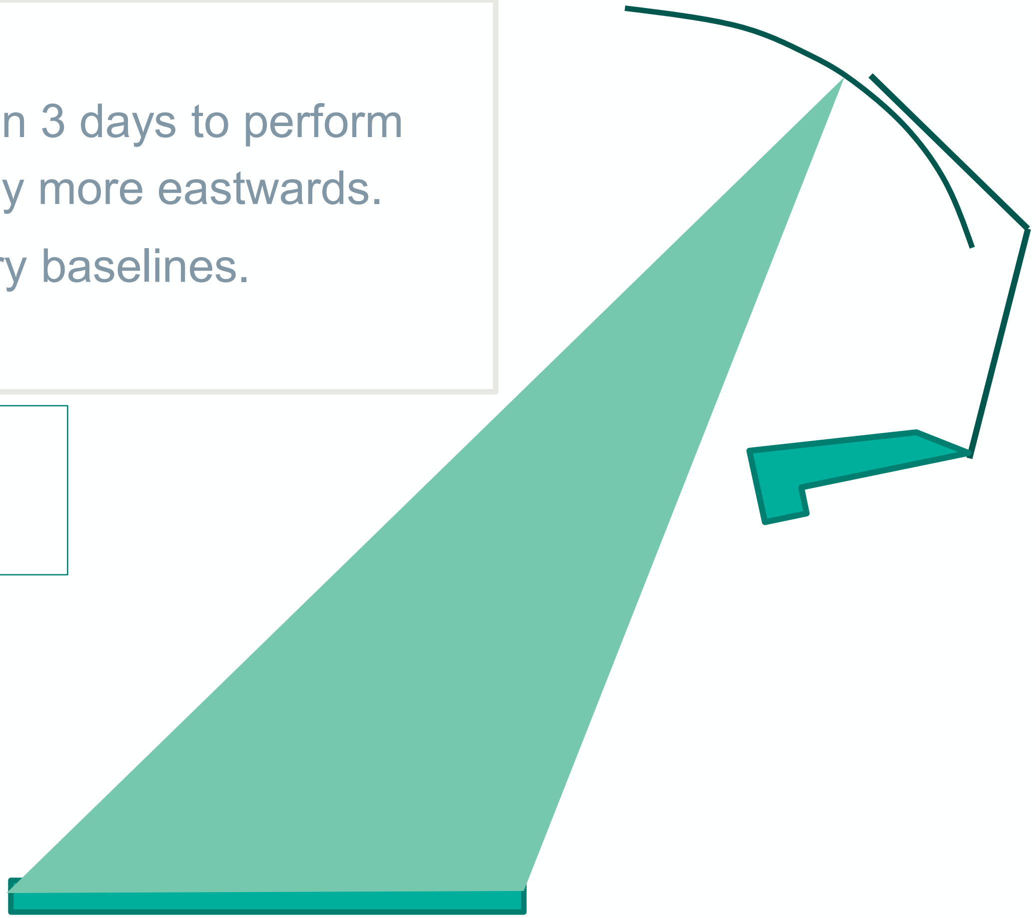
Observation geometry (near repeat cycle orbit)

Biomass will be operated at a slightly higher altitude.

This means that the spacecraft will take a little longer than 3 days to perform the 44 orbits, and the Earth will have time to rotate slightly more eastwards.

This longitude drift is leveraged to generate the necessary baselines.



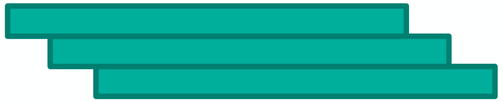


Observation geometry (swath 1)

Tomographic coverage

Interferometric coverage

If Biomass would stay always in its drifting orbit, it would take too long to achieve global coverage.

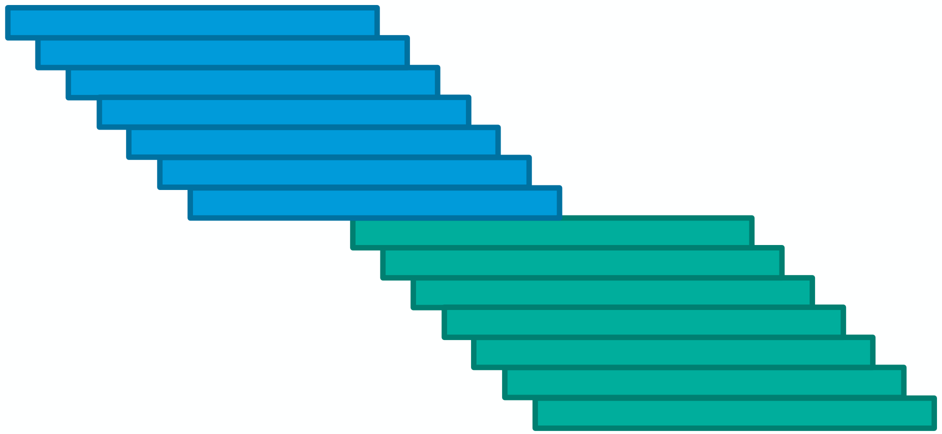


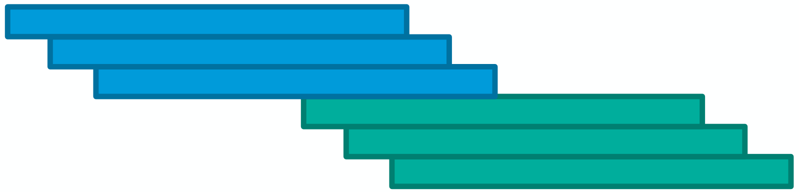
Observation geometry (swath 1 & swath 2)

Tomographic coverage

Interferometric coverage

If Biomass would stay always in its drifting orbit, it would take too long to achieve global coverage.
The solution is to perform a roll manoeuvre to observe the adjacent areas once a full observation stack has been acquired.



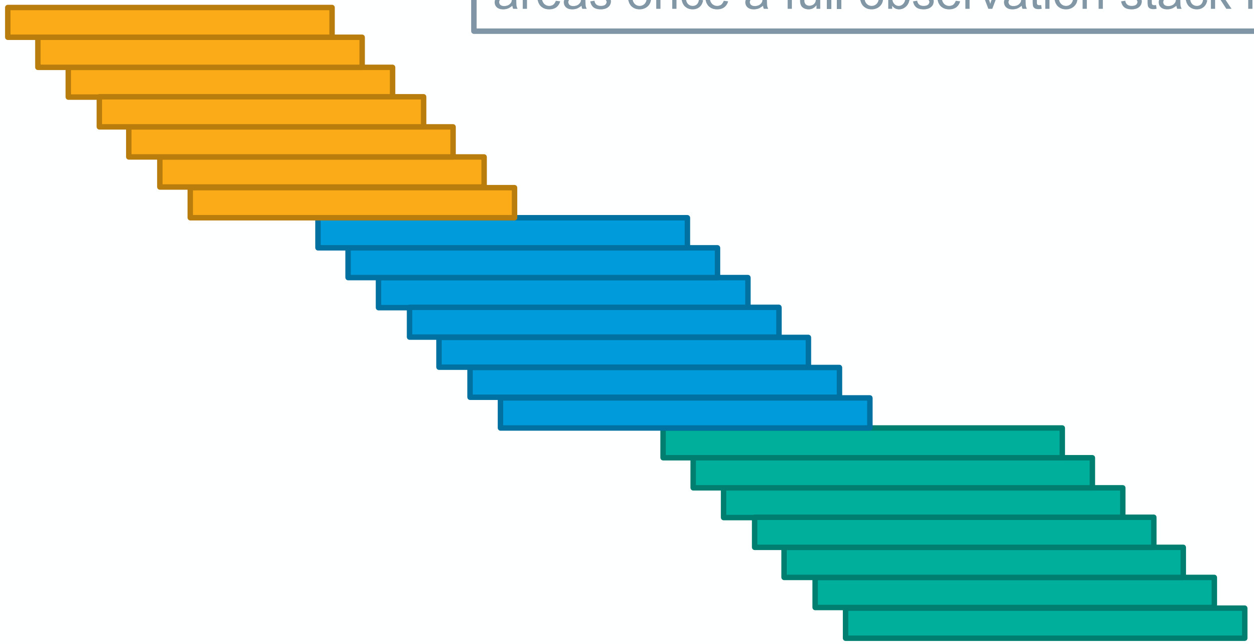


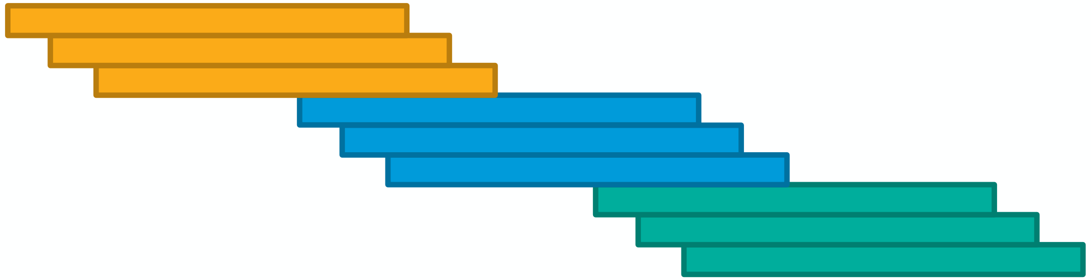
Observation geometry (swath 1 & swath 2 & swath 3)

