

Copernicus Global Land Operations

“Vegetation and Energy”

”CGLOPS-1”

Framework Service Contract N° 948120 – IPR - 2023

ALGORITHM THEORETICAL BASIS DOCUMENT

NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI) 300M

VERSION 3

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List of Acronyms

6S	Second Simulation of a Satellite Signal in the Solar Spectrum
AC	Atmospheric correction
AD	Applicable document
AOT	Aerosol Optical Thickness
APU	Accuracy Precision Uncertainty
ATBD	Algorithm Theoretical Design Document
AVHRR	Advanced Very High-Resolution Radiometer
B	Bias
C	Collection
BRDF	Bidirectional Reflectance Distribution Function
CAL/VAL	Calibration/Validation
CEOS	Committee on Earth Observation Satellites
CGLOPS	Copernicus Global Land Operations
CLMS	Copernicus Land Monitoring Service
COG	Cloud-Optimized GeoTiff
ECV	Essential Climate Variable
ENVISAT	ENVironment SATellite
ESA	European Space Agency
EVI	Enhanced Vegetation Index
FAPAR	Fraction of absorbed photosynthetically active radiation
GAUL	Global Administrative Unit Layers
GBOV	Ground-Based Observations for Validation
GCOS	Global Climate Observing System
GEMI	Global Environment Monitoring Index
INSPIRE	Infrastructure for Spatial Information in Europe
JRC	Joint Research Center
LANDVAL	Land Validation
LPV	Land Product Validation
MCD43A1	MODIS Terra+Aqua BRDF/Albedo Model Parameters Daily Product
MCD43A2	MODIS Terra+Aqua BRDF/Albedo Quality Daily Product
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NetCDF	Network Common Data Format
NIR	Near InfraRed
Nobs	Number of observations used in ReBeLS for the BRDF-correction
Nobs _{snow}	Number of snow observations in ReBeLS in the BRDF-correction
NOBS	Number of Observations of the NDVI product, derived from Nobs
NOBS_SNOW	Number of snow observations in the NDVI product, derived from Nobs _{snow}
OLCI	Ocean and Land Color Imager
PROBA-V	Project of on-board autonomy – VEGETATION instrument

PUM	Product User Manual
QAR	Quality Assessment Report
QFLAG	Quality Flag
QUIL	Quality Information Layer
ReBeLS	Regularized Brdf Inversion for Land Surface reflectances
RMSD	Root Mean Square Deviation
S1	Daily synthesis
S2GM	Sentinel-3 Global Mosaic
S3	Sentinel-3
S10	10-daily synthesis
SLC	Soil-Leaf-Canopy model
SLSTR	Sea and Land Surface Temperature Radiometer
SMAC	Simplified Method for Atmospheric Correction
SPOT	Satellite Pour l'Observation de la Terre
SRF	Spectral Response Function
STD	Standard Deviation
TOA	Top of Atmosphere
TOC	Top Of Canopy Reflectances
TOC-r	Top Of Canopy Normalized Reflectances
VGT	VEGETATION sensor on SPOT platform
VITO	Flemish Institute for Technological Research
WGS	World Geodetic System
ZAR	Zip Archive

List of Symbols

ρ	Surface Reflectance
Δ	Uncertainty

EXECUTIVE SUMMARY

The Copernicus Land Monitoring Service (CLMS) produces a series of qualified bio-geophysical products on the status and evolution of the land surface. The products are used to monitor vegetation, crops, water cycle, energy budget and terrestrial cryosphere. Production and delivery of the parameters take place in a timely manner and are complemented by the constitution of long-term time series.

The CLMS portfolio contains a global Normalized Difference Vegetation Index (NDVI) product at 300m spatial resolution. The NDVI Version 3 product is derived from the 10-daily Bidirectional Reflectance Distribution Function (BRDF)-normalized reflectances, generated from the data of the Ocean and Land Colour Instrument (OLCI) onboard the Sentinel-3 (S3) satellite and from Collection 2 (C2) of the PROBA-V (PV) data. The product consists of the NDVI layer, its associated uncertainty, the number of clear observations in the compositing window and a quality flag.

This Algorithm Theoretical Basis Document (ATBD) aims at describing the algorithm for the Version 3 of the NDVI 300m product. The algorithm combines 4 OLCI bands in the red and Near Infrared (NIR) spectrum to derive the NDVI. The NDVI derived from PROBA-V is empirically corrected to this NDVI in order to have a consistent time series.

