BIOMASS Forest Disturbance Product ATBD

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1. Introduction

1.1. Context

BIOMASS is ESA's 7th Earth Explorer mission. The purpose of the BIOMASS is to reduce the uncertainty in the worldwide spatial distribution and dynamics of forest biomass in order to improve current assessments and future projections of the global carbon cycle. This objective will be achieved by the implementation of a P-band SAR mission, providing global maps of forest biomass stocks, forest disturbance and growth.
The BIOMASS mission will also provide 3D views of forests through the "tomographic" phase and will also support additional science needs arising from the opportunity to explore the Earth for the first time with a P-band SAR system from space offering the possibility to "see" below the vegetated areas and in beneath bare soil or icy regions.

To achieve its challenging objectives, the BIOMASS mission requires a specific data processing strategy that combines different technologies at different processing level in order to generate the final Above Ground Biomass global map.

1.2. Scope of the document

The purpose of this document is to provide the "Forest Disturbance Algorithms Theoretical Baseline Document (ATBD)" for the BIOMASS Processing Suite (BPS) project.
This document is organized as follows:

- Section 1: Overview of the document;
- Section 2: Brief introduction about BPS and Forest Disturbance processing;
- Section 3: Description of L2a Forest Disturbance algorithms;
- Section 4: Description of L2b/L3 Forest Disturbance algorithms.

1.3. Acronyms

Acronym	Description
AD	Applicable Document
ADS	Annotation datasets
ACM	Average Covariance Matrix
AGB	Above-ground biomass
ARESYS	Advanced Remote Sensing and Systems
ATBD	Algorithm Theoretical Baseline Document
AUX	Auxiliary

Acronym	Description
BIODEMPP	Biomass DEM Prototype Processor
BPS	BIOMASS Processing Suite
CFI	Customer Furnished Items
CFM	Computed Forest Mask
CM	Covariance Matrix
CoSCS	Coregistered SCS
CP	co-polarization
DEM	Digital Elevation Model
DGG	Discrete Global Grid
DTM	Digital Terrain Model
ECSS	European Cooperation for Space Standardization
EO-CFI	Earth Observation Custom Furnished Items
ESA	European Space Agency
GPP	Ground Processor Prototype
GPS	Global Positioning System
FD	Forest Disturbance
FH	Forest Height
FNF	Forest/Non-Forest Mask
GN	ground cancellation (Ground Notching)
IERS	International Earth Rotation Service
InSAR	Interferometric Synthetic Aperture Radar
INT	Interferometric Phase
L0	Level-0 product
L1c	Level-1c product
L2a	Level-2a product
L2b	Level-2b product
L3	Level-3 product
LOS	Line Of Sight
LUT	Look-Up Table
PF	Processing Facility
PFD	Product Format Specification Document
RD	Reference Document
SAR	Synthetic Aperture Radar

Acronym	Description
SCS	Single-look Complex Slant-range
SKP	Sum of Kronecker Products
SNR	Signal-to-Noise Ratio
TBD	To Be Defined
TBC	To Be Confirmed
TOM	Tomographic Phase
XML	eXtended Markup Language
XP	cross-polarization

1.4. TBD / TBC Table

Section	TBD / TBC	Page
1.6	BTK_WEB: link must be defined	9

1.5. Applicable documents

[AD1] BIOMASS Production Model, BIO-ESA-EOPG-EEGS-TN-0046, issue 3.5
[AD2] BIO-BPS-TN-PRODMOD, BIOMASS Production Model Technical Note, I/R 1/2/1
[AD3] BIO-BPS-L1-PFD, BIOMASS L1a,b,c products format specification, I/R 1/2/2

1.6. Reference documents

[RD1] BIO-BPS-L1-STACK-ATBD, BIOMASS BPS L1c Stack ATBD, I/R 1/1/2
[RD2] BIO-BPS-L1-SAR-ATBD, BIOMASS BPS L1 SAR ATBD, I/R 1/1/2
[RD3] BIOMASS DEM Product Processor Prototype, DEM Processor Algorithm Theoretical Baseline Document, BIODEMPP-CoSCS-DEM-01, Issue 4.0, June 07th 2021
[RD4] M. Mariotti d'Alessandro, S. Tebaldini, S. Quegan, M. J. Soja, L. M. H. Ulander and K. Scipal, "Interferometric Ground Cancellation for Above Ground Biomass Estimation," in IEEE Transactions on Geoscience and Remote Sensing, vol. 58, no. 9, pp. 6410-6419, Sept. 2020
[RD5] K. Conradsen, A. A. Nielsen and H. Skriver, "Determining the Points of Change in Time Series of Polarimetric SAR Data," in IEEE Transactions on Geoscience and Remote Sensing, vol. 54, no. 5, pp. 3007-3024, May 2016
[RD6] K. Conradsen, A. A. Nielsen, J. Schou and H. Skriver, "A test statistic in the complex Wishart distribution and its application to change detection in polarimetric SAR data," in IEEE Transactions on Geoscience and Remote Sensing, vol. 41, no. 1, pp. 4-19, Jan. 2003
[RD7] BIO-BPS- AUX-FMT,BPS Auxiliary Product Format, I/R 2/1/1

[RD8] BIO-BPS-PPD, BIOMASS BPS Product Performance Description, I/R 2/0/2
[RD9] L2-ATBD-ARE-011567, BIOMASS L2 Algorithm Theoretical Baseline Document, I/R 1/5
[RD10] BIO-BPS-IODD, BIOMASS BPS IODD, I/R 1/1/3
[RD11] BTK_WEB: official link TBD

2. BPS and FD Processing Overview

2.1. BPS Overview

The BIOMASS Processing Suite (BPS) is in charge of processing BIOMASS Level-0 data up to Level-3, generating a wide set of products. Product generation scheme is depicted in the following two figures respectively for the TOM phase and INT phase. The processing foresees the following steps:

- **L1 processing**: the BIOMASS image formation step, taking as input 1 L0 slice and generating as output N>=1 L1 frames;
- **Stack Processing**: the coregistration and stacking processing step that will define the required 7-images Tomographic stacks or the 3-images Interferometric stacks. It includes stack phase calibration;
- **L2a Processing**: processing step for each stack that provides the inputs to the further products Tile Generation performed by the L2b processors. For one global cycle the number of stacks varies mainly with latitude, approximately from a minimum of two at the Equator (ascending/descending) to about six at higher latitudes (three ascending/descending pairs);
- **L2b Processing**: processing that aggregates all the stack-based L2a products insisting on the same location on ground (Tile) in the same time interval and generates a single BIOMASS L2b product. A different number of stacks may be available for each DGG tile [RD8], based on tile dimensions and swath coverage (which is not related to DGG tiling pattern);
- **L3 Processing**: consolidation processing removing discontinuities in L2b products.

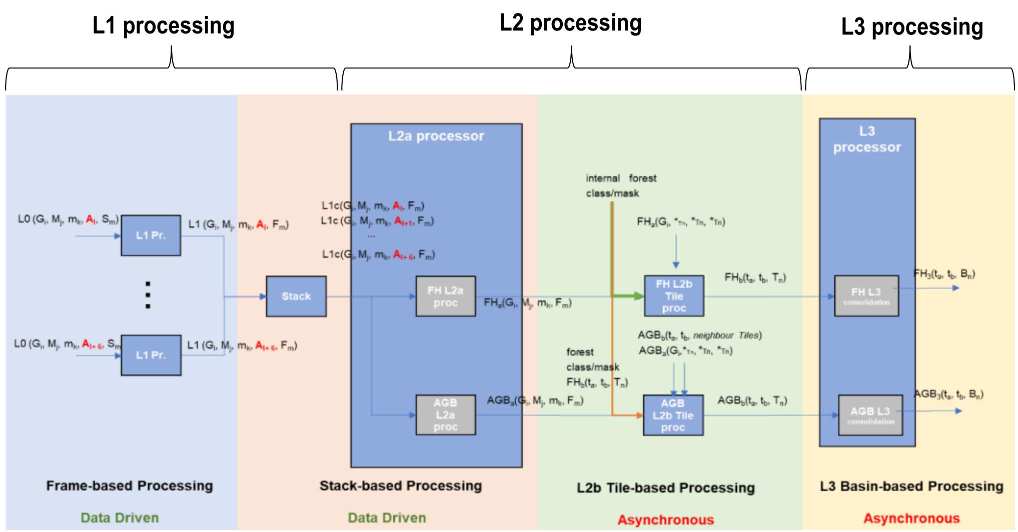

Fig.1 Biomass high-level processing scheme from L0 data to L3 products, TOM phase.

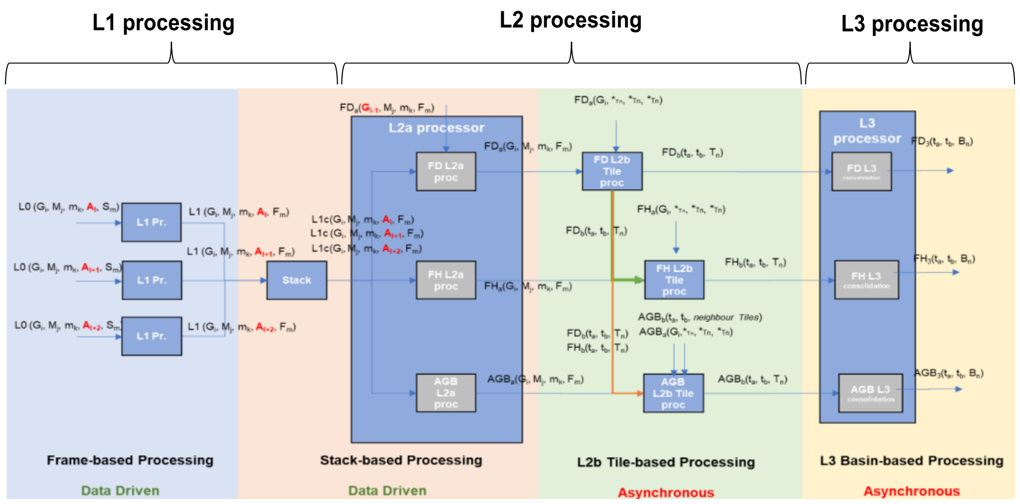

Fig.2 Biomass high-level processing scheme from L0 data to L3 products, INT phase.