Tomographic coverage

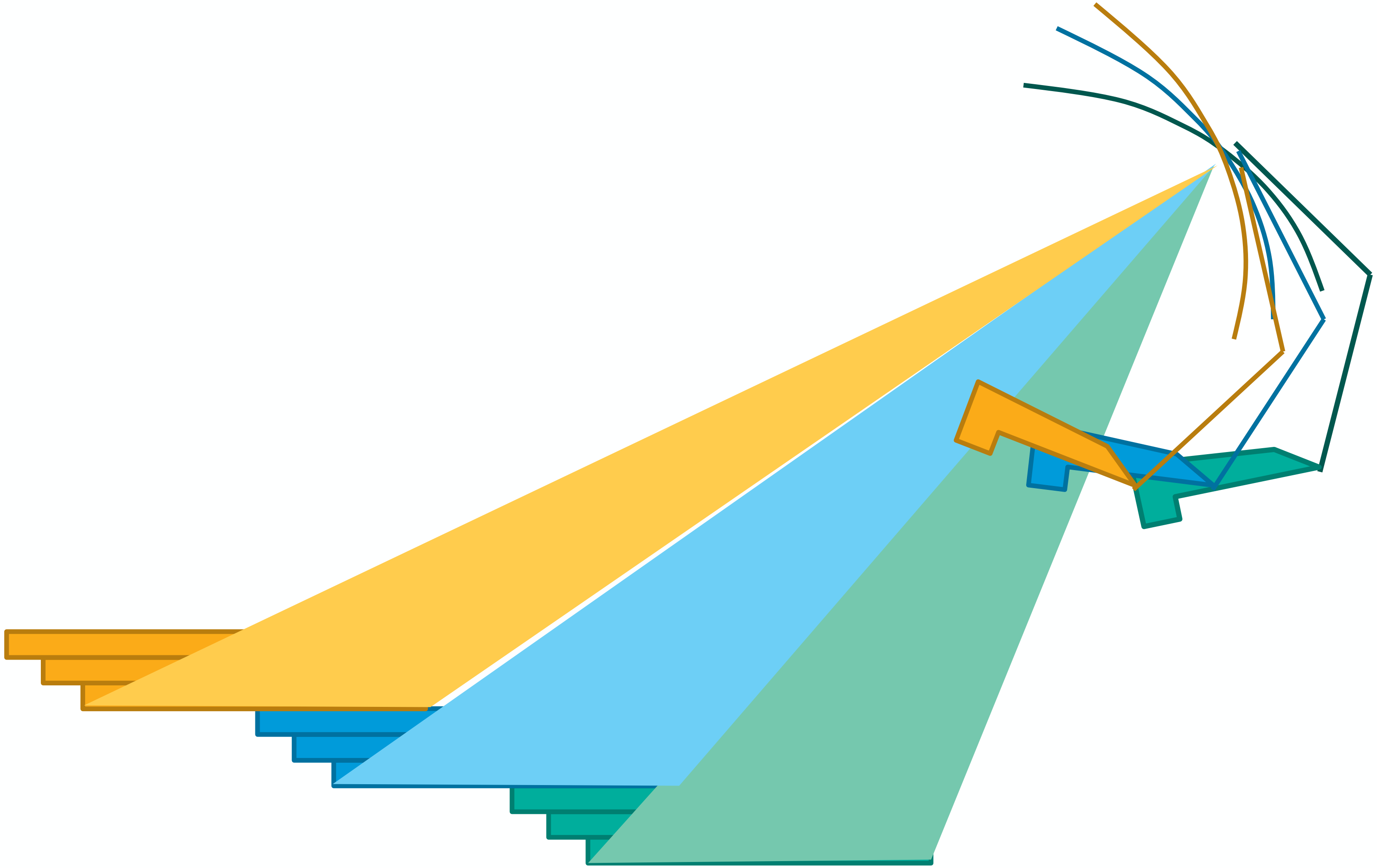
Interferometric coverage

If Biomass would stay always in its drifting orbit, it would take too long to achieve global coverage.
The solution is to perform a roll manoeuvre to observe the adjacent areas once a full observation stack has been acquired.



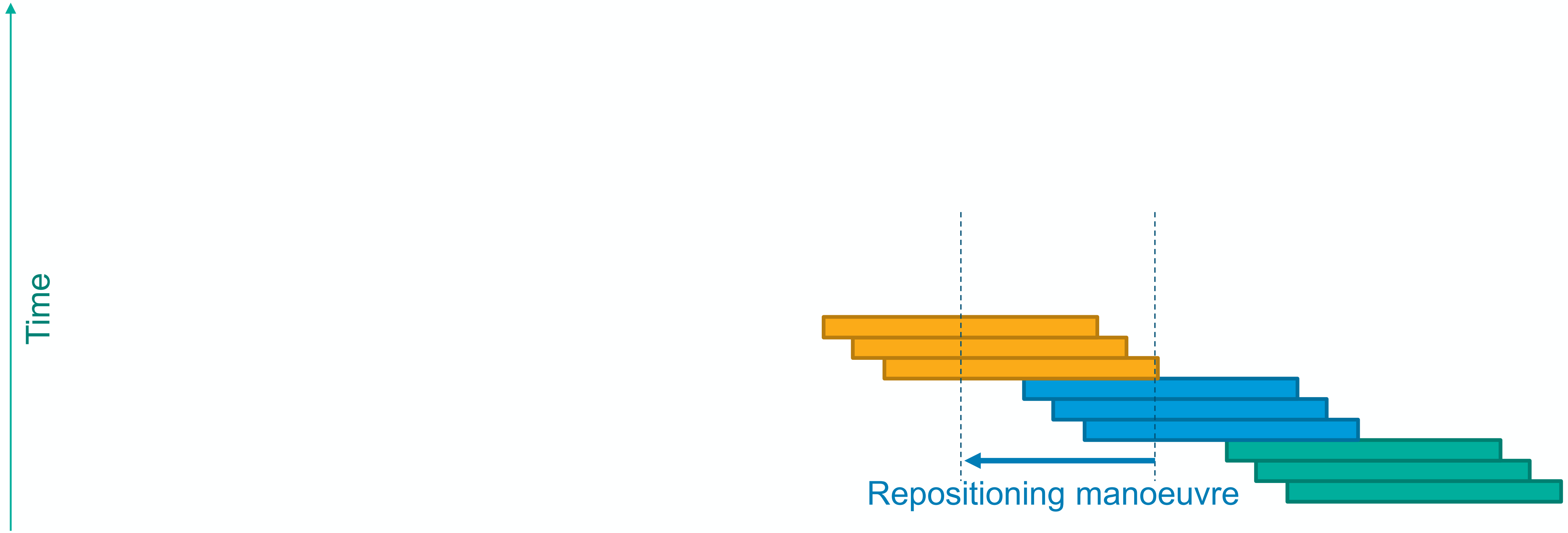


Observation geometry (swath 1 & swath 2 & swath 3)



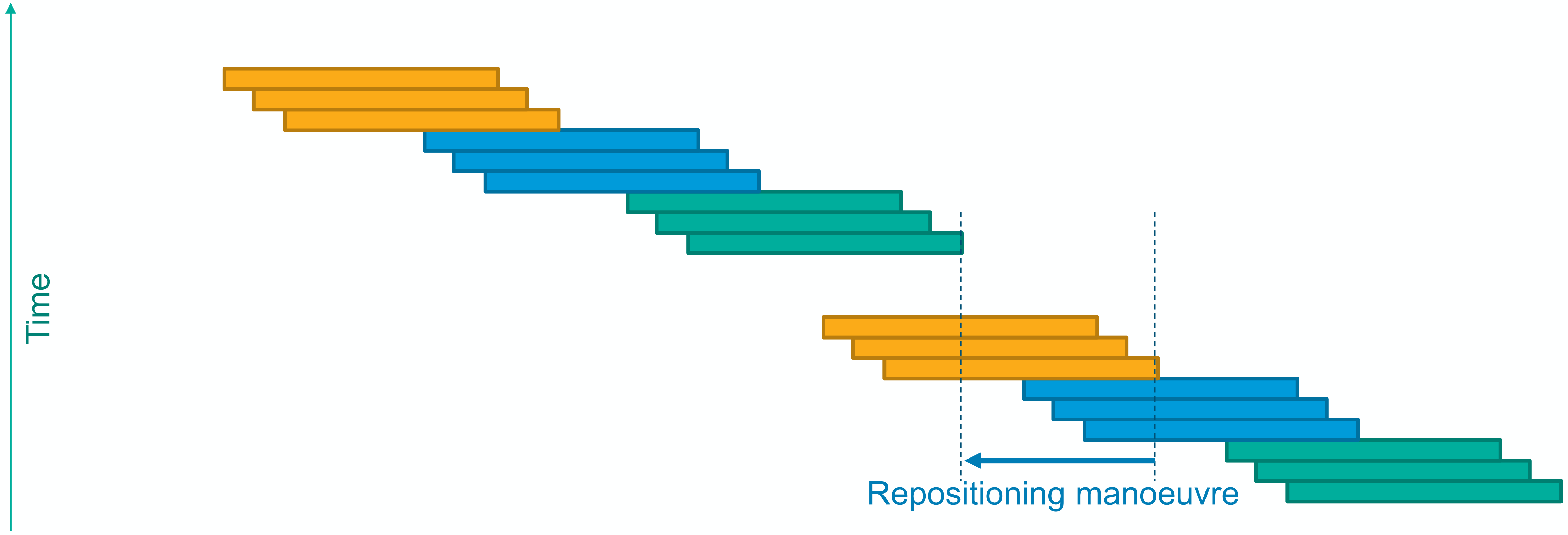
Satellite repositioning manoeuvre

But there is a limit to the possible incidence angle of the observations. Thus, at the end of the observations with the 3 swaths, Biomass raises its orbit so that the longitude drift rate increases.