1 BACKGROUND OF THE DOCUMENT

1.1 SCOPE AND OBJECTIVES

One of the main objectives of the Copernicus program is to provide the proper information required for several applications to the scientific community as well as other stakeholders, including policy makers. The products are then operationally generated and delivered freely through the Copernicus Land Monitoring Service portal (<https://land.copernicus.eu>) in near real-time as well as offline.

The objective of this document is to provide a detailed description and justification of the algorithm proposed for the BRDF-normalized NDVI 300m Version 3 derived from PROBA-V Collection 2 (C2) and Sentinel-3 OLCI data.

1.2 CONTENT OF THE DOCUMENT

This document is structured as follows:

- Chapter 2 recalls the requirements, and the expected performance
- Chapter 3 describes the retrieval methodology

1.3 RELATED DOCUMENTS

1.3.1 Applicable documents

AD1: Part 2: Technical specifications of Framework Service Contract – Operation of the biogeophysical variables systematic monitoring of the Global Land Component of the Copernicus Land Service ‘CGLOPS’ JRC/2023/OP/0273, 19th April 2023.

Available at <https://etendering.ted.europa.eu/cft/cft-display.html?cftId=13795>

1.3.2 Input

Document ID	Descriptor
CGLOPS1_ATBD_S3-AC-V1.1	Algorithm Theoretical Basis Document of the Atmospheric Correction applied on Sentinel-3 OLCI and SLSTR data
CGLOPS1_ATBD_BRDFCorrection300m-V1.6	Algorithm Theoretical Basis Document of the BRDF correction version 1.6
CGLOPS1_PUM_S3-TOC-Reflectance300m-V2.3	Product User Manual summarizing all information about the Sentinel-3 OLCI and SLSTR Top-Of-Canopy Reflectances Version 2.3

CGLOPS1_QAR_S3-CloudMask

Quality Assessment Report of Sentinel-3 OLCI and SLSTR cloud, cloud shadow and snow detections

1.3.3 Output

Document ID

Descriptor

CGLOPS1_PUM_NDVI300m-V3

Product User Manual summarizing all information about the NDVI 300m Version 3 product

CGLOPS1_QAR_NDVI300m_V3

Report describing the results of the scientific quality assessment of the NDVI 300m Version 3 product

1.3.4 External documents

Document ID

Descriptor

GCOS#245

The 2022 GCOS ECVs requirements, World Meteorological Organization, Geneva, Switzerland (2022)

Available online at: <https://library.wmo.int/idurl/4/58111>

PROBA-V C2 PUM

PROBA-V Collection 2 Products User Manual

Available online at: https://proba-v.vgt.vito.be/sites/probavvtg/files/downloads/PROBA-V_C2_Products_User_Manual.pdf

PROBA-V C2 ATBD AC

PROBA-V Collection 2 Algorithm Theoretical Baseline Document of the Atmospheric Correction.

Available online at: https://proba-v.vgt.vito.be/sites/probavvtg/files/downloads/PROBA-V_C2_Atmospheric_Correction_ATBD.pdf

2 REQUIREMENTS

According to the applicable documents [AD1], the requirements relevant for CLMS global NDVI product are described below.

2.1 SPECIFIC TECHNICAL DETAILS AND REQUIREMENTS

PRODUCT SPECIFICATION	
Geometric Properties:	
Spatial resolution	300m,
Geolocation precision	Better than 0.5 pixels
Coordinate position	Centre of the pixel
Geodetic datum	WGS84
Geographic projection	regular latitude/longitude grid
Geographic Coverage	Global
Temporal resolution	10-day period (dekad: days 1-10, 11-20, 21 end of month)
Timeliness	Within 2 days (optimally 1 day) after the end of each dekad

NDVI – NORMALIZED DIFFERENCE VEGETATION INDEX	
The Normalized Difference Vegetation Index (NDVI) is a dimensionless parameter that is chlorophyll sensitive and indicative for the greenness of the biomes and is expressed as the difference between the near-infrared and red bands, normalized to the summation.	
Uncertainty (2-sigma)	Threshold: 5% Goal: 2,5%
Stability (per decade, i.e. 10 years)	Threshold: 3% Goal: 1.5%

2.2 FURTHER REQUIREMENTS

2.2.1 Output product composition

Products may contain various information layers and ancillary information – the base reference for product packages are the operational products as on 01.03.2023.

2.2.2 Data Structure

Data coding¹ shall be compatible with the Global Land products as on 01.03.2023 and/or follow the INSPIRE specifications, where applicable.