2.2. FD Processing Overview

The FD processing runs during INT phase only and has as main goal the generation of maps of high-intensity change between successive temporal cycles due to deforestation (logging, fire etc.) at a spatial resolution roughly equivalent to ~50 m x 50 m (i.e. 0.25 ha) at the Equator [RD9]. It receives as input a stack of BIOMASS Level-1c images (SCS co-registered and calibrated stack), including its relevant annotated data [AD3]. The FD processing is divided into three levels:

- L2a, generates a map of the probability of change from each L1c stack based on statistical hypothesis testing algorithm, as well as a forest disturbance map and a Computed Forest Mask (CFM), accounting for the cumulative disturbance updates;
- L2b, generates a forest disturbance map merging all the L2a products on a geographic grid tile, as well as an aggregated probability of change map and CFM;
- L3, consolidates the result removing discontinuities in L2b products.

The production model foresees the additional optional possibility of having an FD product also from TOM phase [AD1]. In this case the product would contain only average covariance information (ACM) to be used during the first INT cycle for the computation of disturbance (Section 3.7.4.3).

NOTE: L3 processing currently does not entail any additional step with respect to L2b. This will be confirmed/reassessed at future milestones. For the moment L3 is kept as a placeholder for eventual future evolutions. Eventually, L2b can be an empty container and the product will be copied to L3.

NOTE: Provided that FD algorithm proper validation will only be possible with BIOMASS in orbit, the strategy proposed to deal with FH/AGB dependency on FD is to initially input to

FH/AGB a forest/non-forest mask generated outside of BPS [AD1][AD2]. After testing FD performance with BIOMASS in orbit, FD dependency can be switched on again, provided it has a satisfactory performance. The diagram of Fig.2 reports nonetheless FD input for completeness.

NOTE: L2 processor receives from Stack processor L1c products with two co-polarization (CP) channels and one cross-polarization (XP) channel. Details on the aggregation of XP channels into one XP are reported in [RD1].

NOTE: Regarding stack images cardinality, their number can vary (not always 3 or 7) due to contingency reasons and it can go up to 8 in TOM phase.

2.3. FD Processing Workflow and Algorithmic Overview

The main steps of FD processing workflow are depicted in the following figure and described in detail in the following sub-sections. This algorithm is an enhancement of the one described in [RD9].

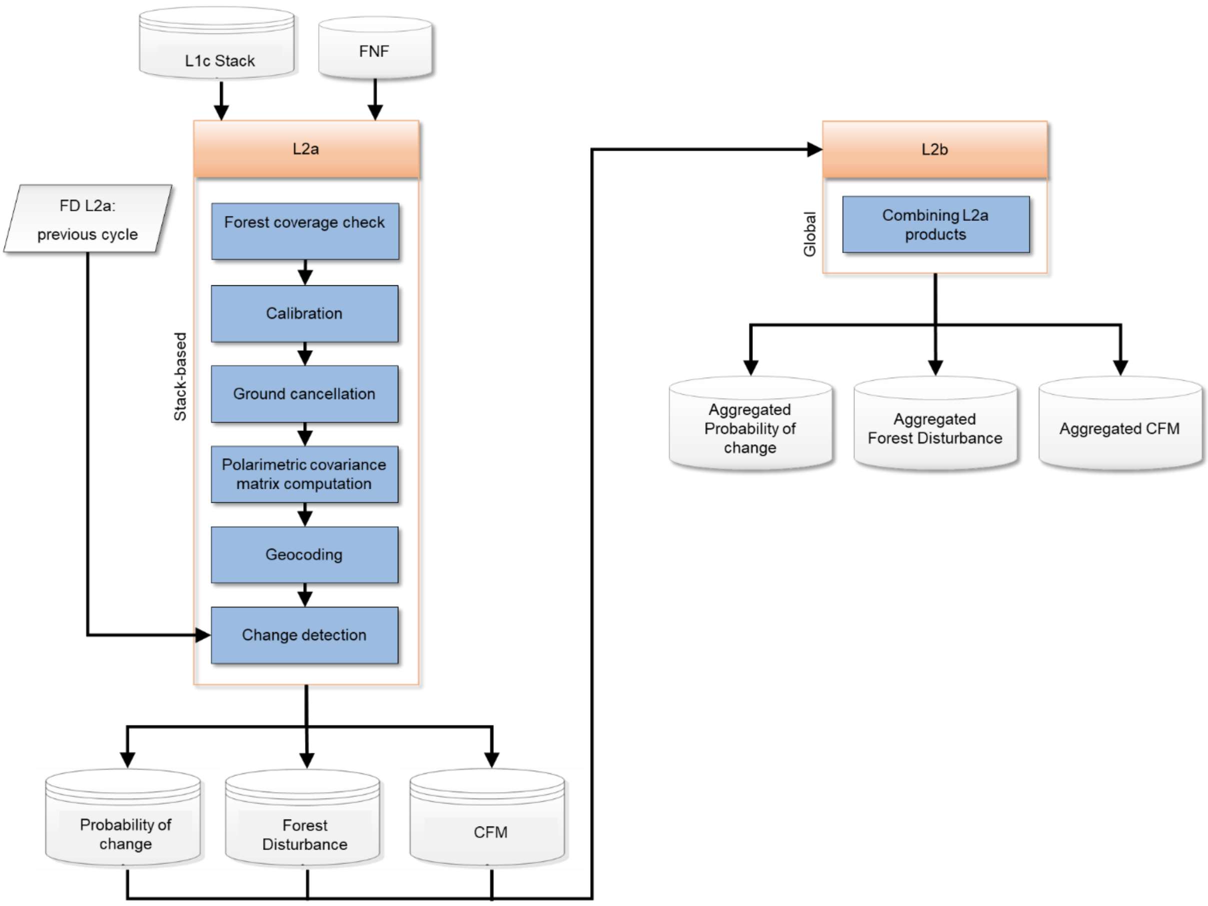

Fig.3 FD processing detailed workflow.

2.3.1. Change detection (L2A_P)

The main steps of the stack-based L2a block are:

- forest coverage check: predetermine which input data (as a whole image) should need to be processed;
- calibration: application of phase calibration and ground steering (terrain at zero elevation) screens to the stack;
- ground cancellation: removes the contribution of the ground scattering from the stack;
- polarimetric covariance matrix computation: computes the polarimetric covariance matrix from ground cancelled data;
- geocoding: projects the processed data on a geographic map, accounting for the different forest point locations with respect to the reference DEM;
- change detection: computes the probability of change from hypothesis testing between the covariance of the current and previous cycles and computes disturbance maps from L2a probabilities of change for each stack.

2.3.2. Change detection aggregation (L2B_FD_P)

The main steps of the L2b block are:

- combining: fusion of L2a estimates at map level.

2.3.3. Note on interpretation of inputs and outputs tables

Inputs and outputs for each processing sub-step are summarized in specific subsections (two subsections for each substep). A specific tabular format is defined to improve the access to the document. The meaning of each column is exemplified in the following table.

Symbol	Name	Origin/ Destination	Size	Variability	Default	Description
Mathematical symbol of the quantity appearing in formulas.	Name of the quantity as related to other BPS documentation (e.g., AUX_FMT, L1 ATBDs, …)	BPS document name describing the origin of the quantity or processing step of origin/destination or BPS product of destination.	Dimensions of the quantity.	Range of values or update rate of an internal resource.	Default value for configuration parameters.	Verbal description of the quantity and its characteristics (e.g. measure units, …)

3. Change detection

The overall scheme of the L2a processing is reported in Fig.3.
The key steps are ground cancellation and the change computation. These steps are described in detail in the following subsections.

3.1. Forest Coverage Check

3.1.1. Overview and rationale

The availability of a general FNF map allows to predetermine which input data (as a whole image) should need to be processed. A threshold (*mF*) must be set as input parameter to select the minimum forest coverage (as a percentage of the whole area covered by the images) to start or skip computation.

The step is optional. If unset, change detection computation is always performed for all the data elements.

3.1.2. Inputs

Symbol	Name	Origin	Size	Variability	Default	Description
FNF	FNF	Internal resource (IODD)	$[N_{lat,FNF} \times N_{lon,FNF}]$	Yearly	-	A global forest-non-forest mask given as input
mF	forestCoverageThreshold	AUX_PP2_2A (AUX_FMT)	float value [scalar]	0.0-100.0	5.0	The minimum [%] relative forest coverage that triggers the computations
BB	Footprint	L1c main product header (L1_PFD)	lat-lon vertices [4 couples]	-	-	The extent of the L1c input data in geographical coordinates

3.1.3. Outputs

Symbol	Name	Destination	Size	Variability	Default	Description
TR	trigger	*Next steps*	Boolean [scalar]	-	True	Allows to trigger (True) the computation of

Symbol	Name	Destination	Size	Variability	Default	Description
						the change detection

3.1.4. Algorithm mathematical background

The values of the FNF mask that lie within the area covered by the image, defined by the bounding box *BB*, are extracted from the global FNF mask. The relative number of forested pixels is compared to the required minimum threshold *mF* to trigger any subsequent computation.

$$TR = \left(100 * \frac{ForestedArea|_{BB}}{TotalArea|_{BB}} > mF\right) \tag{3.1}$$

3.1.5. Notes on implementation

The substep should be as fast as possible, as its unique role is to avoid any un-useful computation. Thus, comparison is carried on at the original FNF mask spatial sampling (i.e. no reprojection needed), as any resampling does not have any impact on the relative percentage of forested area with respect to the total covered area.
It must be noted that any noValue pixel in FNF is treated as ForestedArea sample to avoid skipping computation because of the presence of noValues in FNF.
Details on the derivation of external FNF are reported in [RD10].

3.2. INT subsetting (TOM only)

3.2.1. Overview and rationale

The algorithm applies only to TOM stacks and subsets the stack in order to select the acquisitions to operate as in INT phase. The only rule applicable at the moment follows a geometric criterion. Other rules could be defined post-launch.