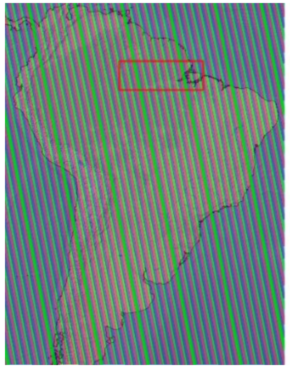


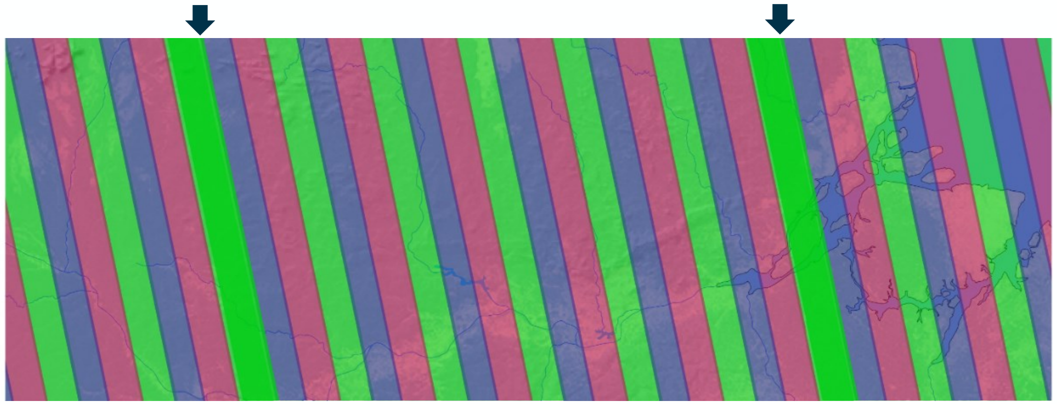
Satellite repositioning manoeuvre

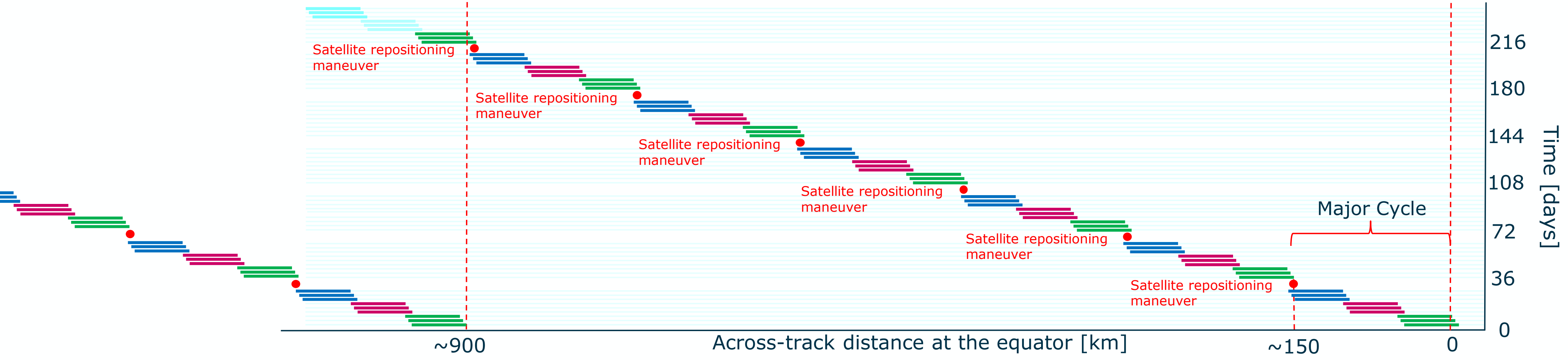
But there is a limit to the possible incidence angle of the observations. Thus, at the end of the observations with the 3 swaths, Biomass raises its orbit so that the longitude drift rate increases.
Once the drift is sufficient, the spacecraft returns to its nominal orbit and a new cycle begins.



Putting the pieces together







Ground Segment Overview

The Ground Segment is composed of the major elements:

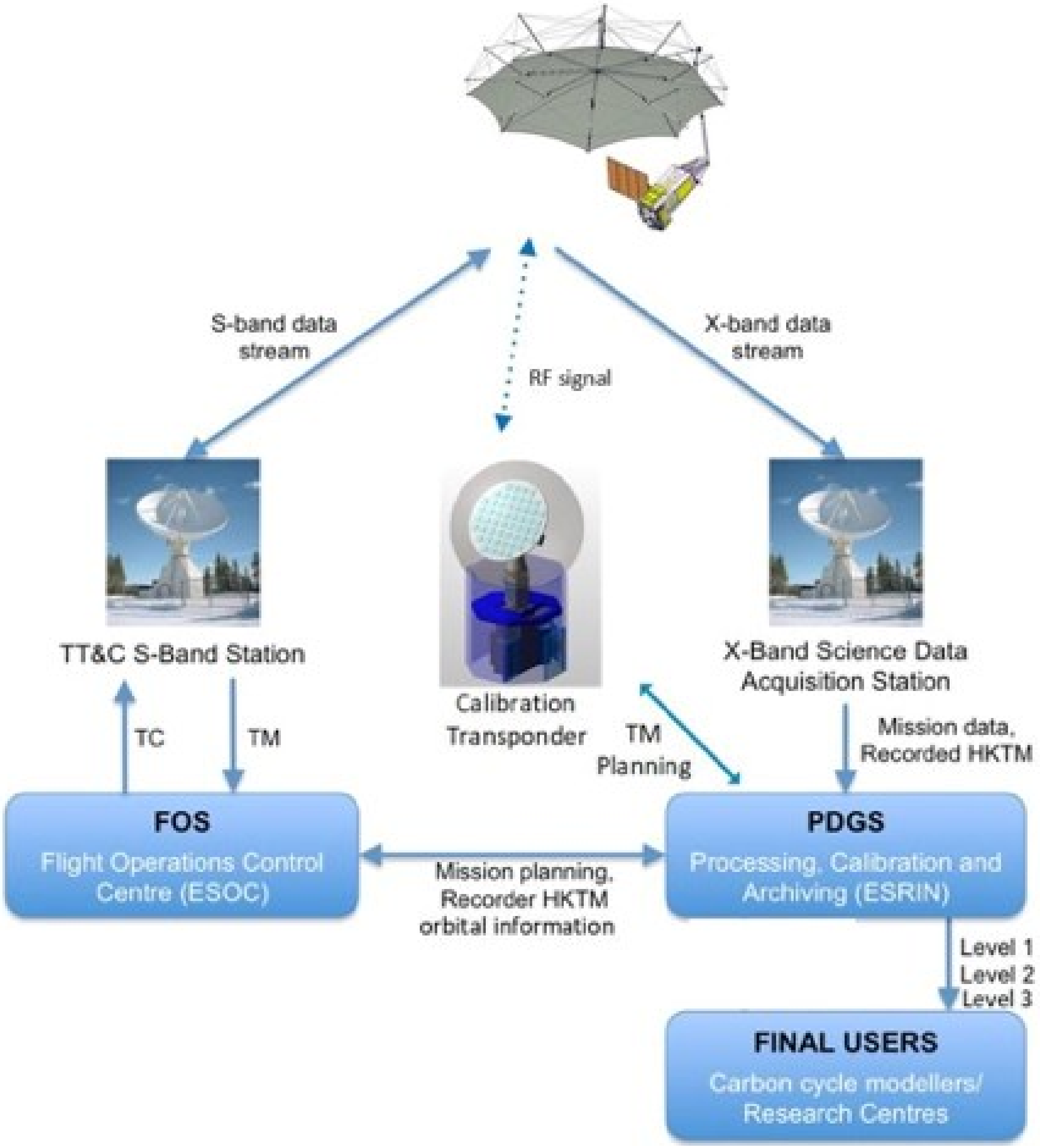
Flight operation segment / FOS
monitoring and operating the Biomass mission:

- TMTC communication with the spacecraft
- mission planning
- satellite control and status monitoring
- orbit and attitude determination
- on-board software maintenance

Payload Data Ground Segment / PDGS
implementing all science data functions:

- payload and X-band activities planning
- science data / X-band data acquisition
- payload data processing, quality control, archiving
- provision of data access and user services

Biomass Calibration Transponder / BCT
- located in Western Australia, ESA's New Norcia Site
- Antenna diameter: 4.8 m



Polarimetric Active Radar Calibrator (PARC)

- first of its kind active, fully polarimetric P-band transponder, four independent polarimetric signature matrices
- satellite tracking in azimuth/elevation: ensure consistent measurements with maximum transponder antenna gain
- control & microwave sub-system including microwave sub-system, digital sub-system
- transponder calibration sub-system, supporting the transponder external calibration

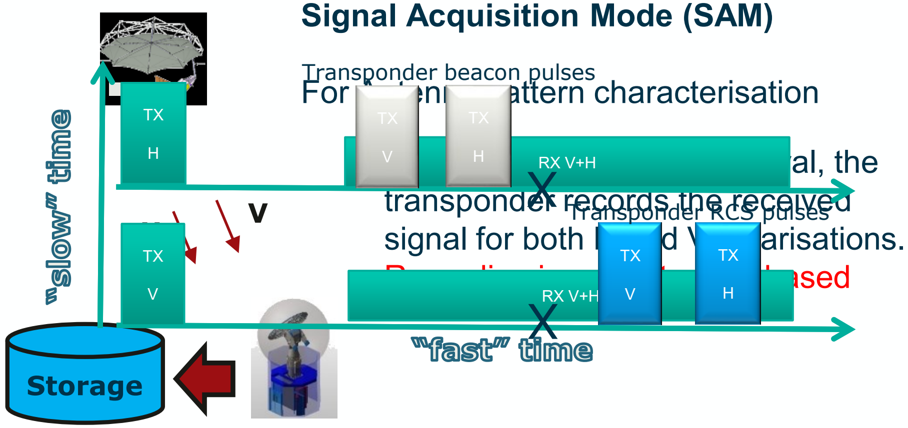
Feature	Description
Antenna design	2D array with a 4.8 diameter. 4 quarter composed by 13 patches each (10 active)
Antenna Beam	12 deg HPBW. Gain 22.7 dBi
Simulated RCS	85 dB(m^2) with an uncertainty < 0.2 dB (1σ)
Gain stability	< 0.1 dB (1σ) over the entire mission lifetime
Sensitivity	Capability to detect PFD > -90 dBm/m^2
Cross-Polar isolation	< 40 dB (1-way) in both Tx and Rx
Channel Imbalance	< 0.1 dB (1σ) in amplitude and < 0.77 deg (1σ) in phase, including the antenna (2-way)
Signal to Multipath Ratio	> 43.5 dB
Steering	Azimuth and Elevation. Biomass tracked during the overpass
Absolute pointing error	< 0.5 deg (3σ) azimuth and elevation combined
Calibration	Internal calibration network (I-CAL) + External calibration disk with a known RCS (Ex-CAL)
Operational Modes	3 operational modes that can be run in any combination (details in the next slide)

Courtesy of C-CORE (pictures Karl Tuff)

PARC Operational Modes

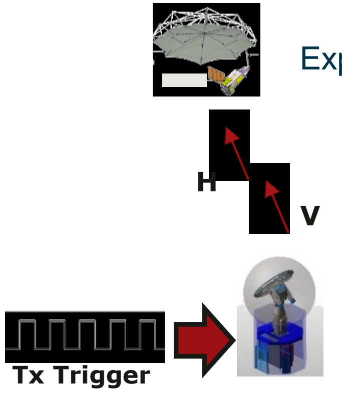
Three mutually inclusive modes:

Signal Acquisition Mode (SAM)



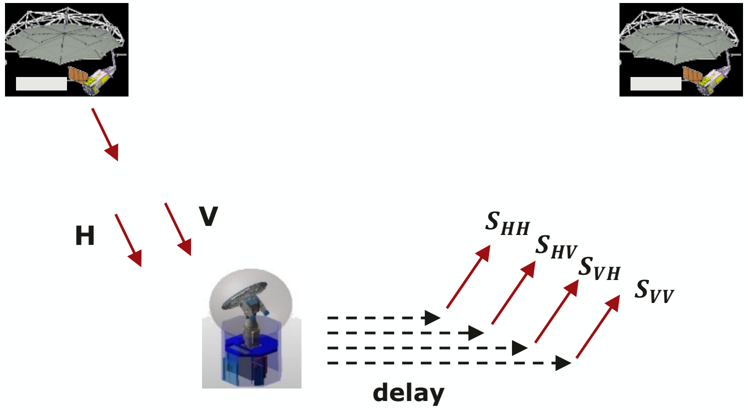
Self-generated Transmit Mode (STM)

Experimental mode



Transponder transmits toward Biomass delayed H and V pulses generated by the transponder itself. The transmission can be triggered by the detection of a pulse received from Biomass or according to a timeline synchronized with the Biomass Rx window (beacon mode)

Echo Generation Mode (EGM)

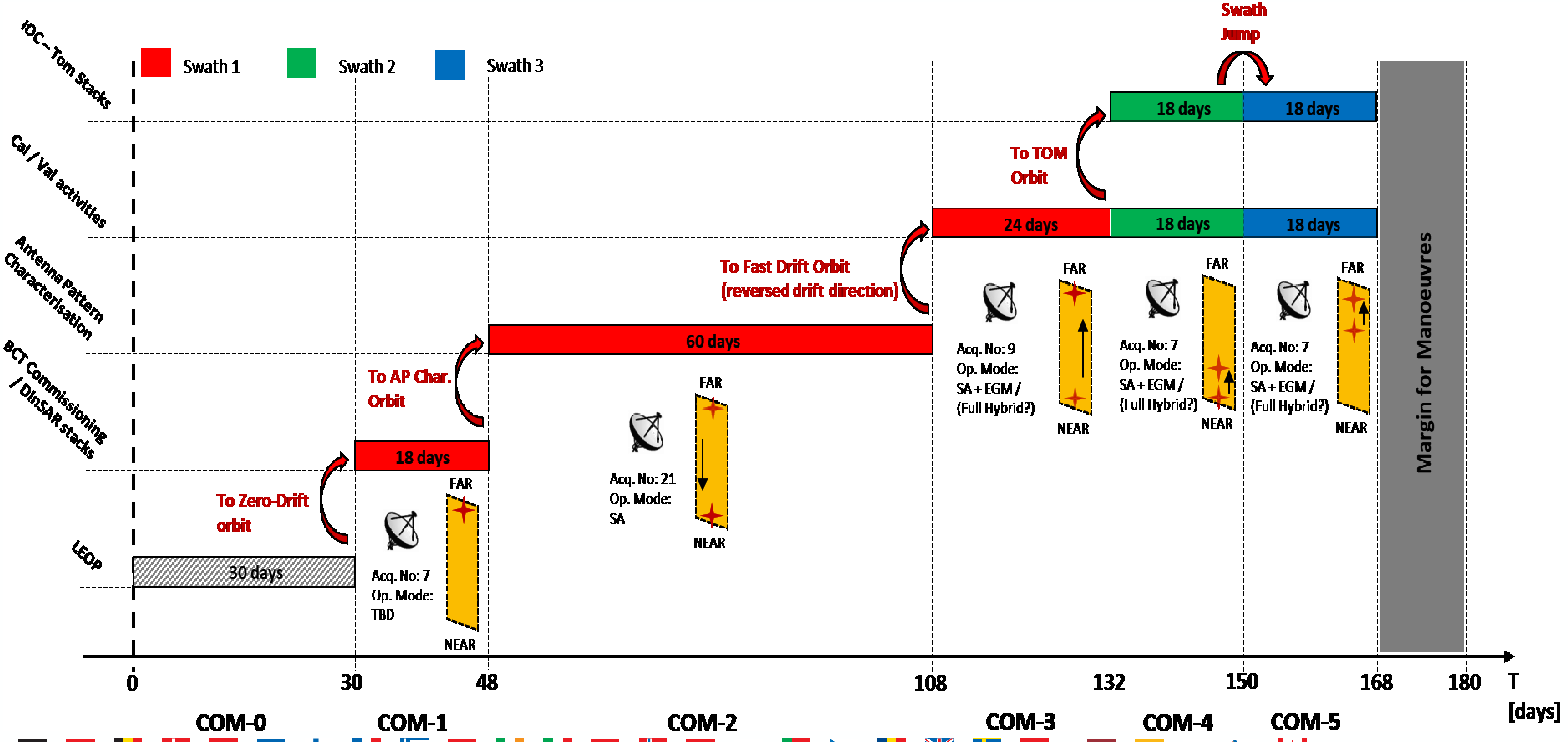


For system calibration: radiometry, polarimetry, geometry

The detection of a received pulse, triggers the re-transmission of four delayed pulses, each one associated with a polarimetric signature and properly amplified to simulate a given RCS.

$$S_{HH} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}; \quad S_{HV} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}; \quad S_{VH} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}; \quad S_{VV} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

IOC Baseline Plan [1/2]