This step is mandatory for TOM only.

3.2.2. Inputs

Symbol	Name	Origin	Size	Variability	Default	Description
SCS	L1c	Stack processor (L1_PFD)	M, each acquisition $[N_{rg} \times N_{az}]$	M=7/8 acquisitions (TOM phase), with two CP and one XP	-	L1c stack

Symbol	Name	Origin	Size	Variability	Default	Description
-	subsettingRule	AUX_PP2_2A (AUX_FMT)	String	-	“geometry”	Select 3 acquisitions from the 7/8 of TOM phase, choosing, with a geometrical rule, the baselines corresponding to the ones of INT phase.

3.2.3. Outputs

Symbol	Name	Destination	Size	Variability	Default	Description
SCS	L1c	*Calibration step*	M, each acquisition $[N_{rg} \times N_{az}]$	M=3 acquisitions, with two CP and one XP	-	L1c stack

3.2.4. Algorithm mathematical background

3.2.4.1. Geometry criterion

The "geometry" criterion for subsetting selects among the seven/eight TOM stack the three acquisitions that give nominally consistent baselines with INT phase. As different combinations are possible, see Fig.4, the default rule is to select the central combination, which is corresponding to exactly the same nominal situation as INT. In case this combination presents a missing acquisition, the rule is to then evaluate remaining combinations in sequential order until a three-acquisitions combination is found. If no combination of three exists, the minimum required is two and the maximum baseline is equivalent to double TOM spacing. The contingency case with eight TOM acquisitions is reported in Fig.5.

```
                         0    1    2    3    4    5    6          TOM stack
Evaluation order         *    *    *    *    *    *    *
             2           *         *         *
             1                *         *         *               <-default
             3                     *         *         *
```

Fig.4 Selection for seven TOM.

	0	1	2	3	4	5	6	7	TOM stack
Evaluation order	*	*	*	*	*	*	*	*	
2	*		*		*				
1		*		*		*			<-default
3			*		*		*		
4				*		*		*	

Fig.5 Selection for eight TOM (contingency).

3.3. Calibration

3.3.1. Overview and rationale

The calibration algorithm makes use of the L1c annotation [AD3] to apply phase calibration to L1c necessary for the L2a processing.

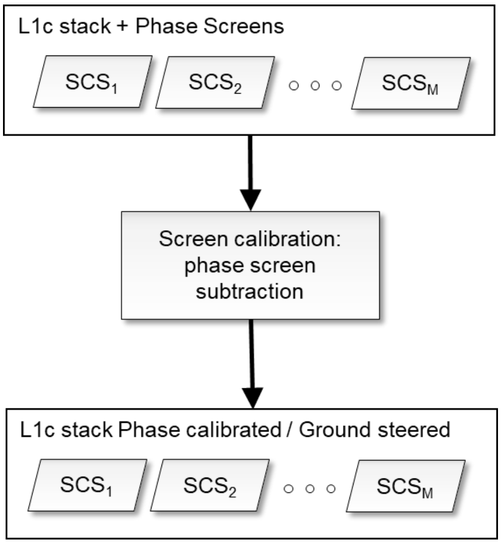

Fig.6 Calibration.

The step is mandatory. If disabled for debug, default rule is to copy inputs as step output.

3.3.2. Inputs

Symbol	Name	Origin	Size	Variability	Default	Description
SCS	L1c	Stack processor, or *INT subsetting step*	M, each acquisition $[N_{rg} \times N_{az}]$	M=3 acquisitions, with two CP and one XP	-	L1c stack
φ_{skp}	skpCalibrationPhasesScreen	L1c reference acquisition ADS (L1_PFD)	M, each $[N_{rg,\varphi} \times N_{az,\varphi}]$ (zero for reference acquisition)	-	-	SKP calibration phase screens [rad]
$\varphi_{flattening}$	flatteningPhasesScreen	L1c reference acquisition ADS (L1_PFD)	M, each $[N_{rg,\varphi} \times N_{az,\varphi}]$ (zero for reference acquisition)	-	-	Ground steering (flattening) geometry phase screens [rad]
-	applyCalibrationScreen	AUX_PP2_2A (AUX_FMT)	string	‘skp’, ‘geometry’, ‘none’	skp	Choose the phase calibration to be performed: skp or geometry if phase screens calibration should be applied, none otherwise.

3.3.3. Outputs

Symbol	Name	Destination	Size	Variability	Default	Description
SCS	L1c	*Ground cancellation processing step*	M, each acquisition $[N_{rg} \times N_{az}]$	M=3 acquisitions, with two CP and one XP	-	Phase calibrated and ground steered (terrain at zero level) L1c stack

3.3.4. Algorithm mathematical background

This step aims to remove all the phase disturbances from the L1c stack and set terrain phase at zero height (i.e., subtract DTM phase). Each polarization channel is processed independently. The SCS L1c stack provided as input contains a set of calibration and ground steering phase screens (SKP calibration screens and flattening phases screens described in [RD1]). Depending on *applyCalibrationScreen* configuration, the used screen is:

$\varphi = \varphi_{skp} + \varphi_{flattening}$ if *applyCalibrationScreen= "skp"*

$\varphi = \varphi_{flattening}$ if *applyCalibrationScreen= "geometry"*

The operation implemented in the calibration step of the L2 processor is simply the subtraction of the selected calibration phase screens from the input image stack phase. The operation can be expressed as:

$$SCS(r,a,n) = SCS(r,a,n)e^{+j\varphi(r,a,n)} \quad (3.2)$$

where $\varphi(r,a,n)$ is the phase screen accounting for all the disturbance terms and terrain topography relative to the baseline n for each pixel in azimuth a, slant-range r. In the case of the reference acquisition, no compensation is done (zero baseline). If the phase screens have a lower resolution than the SCSs then a preliminary interpolation step is needed. The operation can be expressed as:

$$\varphi(r,a,n) = f\left[\varphi(r,a,n)|_{(rg,\varphi,az,\varphi)}\right]\Big|_{(rg,az)} \quad (3.3)$$

where *f* is a bilinear interpolant function. Other alternate interpolating function are detailed in [RD11].

3.4. Ground cancellation

3.4.1. Overview and rationale

Ground cancellation [RD4] is the interferometric combination of two or more images so that the backscattered echo coming from the ground level is cancelled. This processing step can be carried out starting from the calibrated and ground steered stack of SAR images (so that the phase of the ground contribution is aligned in the images). Consequently, the radar signal coming from a particular elevation gets emphasized. This specific elevation depends on the spatial baseline characterizing the interferometric system, depending on the geometry of acquisition, and cannot usually be chosen when processing the data. However, the availability of more than two interferometric images allows this specific elevation to be selected. This is referred to as interpolated ground cancellation, which is the default setting. The processing steps are described in the following, for two images and with several images.

The step is mandatory. If disabled for debug, default rule is to set I_{GN} (see section 3.4.3) to primary image acquisition.

3.4.2. Inputs

Symbol	Name	Origin	Size	Variability	Default	Description
SCS	L1c	*Calibration processing step*	M, each acquisition $[N_{rg} \times N_{az}]$	M=3 acquisitions, with two CP and one XP	-	Phase calibrated and ground steered

Symbol	Name	Origin	Size	Variability	Default	Description
						(terrain at zero level) L1c stack
k_z	Wavenumber	L1c Stack ADS (L1_PFD)	M, each $[N_{rg,k} \times N_{az,k}]$ (zero for reference acquisition)	-	-	Vertical wavenumbers [rad/m] computed with respect to incidence on inflated ellipsoid
z_0	emphasized ForestHeight	AUX_PP2_2A (AUX_FMT)	float value [scalar]	Global single value* for all polarizations and all pixels	30.0	Desired elevation emphasized from ground cancellation, meters [m]
-	disableGroundCancellationFlag	AUX_PP2_2A (AUX_FMT)	Boolean [scalar]	-	False	True to disable ground cancellation: for debug.
-	operationalMode	AUX_PP2_2A (AUX_FMT)	String	-	“single reference”	Choose the Ground Cancellation method to use
-	imagesPair Selection	AUX_PP2_2A (AUX_FMT)	List of integers	-	-	Optional, needed only when operationMode=”insarPair” and more than 2 images are available

**NOTE: analysis can be carried out post-launch to assess whether this value can be made forest-class dependent.*

The default operation mode of ground cancellation is operationalMode="single reference" with full INT stack [RD7]. To operate with a single pair configuration must be set to “insar pair” and the pair can be selected through imagesPairSelection. In case of only two images available, the operationalMode is automatically set to “insar pair”.

3.4.3. Outputs

Symbol	Name	Destination	Size	Variability	Default	Description
I_{GN}	-	*Polarimetric covariance*	$[N_{rg} \times N_{az}]$	Two CP and one XP	-	Ground cancelled complex image

Symbol	Name	Destination	Size	Variability	Default	Description
		matrix computation		(independent from M)		

3.4.4. Algorithm mathematical background

The flowcharts of the ground cancellation algorithm are shown in Fig.7, Fig.8. Each polarization channel is processed independently. A preliminary interpolation step is needed to bring wavenumbers onto the same L1c grid, in similar fashion as for the calibration screens (Section 3.3.4).

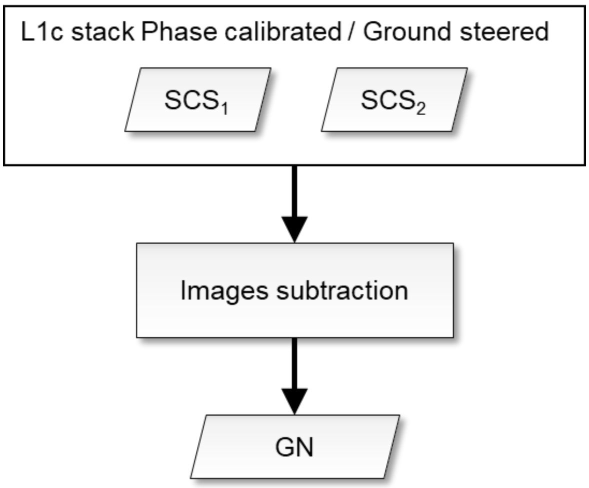

Fig.7 Ground cancellation algorithm with two images.