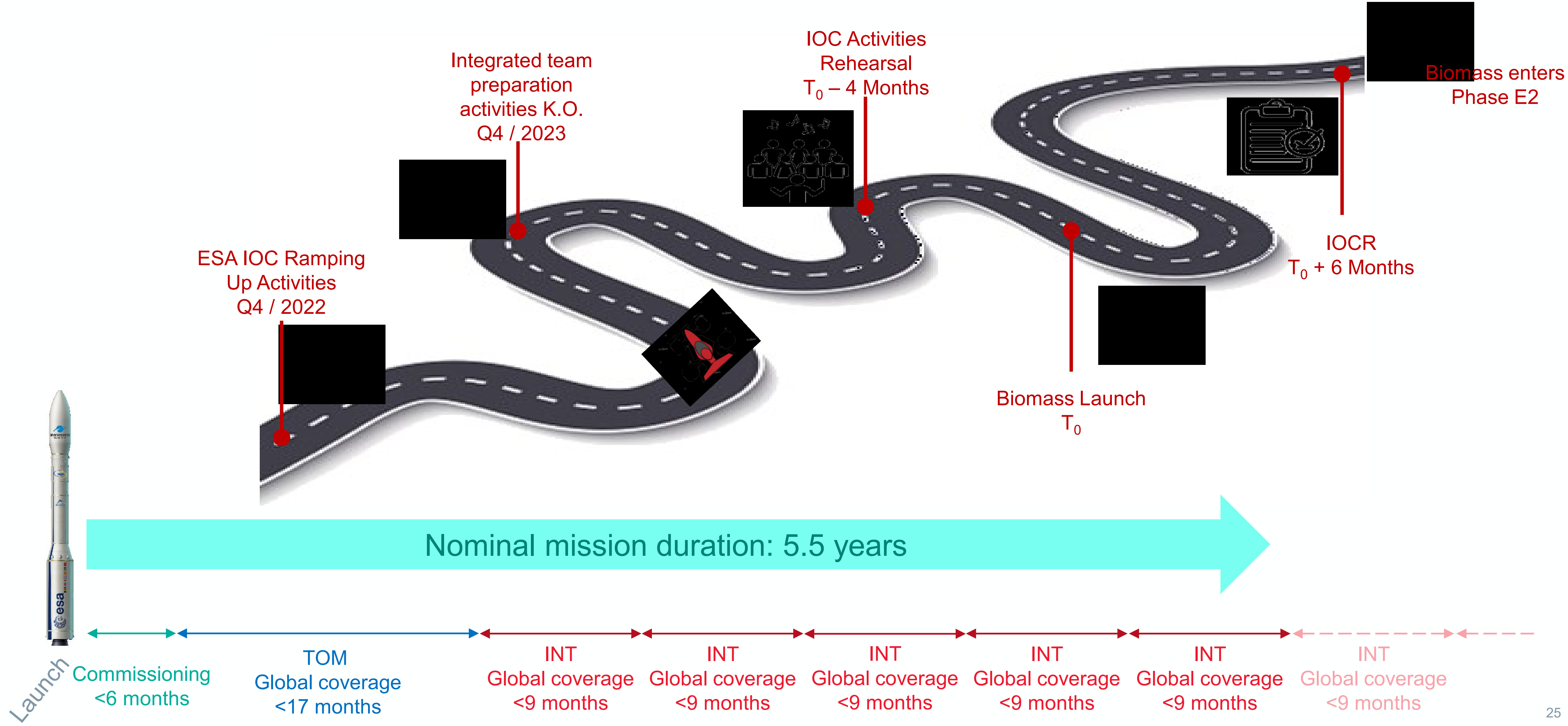


IOC Baseline Plan [2/2]

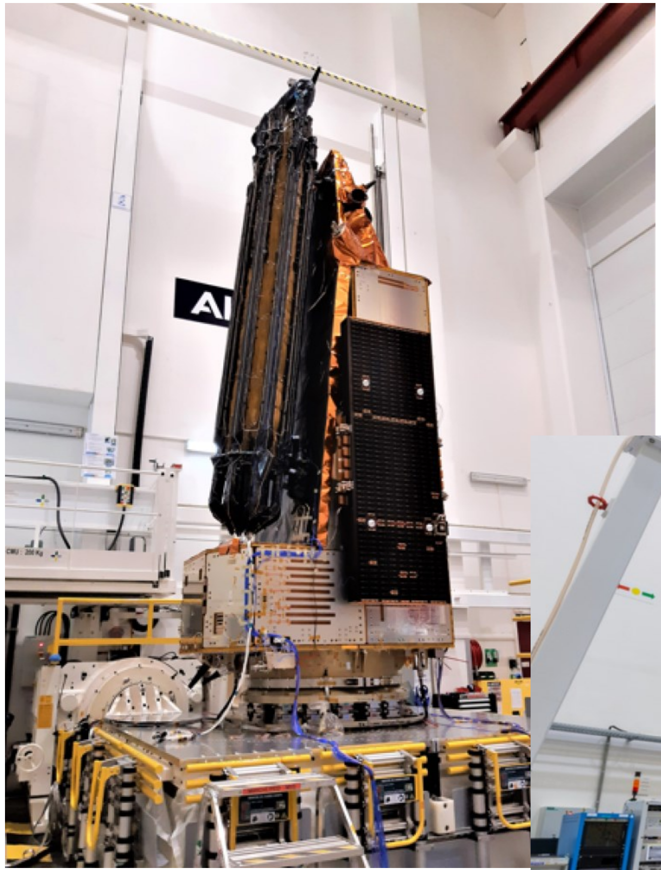
Sub-phase	Title	Orbit type / requirements	Task duration	Comments
COM-0	Platform-Instrument functional checkout	From end of LEOP, on the move to Zero Drift orbit	30 days (max)	
COM-1	BCT – S/C characterisation	Zero Drift orbit	18 days (7 overpasses max), allowing to build a stack with 7 acquisitions	Pre-requisite: Zero Drift orbit must be achieved All SWs possible (BCT seen at far edge of SW1) Manoeuvre: 3 Up
COM-2	Antenna pattern characterisation	"normal" COM orbit (2.85 km West drift)	60 days, 21 overpasses (BCT)	BCT seen in SW1 only Manoeuvre: 3 Down
COM-3	Cal./Ver. activities	Fast drifting orbit (12 km East drift)	24 days, 9 overpasses (BCT)	BCT seen in SW1 Manoeuvre: 3 Up
COM-4	Move to TOM SW2	TOM orbit (0.868 km East drift)	18 days, 7 overpasses (BCT)	BCT seen at near edge of SW2 Manoeuvre: 9 Down
COM-5	Move to TOM SW3	TOM orbit (0.868 km East drift)	18 days, 7 overpasses (BCT)	BCT seen at far edge of SW3
Repeat cycle: 3 days Cycle length: 44 orbits BCT location: -31.05212, 116.1919 (lat, lon)				

- In addition to cal transponder passes, additional targets – including Level-2 validation sites – will be acquired as well as for specific purpose (e.g. ionospheric characterisation and channel imbalance verification)
    - Planning being finalised

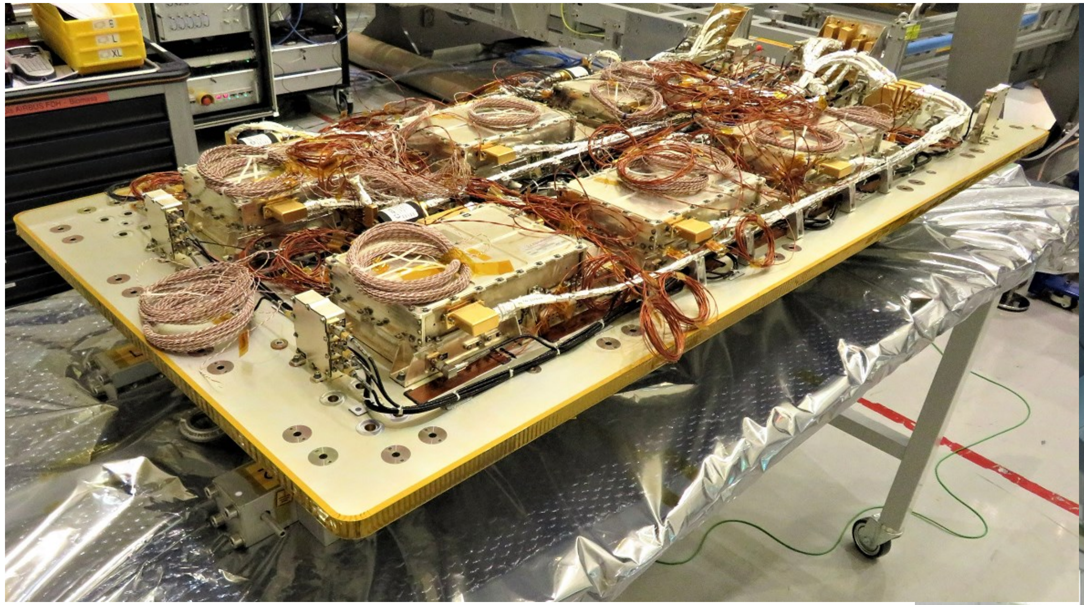
The road to Phase E2: Biomass' exploitation phase

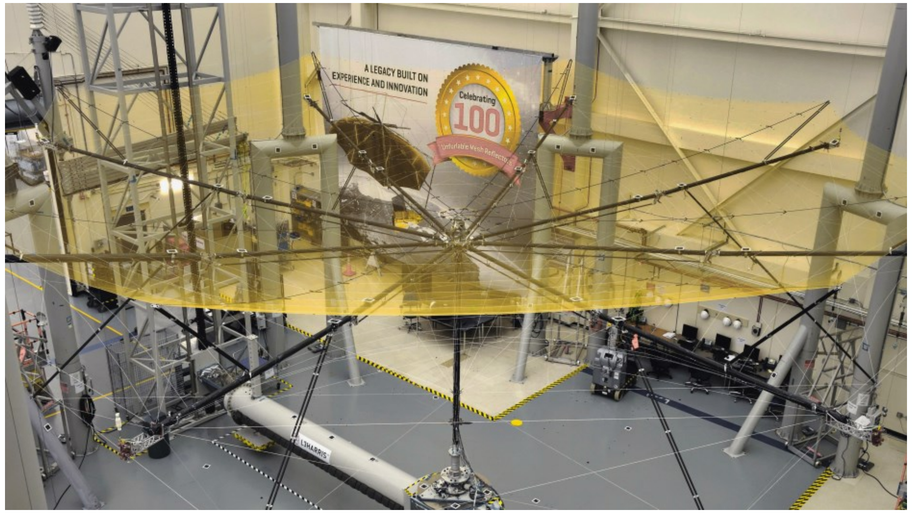


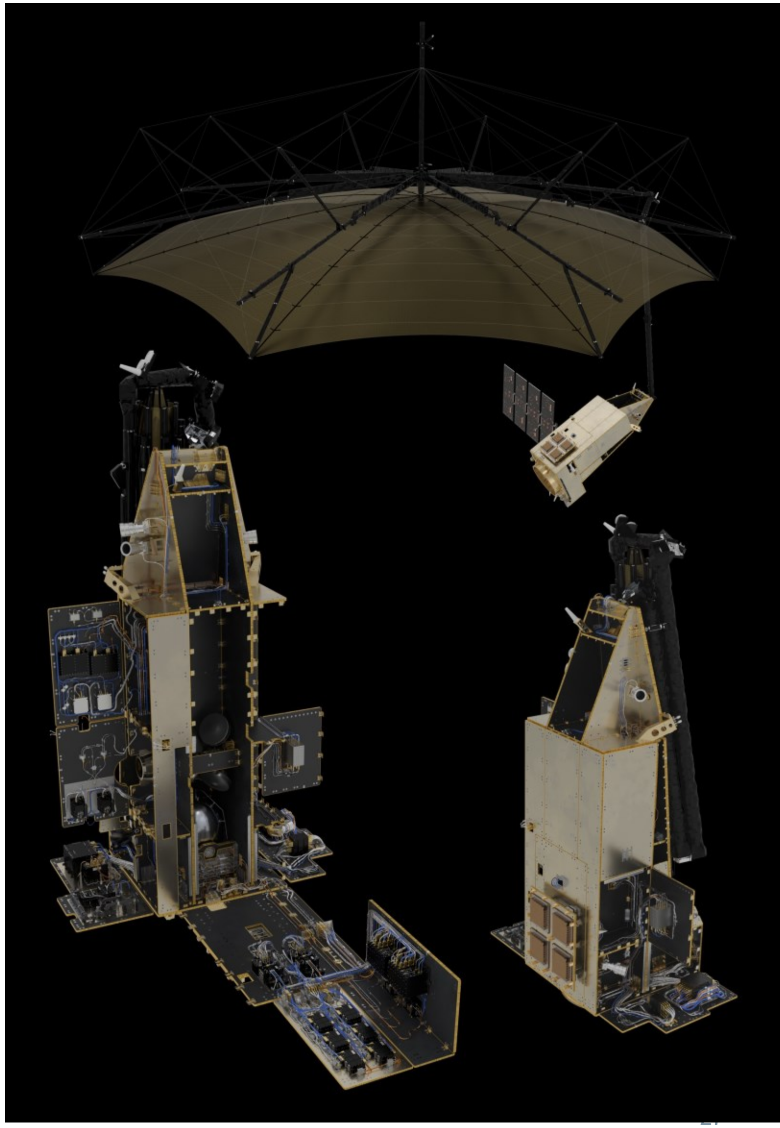
Biomass Assembly, Integration & Testing



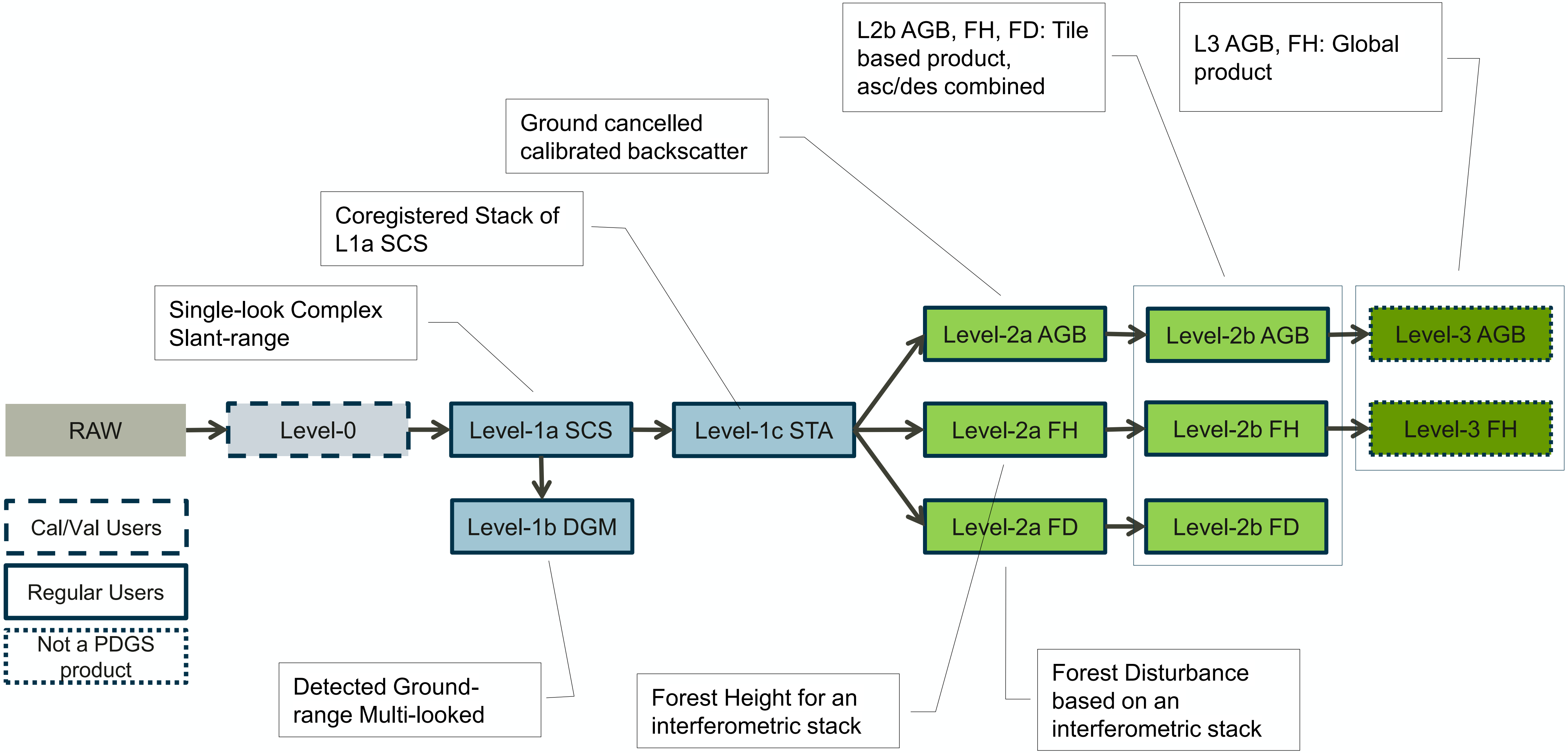
Biomass getting ready for launch







Biomass Product Tree



CEOS Hierarchy of Validation

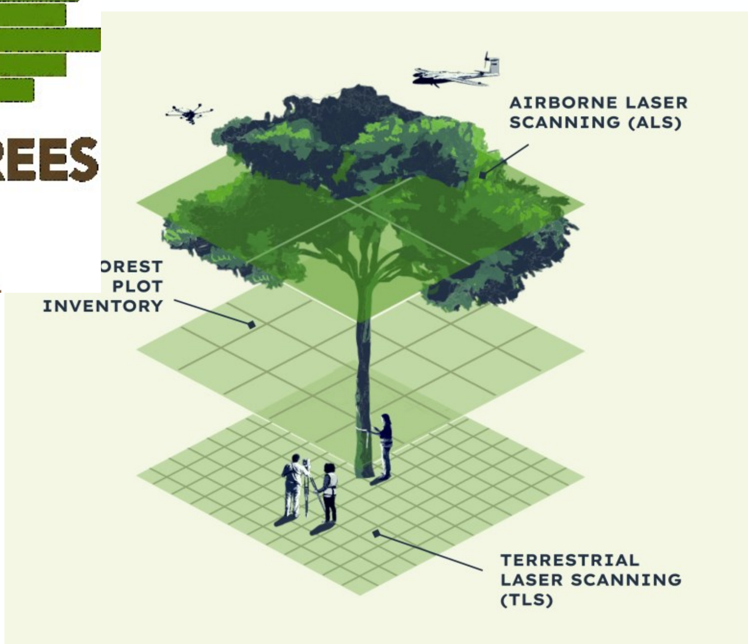
Validation Stage - Definition and Current State	
0	No validation. Product accuracy has not been assessed. Product considered beta.
1	Product accuracy is assessed from a small (typically < 30) set of locations and time periods by comparison with in-situ or other suitable reference data.
2	Product accuracy is estimated over a significant (typically > 30) set of locations and time periods by comparison with reference in situ or other suitable reference data. Spatial and temporal consistency of the product, and its consistency with similar products, has been evaluated over globally representative locations and time periods. Results are published in the peer-reviewed literature.
3	Uncertainties in the product and its associated structure are well quantified over a significant (typically > 30) set of locations and time periods representing global conditions by comparison with reference in situ or other suitable reference data. Validation procedures follow community-agreed-upon good practices. Spatial and temporal consistency of the product, and its consistency with similar products, has been evaluated over globally representative locations and time periods. Results are published in the peer-reviewed literature.
4	Validation results for stage 3 are systematically updated when new product versions are released or as the interannual time series expands. When appropriate for the product, uncertainties in the product are quantified using fiducial reference measurements over a global network of sites and time periods (if available).