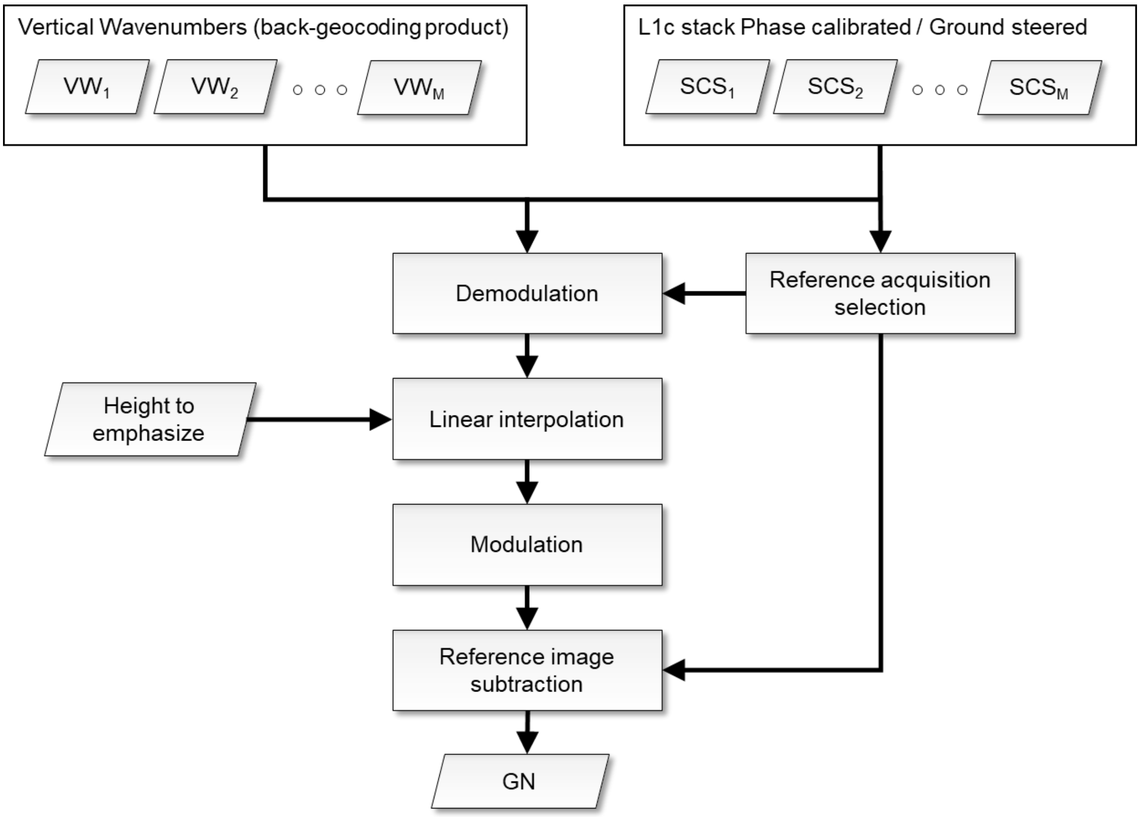

Fig.8 Ground cancellation algorithm with more than two images.

3.4.4.1. Case of two images

The processing for just two images is a simple subtraction of the second image from the first, as represented by

$$I_{GN}(r,a) \;=\; SCS(r,a,1) \;-\; SCS(r,a,2) \tag{3.4}$$

which holds for each polarization channel, for pixel in azimuth a, slant-range r. The first image is not required to be the reference acquisition, as symmetrical quantities, such as the covariance matrix or impulse response function of the ground cancellation (absolute value) are not affected by the order chosen for subtraction [RD4].

3.4.4.2. Interpolated ground cancellation single reference

For a stack of coherent ground steered SCS images (M>2) a further degree of freedom is available: a given elevation above the ground level can be chosen and emphasized together with removal of the ground echo. The desired elevation z_0 must be converted into a wavenumber before feeding it to the routine, using the relation:

$$k_{z_0} = \frac{\pi}{z_0} \tag{3.5}$$

A synthetic SCS associated with the desired wavenumber can be produced by linearly interpolating the stack. To ensure that the backscattering contribution associated with the desired elevation is not distorted by the interpolation process the stack is demodulated so that the desired elevation is steered around 0 m; the elevation to be demodulated coincides with half of the desired elevation. The demodulation is expressed by

$$I_{k_z}(r,a,n) = SCS(r,a,n)e^{-jk_z(r,a,n)\frac{z_0}{2}} \tag{3.6}$$

The linear interpolation algorithm must recognize the previous $k_z^-(r,a) = max\{k_z(r,a,n)\epsilon[k_z(r,a,n) < k_{z_0}]\}$ and the next $k_z^+(r,a) = min\{k_z(r,a,n)\epsilon[k_z(r,a,n) > k_{z_0}]\}$ sampled wavenumbers of the stack and then implement

$$I_{k_{z_0}}(r,a) \;=\; I_{k_z}^-(r,a) + [I_{k_z}^+(r,a) - I_{k_z}^-(r,a)]\frac{k_{z_0} - k_z^-(r,a)}{k_z{}^+(r,a) - k_z^-(r,a)} \tag{3.7}$$

where $I_{k_z}^-$ and $I_{k_z}^+$ are the SCS images associated with the wavenumbers k_Z^- and k_Z^+ respectively. After interpolation the spectrum is shifted back.

$$I_{k_{z_0}}(r,a) = I_{k_{z_0}}(r,a)e^{jk_{z_0}\frac{z_0}{2}} \tag{3.8}$$

The synthetic image (independent from M) is then subtracted from the reference image

$$I_{GN}(r,a) \;=\; I_{ref}(r,a) \;-\; I_{k_{z_0}}(r,a) \tag{3.9}$$

3.4.4.2.1. Reference acquisition selection

In this case the reference acquisition I_{ref} should be chosen as the one guaranteeing the widest scene coverage where interpolation can be performed, around the desired value k_{z_0}

$$I_{ref} = max_{SCS_n} \sum_{r,a} ({k_z}^{n}_{min}(r,a) < k_{z_0})(k_{z_0} < {k_z}^{n}_{max}(r,a)) \tag{3.10}$$

where ${k_z}^{n}_{min}$ and ${k_z}^{n}_{max}$ are the maximum and minimum wavenumbers of the set $k_z(r,a,n) - k_z(r,a,ref)$ assuming SCS_n as I_{ref}.

The reference acquisition selection is performed in a fully automatic way by the algorithm and requires no configuration inputs or others. The aim of this step is to set the reference acquisition to the one guaranteeing correct scene coverage and avoid gaps. The reference selected by this step is not necessarily corresponding to the original L1c reference of the stack. Anyway, the change of reference computed by this step is valid only for the purpose of ground cancellation computation and does not imply any change of reference outside the scope of this step. This step applies only to the interpolated single reference case, since in the two images case there is no need to specify a reference acquisition as described in sec. 3.4.4.1).

3.5. Polarimetric covariance matrix computation

3.5.1. Overview and rationale

The polarimetric covariance estimation block aims to estimate the second order statistics of the ground cancelled complex data.

The step is mandatory.

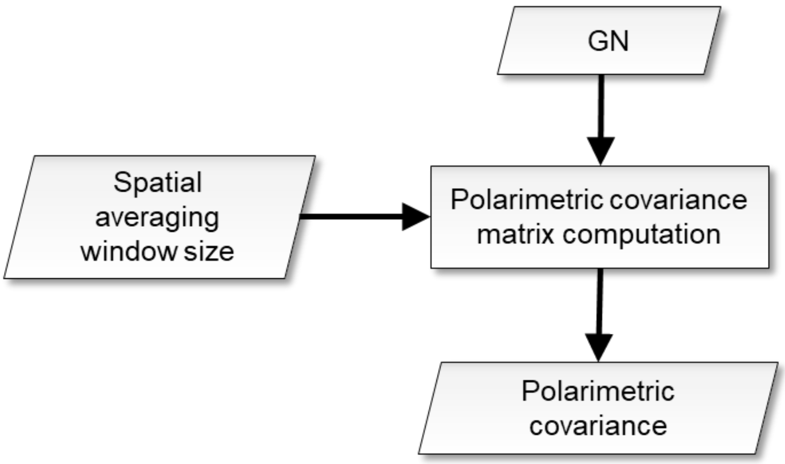

Fig.9 Polarimetric covariance estimation.

3.5.2. Inputs

Symbol	Name	Origin	Size	Variability	Default	Description
I_{GN}	-	*Ground cancellation processing step*	$[N_{rg} \times N_{az}]$	Two CP and one XP (independent from M acquisitions)	-	Ground cancelled complex image
pRes	productResolution	AUX_PP2_2A (AUX_FMT)	float value [scalar]	-	50.0	Value in [m] to be used as the resolution on ground range map and also to perform the covariance averaging in radar coordinates
-	upsamplingFactor	AUX_PP2_2A (AUX_FMT)	int value [scalar]	-	2	upsampling factor, that modules the

Symbol	Name	Origin	Size	Variability	Default	Description
						overall decimation in multilooking within covariance computation
θ	incidenceAngle	L1c reference acquisition ADS (L1_PFD)	$[N_{rg,\theta} \times N_{az,\theta}]$	-	-	L1c stack reference acquisition incidence angle (on inflated ellipsoid) annotation [deg]
B_r	L1c range-bandwidth	L1c reference acquisition ADS (L1_PFD)	-	-	-	L1c range bandwidth [Hz]
B_a	L1c azimuth bandwidth	L1c reference acquisition ADS (L1_PFD)	-	-	-	L1c range bandwidth [Hz]
v_a	L1c velocity annotation	L1c reference acquisition ADS (L1_PFD)	-	-	-	Average azimuth velocity [m/s]
Δ_r	L1c range-sampling step	L1c reference acquisition ADS (L1_PFD)	-	-	-	L1c range sampling step [s]
Δ_a	L1c azimuth sampling step	L1c reference acquisition ADS (L1_PFD)	-	-	-	L1c azimuth sampling step [s]