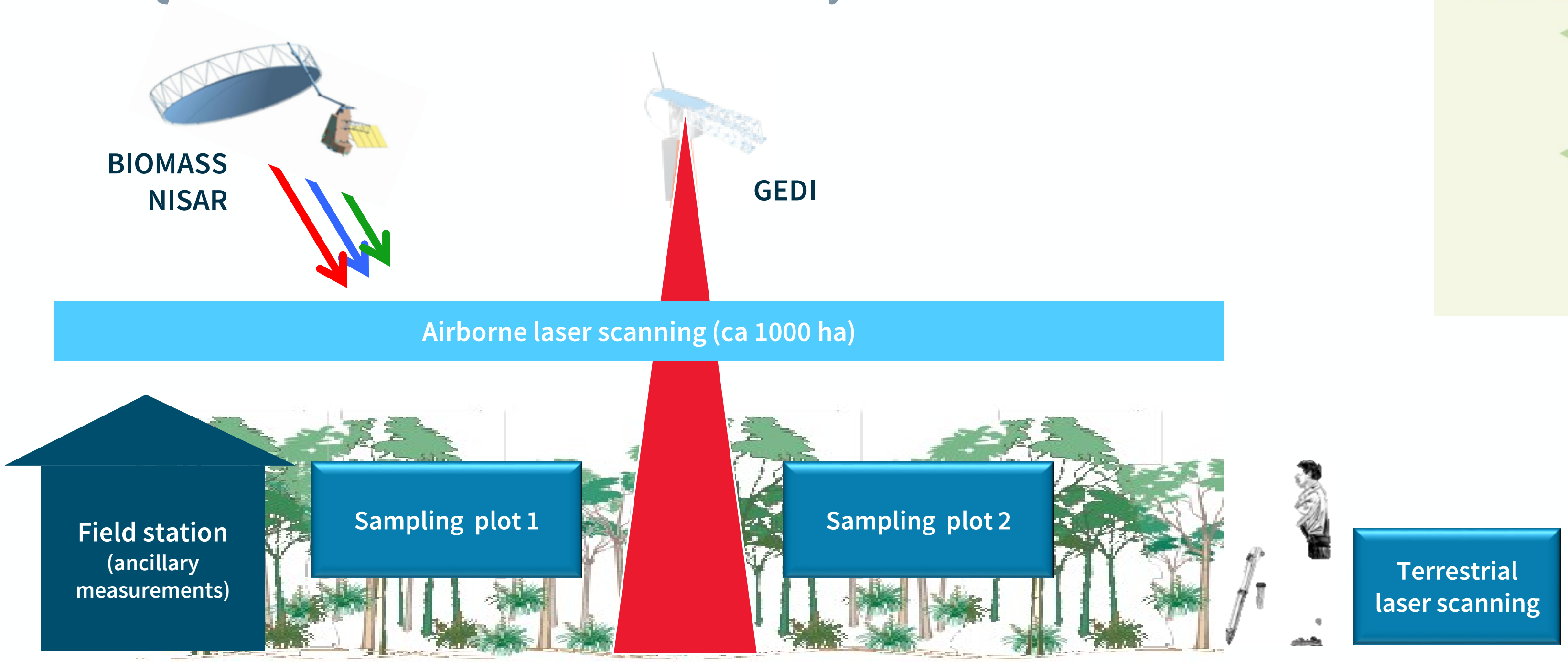
At the end of the Mission, we would like to be here

Validation approach using GEO-TREES [1/3]

GEO-TREES is an equitable and sustainably-funded system of recurrent site-based measurements that will serve as a lasting interface between the Earth Observation agencies and ground-based tree-by-tree measurement initiatives.

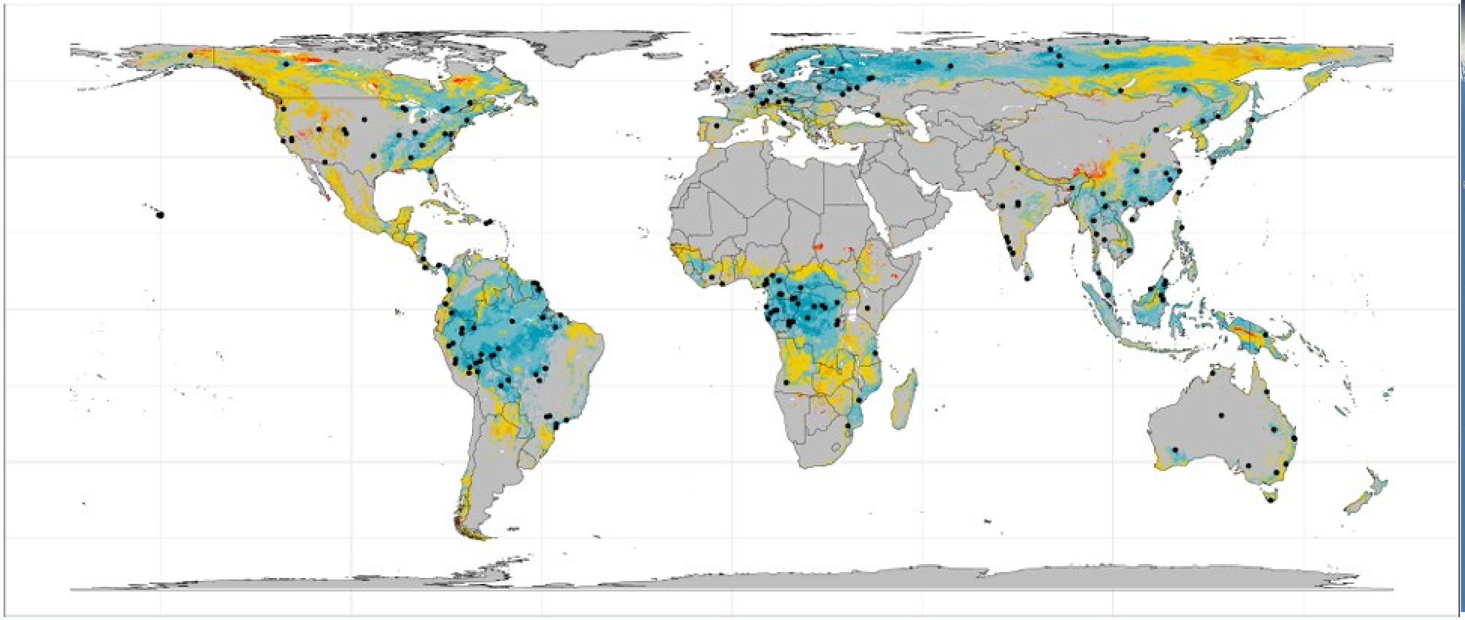
This Fiducial Reference Measurement infrastructure is designed to become a **common good** for the entire EO community.



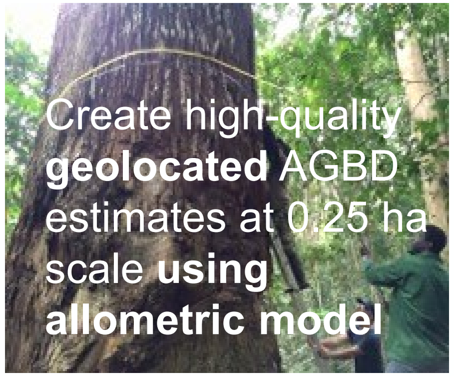


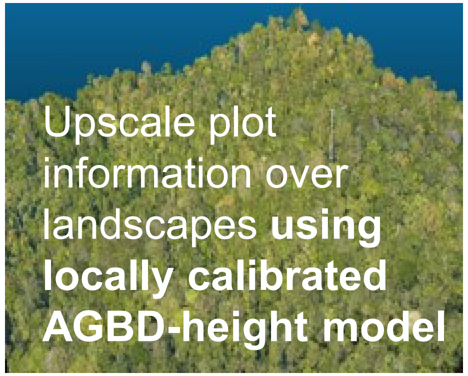
Validation approach using GEO-TREES [2/3]