3.5.3. Outputs

Symbol	Name	Destination	Size	Variability	Default	Description
Cov	-	*Geocoding*	$[N_{pol} \times N_{pol} \times N_{rg,subs} \times N_{az,subs}]$	-	-	Polarimetric covariance of the ground cancelled complex data of current stack

Symbol	Name	Destination	Size	Variability	Default	Description
L	-	*Change detection processing step*	integer value [scalar]	-	-	Number of looks [adimensional]

3.5.4. Algorithm mathematical background

The polarimetric covariance estimation block aims to estimate the second order statistics of the ground cancelled complex data. The size of the spatial averaging window used to estimate the second order statistics depends on the final resolution of the products to be provided as an input. The output of the covariance estimation block is a 4D array with dimensions: $[N_{pol} \times N_{pol} \times N_{rg,subs} \times N_{az,subs}]$ where N_{pol} the number of polarizations, and $N_{rg,subs}$ and $N_{az,subs}$ are the numbers of slant-range and azimuth samples after subsampling (half window size, well complying with the Nyquist-Shannon sampling theorem). For each (subsampled) range-azimuth position a $N_{pol} \times N_{pol}$ multi-polarimetric covariance matrix is returned. Mathematically:

$$Cov[p,q] = \frac{1}{N_{\Omega_r} N_{\Omega_a}} \sum_{r\in\Omega_r} \sum_{a\in\Omega_a} I_{GN_p}(r,a) \cdot I_{GN_q}^{*}(r,a) \tag{3.11}$$

where p and q denote the p-th and q-th polarimetric channels respectively; r and a denote the slant-range and azimuth indices; Ω_r and Ω_a denote the neighborhood in the slant-range and azimuth directions of the desired position; $I_{GN_p}(r,a)$ denotes the pixel value of ground cancelled complex image in polarimetric channel p; $*$ denotes conjugation. The averaging window size is computed as:

$$|\Omega_r| = \left\lceil \frac{pRes}{\rho_r} \sin\theta_m \, (\Delta_r B_r)^{-1} \right\rceil \tag{3.12}$$

$$|\Omega_a| = \left\lceil \frac{pRes}{\rho_a} (\Delta_a B_a)^{-1} \right\rceil$$

where $\rho_r = \frac{c}{2B_r}$ and $\rho_a = \frac{v_a}{B_a}$ denote the L1c resolution computed from system bandwidth, Lightspeed *c*, average azimuth velocity v_a, *pRes* is the L2 resolution, $\theta_m = \frac{1}{N_r N_a}\sum_{r,a} \theta(r,a)$ is the average incidence angle across the swath, while the terms $(\Delta_i B_i)^{-1}, i = r, a$ represent the oversampling factor. SCS invalid pixels will not be used during processing. The presence of an invalid SCS pixel causes the generation of an invalid covariance sample. The number of looks *L* [RD6] is computed as:

$$L = \left\lceil \frac{pRes^2}{\rho_r \rho_a} \sin\theta_m \right\rceil \tag{3.13}$$

3.5.5. Notes on implementation

It should be noted that, as implied by the equations above, multilooking is implicitly performed while computing polarimetric covariance. The ratio of subsampling of the final covariance matrix (i.e., the step where full matrix is sampled) is ruled by the “upsamplingFactor” parameter: when the assumed value is 1, full subsampling is applied ($N_{rg|az,subs} = N_{rg|az}$ / $N_{\Omega r|az}$), while when its value is higher, the final output covariance matrix will be bigger ($N_{rg|az,subs} = N_{rg|az}$ / $N_{\Omega r|az}$ * upsamplingFactor).

3.6. Geocoding

3.6.1. Overview and rationale

The purpose of this step is to project the processed data onto a geographic map, accounting for the different forest points location with respect to reference DEM.

NOTE: It should be noted that the use of the BIOMASS DTM [RD3] is to be preferred to other DEM since it represents the true terrain level at P-band, necessary for correct geocoding.

NOTE: this functionality is used by all three AGB, FD, FH processors with different I/O. mathematical formulation is described highlighting the mapping of the different processors I/O to geocoding formulas in each processor document. The functionality relies on L1c ADS [RD1] and not on the L1 geocoding tool [RD2].

The step is mandatory.

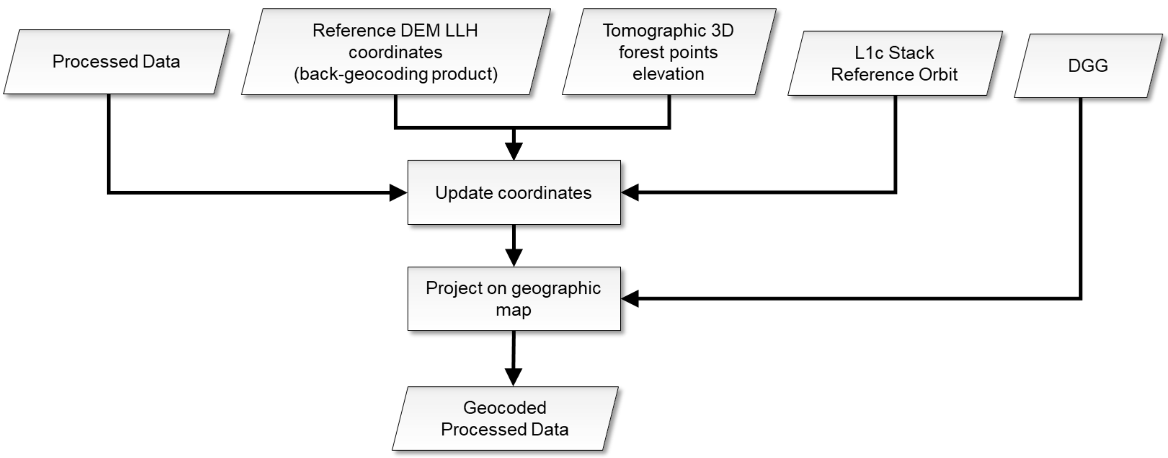

Fig.10 Geocoding.

3.6.2. Inputs

Symbol	Name	Origin	Size	Variability	Default	Description
$Cov \rightarrow Rd$	-	*Polarimetric covariance matrix computation*	$[N_{pol} \times N_{pol} \times N_{rg,subs} \times N_{az,subs}]$	-	-	Processed data, in this case the polarimetric covariance of the ground cancelled complex data of current stack

Symbol	Name	Origin	Size	Variability	Default	Description
(lat, lon, z_{P_0})	latitude longitude height	L1c reference acquisition ADS (L1_PFD)	3x $[N_{rg,\text{llh}} \times N_{az,\text{llh}}]$	-	-	Reference DEM latitude-longitude-height coordinates
$z_0 \rightarrow \delta z_{tomo}$	emphasizedForestHeight	AUX_PP2_2A (AUX_FMT)	float value [scalar]	Global single value (see previous note) for all polarizations and all pixels	30.0	Tomographic 3D forest points elevation [m], in this case the desired elevation emphasized from ground cancellation
DGG	*DGG*	Internal lookup table	-	-	-	DGG sampling
$\hat{\imath}_{az}$	Orbit ADS	L1c reference acquisition ADS	-	-	-	L1c stack reference acquisition orbit annotation

3.6.3. Outputs

Symbol	Name	Destination	Size	Variability	Default	Description
$Rd \rightarrow \boldsymbol{X}$	-	*Change detection processing step*	$[N_{pol} \times N_{pol} \times N_{lat} \times N_{lon}]$	-	-	Polarimetric covariance of the ground cancelled complex data of current stack projected onto a geographic map

3.6.4. Algorithm mathematical background

3.6.4.1.1. Update reference DEM coordinates

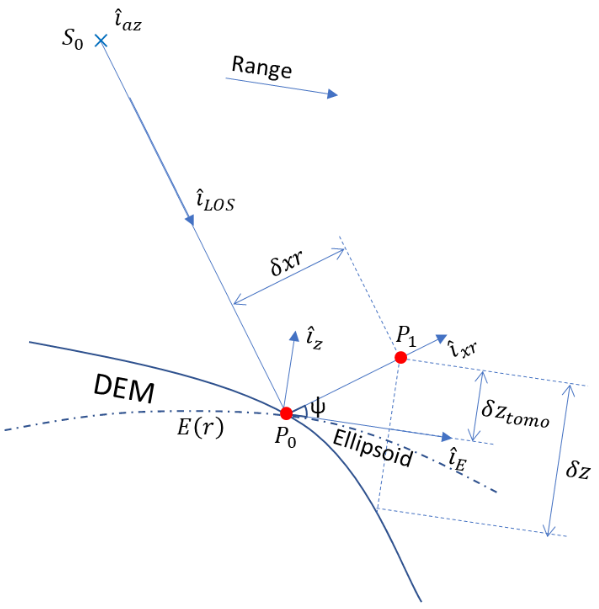

Fig.11 Determining the elevation of one forest point. The picture represents a lateral section for one sensor azimuth position. Details of the represented quantities are given in the text description.