Potential BRM sites

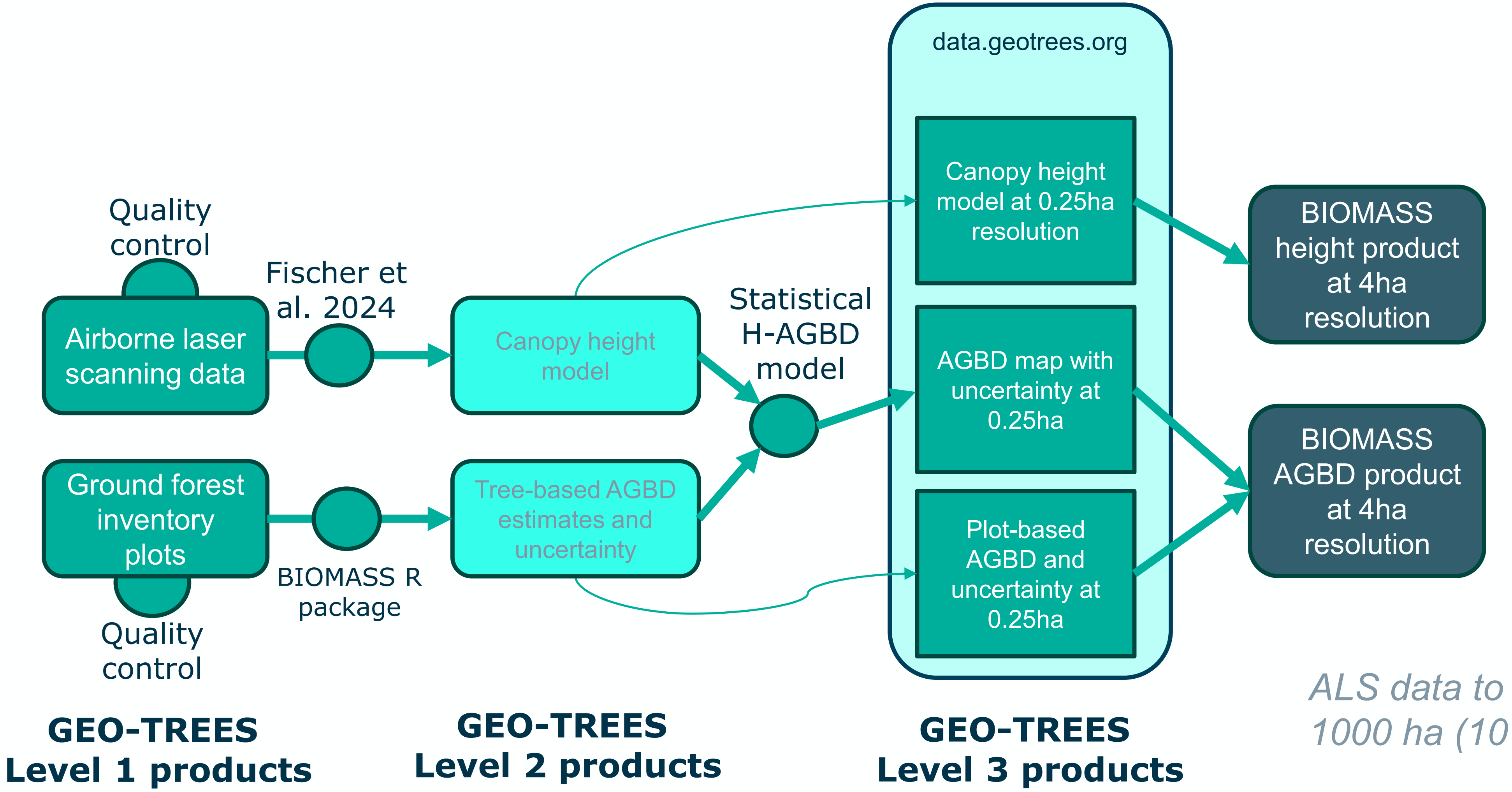


Status August 2024





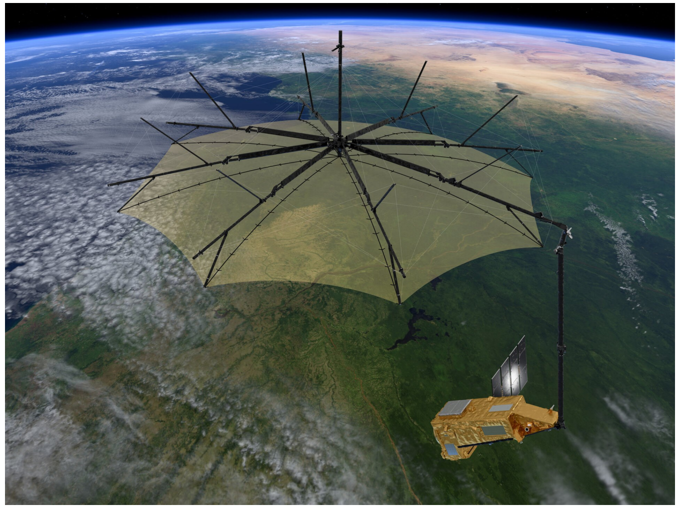
Validation approach using GEO-TREES [3/3]



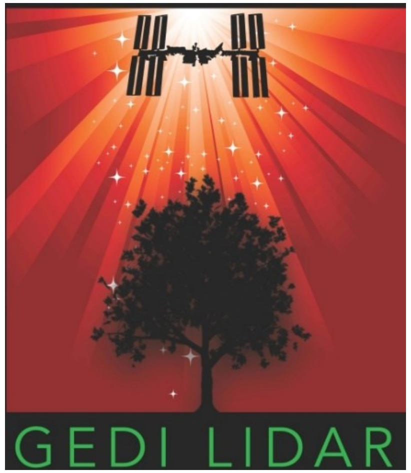
ALS data to cover at least 1000 ha (10 km^2) for each site

BIOMASS in a Global Carbon Observing System

Forest biomass & height (2025-2030)



Forest biomass < 100 t/ha (2025-2035)

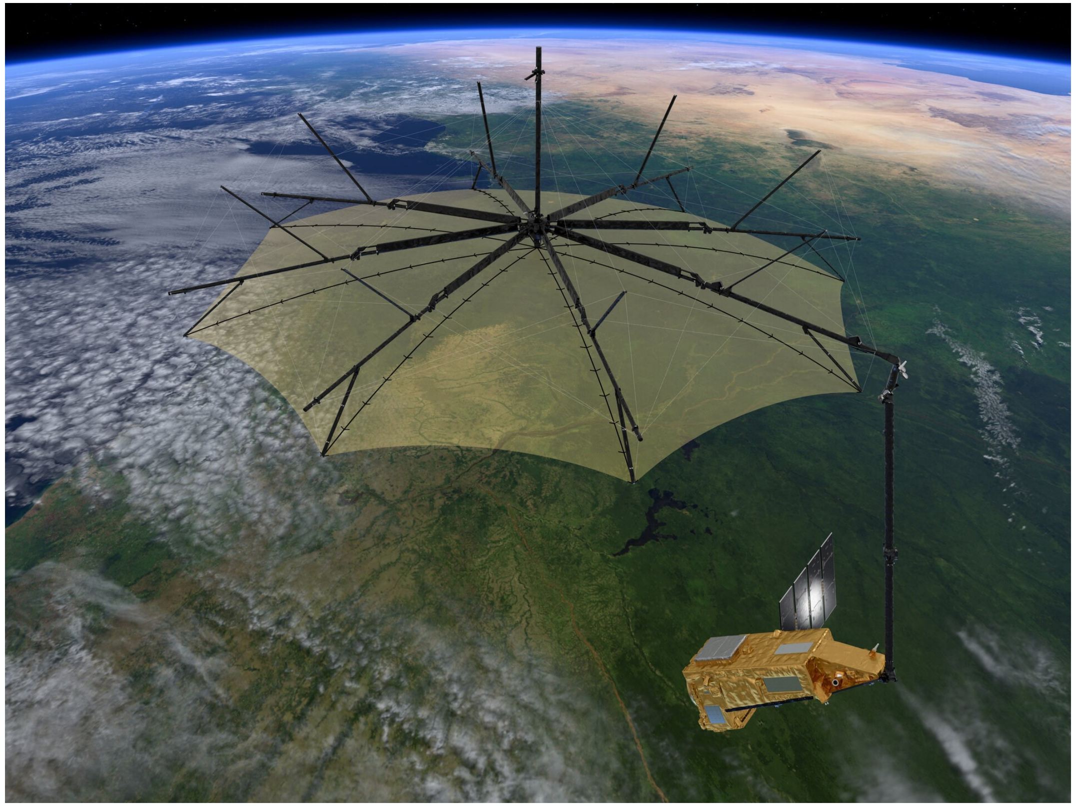


Forest structure & biomass (2018-2023 & 2024 - ?)

The “4th mission”: in-situ networks

- 3 missions dedicated to measuring forest properties
- Major support from ground networks:
  - GEO-TREES
- Other L-band and C-band SAR data, L-band radiometry, IceSAT-2 lidar
- The combined capability is far greater than the sum of its parts
- ESA/NASA Mission Algorithm and Analysis Platform (MAAP)

Outlook



- ESA's EE7 Biomass mission is the first **P-band** SAR and first mission with a systematic **tomographic** mapping phase
- A true Earth Explorer with a lot of **unknowns** and **exciting** science for global biomass mapping
- Satellite completed the final environmental test campaign
- **Launch** on VEGA-C Q2-2025
- Announcement for **Cal/Val activities** by end of December

- The new unique vision of Earth from Biomass will extend beyond forests and into measurements of ice, sub-surface geomorphology in deserts, topography, the ionosphere, ocean ...

- The **combination** of BIOMASS, GEDI and NISAR offers an unprecedented opportunity to estimate biomass accurately from space, and the ESA/NASA MAAP provides a crucial tool enabling this opportunity to be grasped

ESA-ISRO arrangement for Biomass operations

Kulasekharapatnam

Inner Zone

Outer Zone

Satish Dhawan Space Center

Inner Zone

Outer Zone

- Agreement concerning the operational coordination of Biomass operations in case of launch events
- The 433.75 – 434.25 MHz band is used in India by launch vehicle receivers
- Exclusion zone dependent on launch site (Kulasekharapatnam or Satish Dhawan Space Center)
- Inner Zone active T0-3 days; Outer Zone active for T0 when conflicting with Biomass overpass