This step aims to account for the different forest points location with respect to reference DEM. A preliminary interpolation step is needed to bring DEM latitude-longitude-height onto the same L1c grid, in similar fashion as for the calibration screens (Section 3.3.4). Determining the elevation of one forest point is shown in Fig.11:

- (lat, lon, z_{P_0}) is the reference DEM for the point $\boldsymbol{P}_0$, which can be converted to Cartesian coordinates $(\mathrm{X}_{P_0}, \mathrm{Y}_{P_0}, \mathrm{Z}_{P_0})$
- z is normal direction to ellipsoid reported to DEM at point $\boldsymbol{P}_0$, i.e., given the tangent plane to ellipsoid $a\,\mathrm{X} + b\,\mathrm{Y} + c\,\mathrm{Z} + d = 0$ then $\hat{\imath}_z = [a, b, c\,]$
- $\hat{\imath}_{az}$ is the azimuth sensor direction, determined from reference orbit annotation
- $\hat{\imath}_{LOS} = \frac{\boldsymbol{P}_0 - \boldsymbol{S}_0}{|\boldsymbol{P}_0 - \boldsymbol{S}_0|}$ is line of sight vector, $\boldsymbol{S}_0$ is the sensor position for the considered azimuth
- $\hat{\imath}_{xr} = \hat{\imath}_{az} \times \hat{\imath}_{LOS}$ is the cross range vector
- the ellipsoid direction at reference DEM is $\hat{\imath}_E \cdot \hat{\imath}_z = 0$, i.e., $\hat{\imath}_E = \frac{d[\boldsymbol{E}(r)]}{dr}$ and $\boldsymbol{E}(r) = [\mathrm{X}_E(r), \mathrm{Y}_E(r), \mathrm{Z}_E(r)]$ are ellipsoid coordinates as a function of range
- δz_{tomo} is one tomographic forest point elevation, in this case the desired elevation emphasized from ground cancellation

- δz is the elevation of point P1 versus DEM (with respect to WGS84 geodetic system). Note that while this is represented for completeness in Fig.11, it is not explicitly needed to compute P1 [x,y,z] position in the following eq 3.15

Then

$$\delta xr = \frac{\delta z_{tomo}}{|\hat{\imath}_{xr} \times \hat{\imath}_E|} = \frac{\delta z_{tomo}}{sin(\psi)} \tag{3.14}$$

The geographic position of the forest point is:

$$\boldsymbol{P}_1 = \boldsymbol{P}_0 + \hat{\imath}_{xr} \cdot \delta xr \tag{3.15}$$

3.6.4.1.2. Projection onto a geographic map

Once the updated coordinates of the points are computed, interpolation of each raster layer to regular map coordinates projects the processed data onto a geographic map. In this case each $[N_{pol} \times N_{pol}]$ raster layer with dimensions $[N_{rg,subs} \times N_{az,subs}]$ of the polarimetric covariance of the ground cancelled complex data of current stack (being the matrix symmetric only $N_{pol} \times (N_{pol} - 1)/2 + N_{pol}$ layers describe the matrix, i.e. upper or lower triangular). The covariance layers $Rd = Cov$ are geocoded using the effective forest height represented (for all pixels) by $\delta z_{tomo} = z_0$. Geocoding is done in a way that the products are sampled the same way onto the DGG sampling [RD8]. The operation can be expressed as:

$$Rd(lat, lon, z) = f\left[Rd(lat, lon, z)|_{\boldsymbol{P}_1}\right]\Big|_{DGG} \tag{3.16}$$

where *f* is a bilinear interpolant a function, *Rd* is each raster layer to be interpolated.

3.7. Change detection

3.7.1. Overview and rationale

The disturbance processing is concerned with providing maps of high-intensity change between successive temporal cycles under the implicit hypothesis of occurred deforestation (logging, fire etc.). This assumption is further detailed in the section 3.7.4.5. The chosen methodology is by hypothesis testing [RD6][RD5] on geocoded polarimetric covariance estimate of the ground cancelled complex data, where the null hypothesis is that in a time series of polarimetric data no change has occurred (at a given position and up to a given time). If this hypothesis fails at a given level of significance (assuming a Wishart distribution for the complex covariance data), then it is assumed a change has occurred. This is closely related to the Constant False Alarm Rate approach to target detection [RD5], in which the probability that an undisturbed pixel is incorrectly classified as disturbed is fixed. As a first step, the probability of change for each latitude-longitude pixel will be estimated, which is by itself a quality measure. Change detection to compute disturbance maps from L2a probabilities of change for each stack is applied by null hypothesis rejection at a given level of significance.

The step is mandatory.

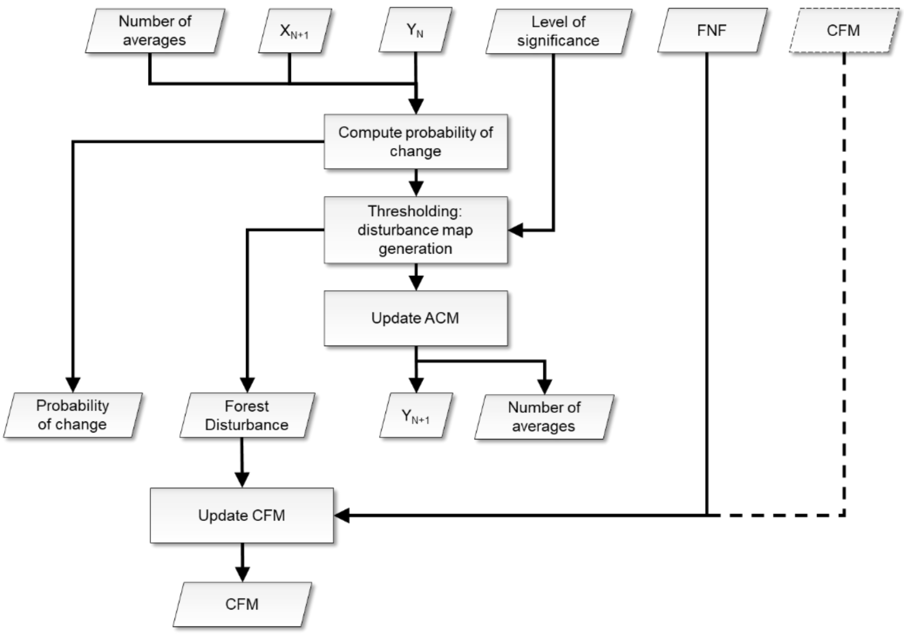

Fig.12 Change detection.

3.7.2. Inputs

Symbol	Name	Origin	Size	Variability	Default	Description
$\boldsymbol{X}$	-	*Geocoding*	$[N_{pol} \times N_{pol} \times N_{lat} \times N_{lon}]$	-	-	Polarimetric covariance of the ground cancelled complex data of current stack projected onto a geographic map
$\boldsymbol{Y}$	ACM	FD L2a product of previous cycle (FD_PFD)	$[N_{pol} \times N_{pol} \times N_{lat} \times N_{lon}]$	-	-	Average Covariance Matrix of previous cycles
q	significanceLevel	AUX_PP2_2A (AUX_FMT)	float value [scalar]	0.0-100.0	1.0	Significance [%] level to be applied in the change detection algorithm
CFM	CFM	FD L2a product of previous cycle (FD_PFD)	$[N_{lat} \times N_{lon}]$	-	-	Computed Forest Mask
L	-	*Polarimetric covariance computation*	integer value [scalar]	-	-	Number of looks
N	numberOfAverages	FD L2a product of previous cycle (FD_PFD)	$[N_{lat} \times N_{lon}]$	lower bound=1	-	Number of averages in ACM computation
FNF	FNF	Internal resource	$[N_{lat,FNF} \times N_{lon,FNF}]$	Yearly	-	A global forest-non-forest mask given as input
fMIT	forestMaskInterpolationThreshold	AUX_PP2_2A (AUX_FMT)	float value [scalar]	0.0-1.0	0.5	Threshold to fix rounding of pixels with decimal values originated

Symbol	Name	Origin	Size	Variability	Default	Description
						from binary FNF interpolation onto L2a grid
detLimit	numericalDeterminatLimit	AUX_PP2_2A (AUX_FMT)	float value [scalar]	>0.0	1.0e-12	Lower Threshold to avoid numerical errors when computing pol covariance matrices determinants

3.7.3. Outputs

Symbol	Name	Destination	Size	Variability	Default	Description
CFM	CFM	FD L2a product of current cycle (FD_PFD)	$[N_{lat} \times N_{lon}]$	-	-	Update of CFM
P_c	Probability of change	FD L2a product of current cycle (FD_PFD)	$[N_{lat} \times N_{lon}]$	-	-	Probability of change map of current stack
FD_{map}	Forest Disturbance	FD L2a product of current cycle (FD_PFD)	$[N_{lat} \times N_{lon}]$	-	-	Forest Disturbance map of current stack
$\boldsymbol{Y}$	ACM	FD L2a product of current cycle (FD_PFD)	$[N_{pol} \times N_{pol} \times N_{lat} \times N_{lon}]$	-	-	Update of ACM
N	numberOfAverages	FD L2a product of current cycle (FD_PFD)	$[N_{lat} \times N_{lon}]$	lower bound=1	-	Update of number of averages in ACM computation

3.7.4. Algorithm mathematical background

3.7.4.1. Hypothesis testing

Each pixel is processed independently. For each pixel of the geocoded ground cancelled polarimetric covariance matrix at current global cycle "*N+1*" multiplied by a factor *L* (corresponding the number of looks [RD6]) $\boldsymbol{X}_{N+1} = L\boldsymbol{X}$, the likelihood ratio statistic is calculated to test the null hypothesis that it is the same as that of the previous *N* cycles (*N*= *numberOfAverages*) Average Covariance Matrix $\boldsymbol{Y}_N = \sum_{i=0}^{N} \boldsymbol{X}_i$

$$R_{N+1} = \left\{\frac{(N+1)^{(N+1)p}}{N^{Np}} \frac{|\boldsymbol{Y}_N|^N \, |\boldsymbol{X}_{N+1}|}{\left|\sum_{i=0}^{N+1} \boldsymbol{X}_i\right|^{N+1}}\right\}^L = \tag{3.17}$$

$$= \left\{\frac{(N+1)^{(N+1)p}}{N^{Np}} \frac{|\boldsymbol{Y}_N|^N \, |\boldsymbol{X}_{N+1}|}{|\boldsymbol{Y}_N + \boldsymbol{X}_{N+1}|^{N+1}}\right\}^L$$

From Section 3.5.4 *L* is the number of looks, |..| denotes determinant, and *p* is the polarimetric dimension of the data matrix (*L=6* and *p=3* as per BIOMASS requirements [RD9]). The polarimetric covariance matrices are (by definition) Hermitian and semi-positive definite: their determinant is real-valued. However, determinant calculation can be ill-posed as its value approaches zero (as numerical errors may arise). It has been chosen to set a lower limit (optional user defined parameter *numericalDeterminantLimit*) to deal with numerical errors and avoid any problems in subsequent equations.

To calculate the probability of rejecting the null hypothesis if all the covariance matrices are the same, the following auxiliary variables are calculated [RD6][RD5]:

$$f = p^2 \tag{3.18}$$

$$\rho_{N+1} = 1 - \frac{2f-1}{6pL}\left(1 + \frac{1}{N(N+1)}\right)$$

$$\omega_{2(N+1)} = -\frac{f}{4}\left(1 - \frac{1}{\rho_{N+1}}\right)^2 + \frac{1}{24L^2} f(f-1)\left(1 + \frac{2N+1}{N^2(N+1)^2}\right)\frac{1}{\rho_{N+1}^2}$$

Under the null hypothesis the probability of change is calculated as:

$$P_c = P(-2\rho_{N+1} \ln R_{N+1} \le z) \approx P\{\chi^2(f) \le z\} + \omega_{2(N+1)}[P\{\chi^2(f+4) \le z\} - P\{\chi^2(f) \le z\}] \tag{3.19}$$

where $z = -2\rho_{N+1} \ln r_{N+1}$, r_{N+1} is the measured value of the statistic R_{N+1} and $\chi^2(..)$ is the chi-squared function. Hence, we can assign a probability to the observed value of r_{N+1} occurring if $\boldsymbol{X}_{N+1}$ is the same as all the previous $\boldsymbol{X}_i$, and hence attach a level of significance to the failure of the null hypothesis.

3.7.4.2. Disturbance map generation

If the null hypothesis is rejected at a given level of significance q, the pixel is assumed to have undergone significant disturbance and so has been deforested between times *N* and *N+1*. FD map generation for each pixel of the current stack is obtained by thresholding the probability of change as:

$$FD_{map} = \{1 - P_c\} < q \tag{3.20}$$

3.7.4.3. ACM update mechanism

History of previous *N* cycles is represented by an Average Covariance Matrix $\boldsymbol{Y}_N$ (equivalent to current Covariance Matrix $\boldsymbol{X}_{N+1}$ as for dimensions and data type), which consists of the stacking of covariance matrices from previous cycles, in case no change occurred. When detection is computed between current CM $\boldsymbol{X}_{N+1}$ and the ACM $\boldsymbol{Y}_N$ for a given pixel, in case of no change current CM is added to ACM to be used in the subsequent cycle (ACM is updated to be the average over the whole series where no change has occurred). In case of change, instead, this ACM is reset to current CM for subsequent cycles and FD will report an indication of change for the corresponding pixels in the disturbance layer. The *numberOfAverages* of the previous *N* cycles, which is a measure of how many objects are averaged in the current ACM, is also reset to 1. The update mechanism is reported in Fig.13 for the ACM $\boldsymbol{Y}_N$.

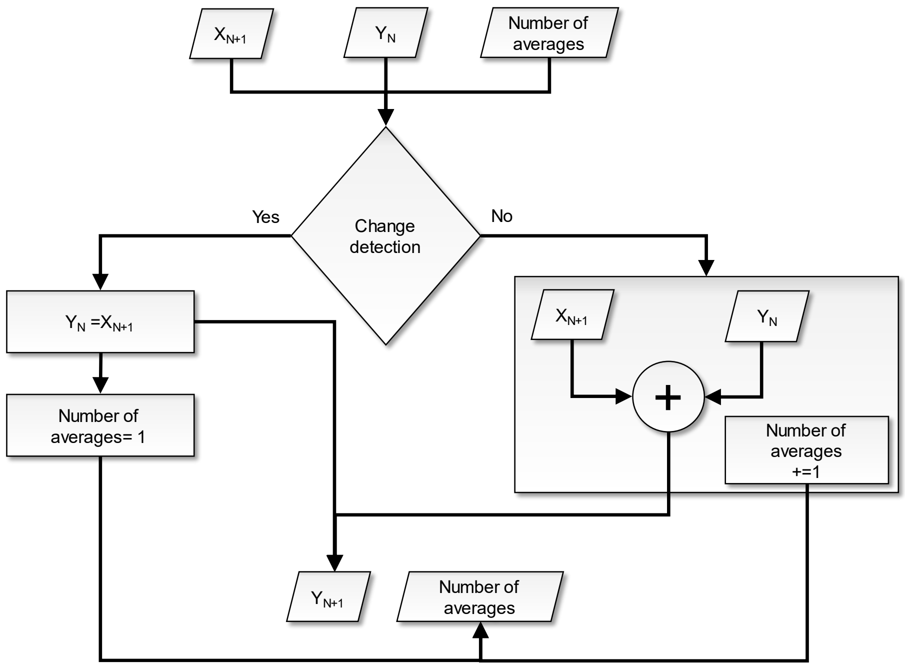

Fig.13 Update mechanism for Average Covariance Matrix.

3.7.4.4. ACM computed in TOM

To have a FD map in the first INT global coverage ACM computed in TOM can be fed (however this option is initially set off). This does not require processing modifications but the generation of an FD product empty but for the ACM. This can be computed by choosing the same baselines of the INT Phase, see sec. 3.2. Otherwise, detection is possible from the second global cycle after the beginning of the Interferometric Phase or at second iteration when the algorithm is started the very first time in case of off-line reprocessing. This is due to the fact that the first cycle is needed to compute first ACM.

3.7.4.5. Computed Forest Mask

A Computed Forest Mask is also generated, accounting for the incremental FD information. At the first cycle this is equal to external FNF. A preliminary FNF interpolation step is needed to bring FNF onto the same FD grid, in the same fashion as for the calibration screens (Section 3.3.4). Since interpolation generates border effects a threshold *fMIT* to fix rounding of pixels with decimal values is applied:

$$FNF = FNF > fMIT \quad (3.21)$$

The CFM update rule from the second global cycle is then:

$$CFM = \{1 - FD_{map}\} \wedge CFM \quad (3.22)$$

where ∧ is the logical *and* operator.

It is worth noting that the current implementation cannot differentiate between the sources of the changes that have occurred (i.e., the disturbances detected as per section3.7.4.2). This means that each disturbed pixel will always be mapped as a ‘Non-Forest’ class in the output CFM.

At the time of the ATBD formulation, this simplified assumption was considered acceptable due to the anticipated application with BIOMASS data (i.e., the nominal production of an FD product between two global coverages). The reliability of the CFM product should be carefully evaluated if the FD algorithm is applied over more extended time ranges.

4. Change detection aggregation

The overall scheme of the L2b processing is reported in figure below.

The key step is fusion of L2a estimates at map level. These steps are described in detail in the following subsections.

The step is mandatory.

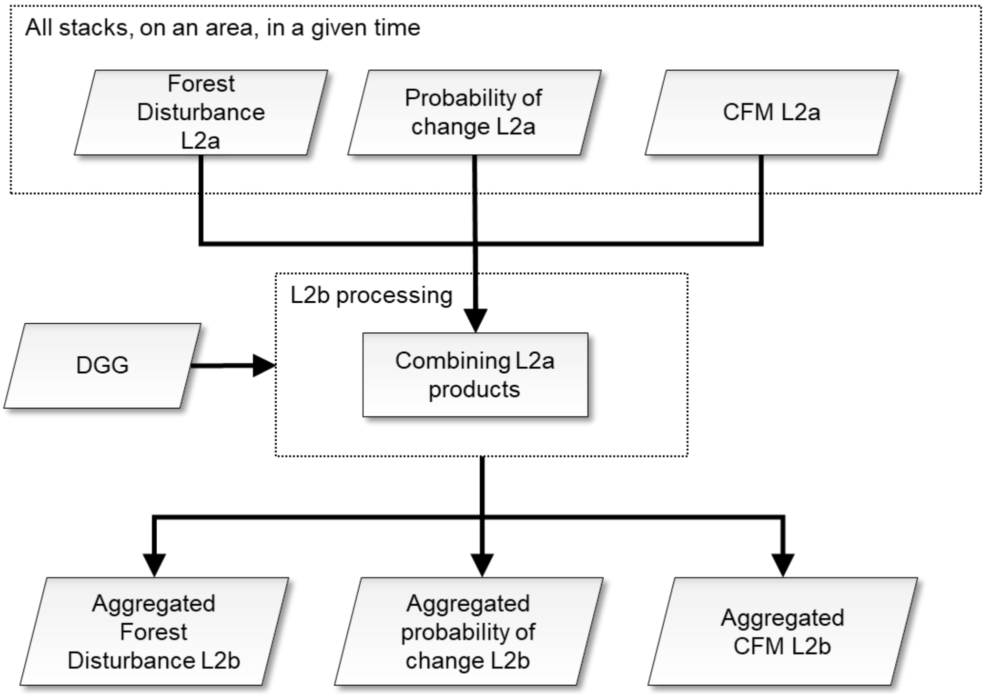

Fig.14 Complete flow-chart of the L2b processing.

4.1. Fusion of L2a products on a Tile within a fixed timespan

4.1.1. Overview and rationale

The disturbance maps allow the combination of different acquisitions in a simple and efficient pixelwise way. L2a products falling onto the same L2b tile within a global cycle are retrieved through geospatial query of information (tile IDs and time tags) in the Main Product Header of the product.
From the disturbance map combined, the extraction of the combined CFM is obtained by a simple logical *and* operator.

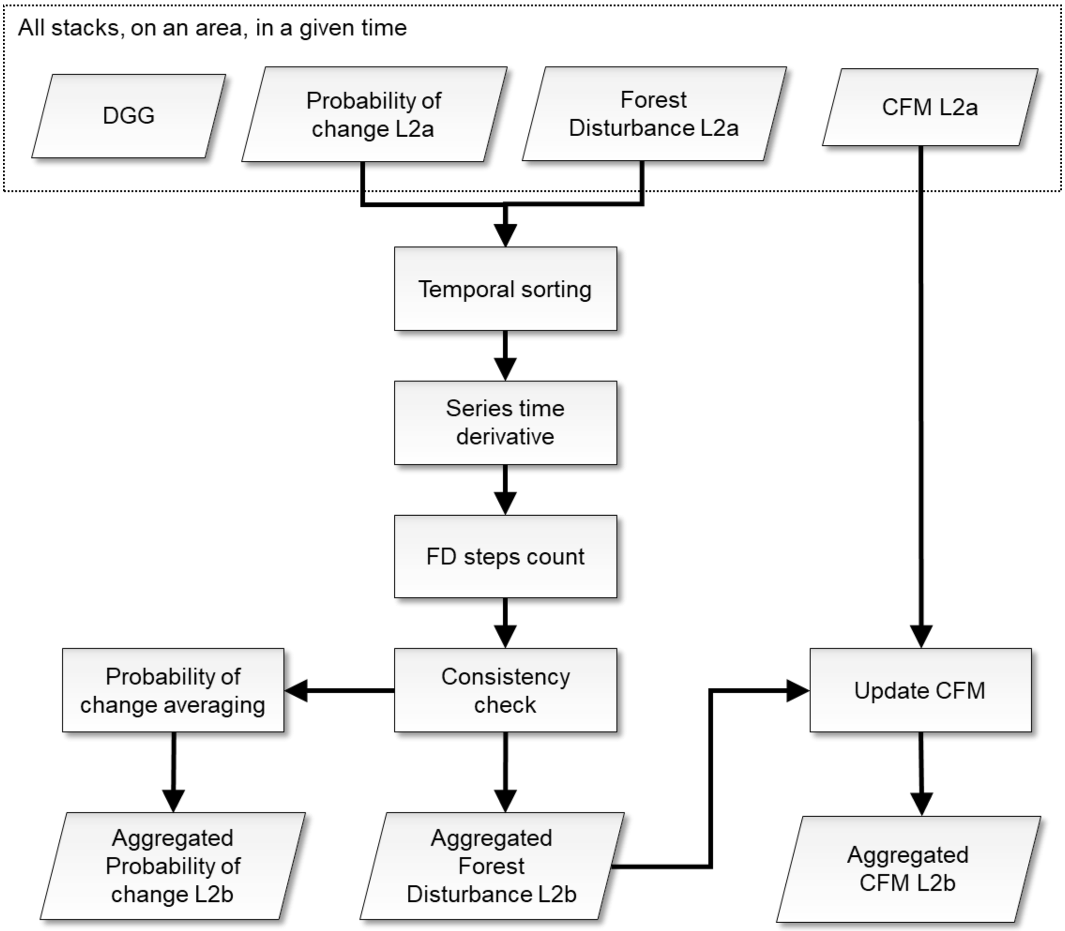

Fig.15 L2a FD fusion.

4.1.2. Inputs

Symbol	Name	Origin	Size	Variability	Default	Description
$FD_{map}{}^{t^i}$	Forest Disturbance	FD L2a products in a DGG tile in a global cycle (FD_PFD)	$[N_{lat} \times N_{lon}]^{t^i}$	-	-	Forest Disturbance map
CFM^{t^i}	CFM	FD L2a products in a DGG tile in a global cycle (FD_PFD)	$[N_{lat} \times N_{lon}]^{t^i}$	-	-	CFM
$P_c{}^{t^i}$	Probability of change	FD L2a products in a DGG tile in a global cycle (FD_PFD)	$[N_{lat} \times N_{lon}]^{t^i}$	-	-	Probability of change map

Symbol	Name	Origin	Size	Variability	Default	Description
DGG	DGG	Internal lookup table	-	-	-	DGG tile
BB^i	Footprint	L2a main product header (FD_PFD)	lat-lon vertices (4 couples)	-	-	The extent of the L2a input data in geographical coordinates
mDGG	minimumL2a Coverage	AUX_PP2_ FD (AUX_FMT)	float value [scalar]	0.0-100.0	10.0	The minimum [%] tile coverage that triggers the computation s

4.1.3. Outputs

Symbol	Name	Destination	Size	Variability	Default	Description
$FD_{map}{}^{aggregated}$	Forest Disturbance	FD L2 b product (FD_PFD)	$[N_{lat,L2b} \times N_{lon,L2b}]$	-	-	Forest Disturbance map aggregated
$CFM^{aggregated}$	CFM	FD L2 b product (FD_PFD)	$[N_{lat,L2b} \times N_{lon,L2b}]$	-	-	CFM aggregated
$P_c{}^{aggregated}$	Probability of change	FD L2 b product (FD_PFD)	$[N_{lat,L2b} \times N_{lon,L2b}]$	-	-	Probability of change map aggregated
HM	heat map	FD L2b product (FD_PFD)	$2[N_{lat,L2b} \times N_{lon,L2b}]$	0-	-	heat map (couple of integer values per pixel)

4.1.4. Algorithm mathematical background

As a first step, the minimum required coverage over L2b DGG tile *j* is checked to proceed with computations:

$$TR = \left(100 * \frac{A(\cup_i BB^i|_{DGG} \cap TT^j|_{DGG})}{A(TT^j|_{DGG})} > mDGG\right) \qquad (4.1)$$

where BB^i are the L2a bounding boxes, TT^j is the footprint of the current L2b DGG tile and *A* operator computes the area of the corresponding polygon.

The aggregation at pixel map level of the various L2a disturbance maps is done by examining the consistency of the time series of detections. First, the series of detection is temporally sorted, both ascending and descending orbits:

$$FD_{series}{}^{\mathrm{sorted}}(t) = \left\{FD_{map}{}^{\mathrm{t}^1}, \dots, FD_{map}{}^{\mathrm{t}^\mathrm{i}}\right\} \tag{4.2}$$

$\{\mathrm{t}^1 < \ldots < \mathrm{t}^\mathrm{i}\}$ being the different times at which each product is acquired in a global cycle. Then the derivative of the sorted time series is computed with respect to time and thresholded

$$FD_{series}{}^{\mathrm{steps}} = \left|\frac{d\left[FD_{series}{}^{\mathrm{sorted}}(t)\right]}{dt}\right| > 0 \tag{4.3}$$

Finally, the number of transitions in the derivative vector is counted

$$FD_{steps}{}^{\mathrm{count}} = \sum_{\mathrm{i}} FD_{series}{}^{\mathrm{steps}}(\mathrm{i}) \tag{4.4}$$

If the sum is odd, detection is assumed, and the resulting probability of change is the average of the different probabilities pixel-wise for detection only. Otherwise, the resulting probability of change and FD map is set to zero. If the sum is zero, detection is assumed only if all the acquisitions show detection. The rationale is that change is assumed only if all the acquisitions detecting it are simultaneously consistent. The situation is depicted in Fig.16 for the example of three acquisitions and the corresponding truth table is reported in Tab.1.

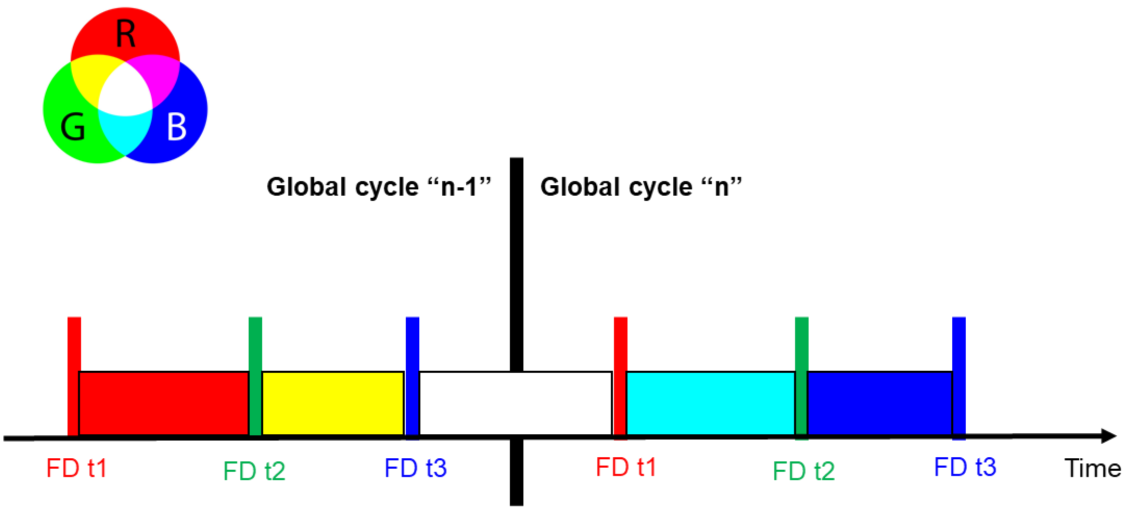

Fig.16 Time of validity for each acquisition among two global cycles, with overlaps shown in RGB colours. The FD relative to various acquisition times within the global cycle are reported. See also Tab.1.

FD t1	FD t2	FD t3	FD steps count	FD map aggregated	HM: contributing	HM: agreeing
0	0	0	0	0	3	3
0	0	1	1	1	3	1
0	1	0	2	0	3	2
1	0	0	1	1	3	1
1	1	0	1	1	3	2
1	0	1	2	0	3	1
0	1	1	1	1	3	2
1	1	1	0	1	3	3

Tab.1 Truth table for the example of three FDs. The color coding for FD t1/3 is the same of Fig.16, where black is the absence of validity.

A heat map *HM* is also stored representing at pixel level:

- the total number of acquisitions contributing to the decision, as reported in Tab.1 – column 6
- the number of acquisitions agreeing to the decision, as reported in Tab.1 – column 7

From the disturbance map combined, the extraction of the forest mask is obtained by a simple update to the initial forest mask.

$$CFM^{aggregated} = \{1 - FD_{map}{}^{aggregated}\} \wedge \{\cup_{t^i} CFM^{t^i}\} \quad (4.5)$$

$\{t^1 < \ldots < t^i\}$ being the different times at which each product is acquired in a global cycle, where ∪ is the union operator.

5. Appendix: effect of GN

The power associated with each pixel of I_{GN} can be expressed as [RD4]

$$|I_{GN}(r,a)|^2 = 2\int \sigma\,(r,a,z)^2[1-\cos(\,k_z(r,a)z)]\;dz \tag{5.1}$$

where $\sigma\,(r,a,z)^2$ is the uncorrelated reflectivity density of the distributed target along z, and $k_z(r,a) = k_z(r,a,1) - k_z(r,a,2)$ is the interferometric pair vertical wavenumber.

Note that quantity in eq 5.1 is never computed within L2A_P