Ancillary information shall be as currently used and include at least the following:

- The number of measurements per pixel used to generate any synthesis product

¹ Data coding is the provision for the number of bits, range of values, usage of reserved values, content of status map, conversion to physical values formulas.

- The per-pixel date of the individual measurement or the start-end dates of the period covered
- Quality indicators, with explicit per-pixel identification of the cause of anomalous parameter result.

The product naming and filename conventions that are used in the Copernicus Global Land component production as on 01.03.2023 shall be followed. This may be adapted for complete product collections upon agreement with the contracting authority during the Framework.

2.2.3 Data format

To ensure interoperability with the current Global Land component (operational product data formats and archive data formats) and other Copernicus services, all datasets will be available in NetCDF. Additional format such as Cloud Optimized Geotiff (COG) or ZAR format can be proposed for production or could be requested by the Contracting Authority during the Framework Contract.

2.2.4 Uncertainties and Validation

Uncertainties indicated in the product specifications above follow the threshold and goal proposed by GCOS#245.

Uncertainties estimates should account for the error propagation uncertainty coming from input data through the retrieval algorithms as during the contract period, ESA plans to imbed uncertainties in the Sentinel-3 ground segment products and, for Sentinel-2, there is an offline tool to determine Level 1 uncertainties; these can be used for propagation in the production chain.

Validation of the products shall conform to at least the CEOS LPV standards. Wherever appropriate the bio-geophysical variables shall be validated and compared to CEOS CAL/VAL data sets and/or [Ground-Based Observations for Validation \(GBOV\) of Copernicus Global Land component](#) when biophysical parameters are available.

2.2.5 Input data

Copernicus Sentinel data are available from <https://dataspace.copernicus.eu>

Bio-geophysical variable products should be based on common base reflectance data:

- Sentinel 3: Derived Top-of-Canopy reflectance may be brokered or produced as it is the case on 01.03.2023 under the CGLOPS contracts;
- Sentinel 2: the Global Land Sentinel-2 Global Mosaic (S2GM)² component provides temporal mosaic of surface spectral bands that can be brokered and/or directly used.

² <https://land.copernicus.eu/en/products/global-image-mosaic>

Up to and including 2019, products archives of the Global Land component have been based on SPOT VGT, PROBA-V, ENVISAT, MODIS, TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, datasets, which are available through the <https://dataspace.copernicus.eu>.

Ancillary satellite data that is purchased through Copernicus and put at disposal of the Services is available through the Data Warehouse and will become available on the Copernicus Dataspace Ecosystem.

Ancillary data sets, other than satellite imagery described above, that might be required shall be the responsibility of the contractor.

2.2.6 Product delivery

Products shall be delivered to the Copernicus Land Component dissemination.

The Copernicus Data Space Ecosystem infrastructure will be used to provide access to the final map products.

3 METHODOLOGY DESCRIPTION

3.1 OVERVIEW

Long term time series of bio-physical parameters derived from space-borne optical sensors play a key role in the monitoring of the Earth land surface. In particular, the Normalized Difference Vegetation Index (NDVI) – the combination of reflectances in the red and near infrared (NIR) spectral bands – is commonly used to perform studies on vegetation dynamics and evolution. The NDVI is a proxy to quantify vegetation amount, is closely related to the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), and is little scale-dependent (Myneni and Williams, 1994). Moreover, analyses of multi-annual NDVI time series with high temporal cadence allow the detection of anomalies in vegetation dynamics.

The use of large swath width sensors implies the gathering of reflectances obtained under different illumination (solar zenith and azimuth angles) and observing (viewing zenith and azimuth angles) conditions. In addition, assembling long time series of such observations can only be achieved by gathering data from different sensors, which have different overpass times and thus illumination conditions. Since observed surface reflectances are wavelength-dependent and highly anisotropic, spurious deviations and large scatter in atmospherically corrected reflectance time series are usually associated to directional effects. Therefore, the NDVI is based on Top-Of-Canopy (TOC) reflectances that are “normalized” to a common illumination and observing geometry to seamlessly join long-term and (or) multi-sensor time series.

This new version (V3) of the NDVI 300m is based on TOC reflectances V2.3 data from the Sentinel-3A and -3B OLCI sensor and TOC reflectances from the PROBA-V Collection 2 daily synthesis (S1) 300 m data, normalized using ReBeLS v1.6 (with improved outlier detection, and filtering of extreme geometries compared to the previous version). The Sentinel-3-based NDVI dataset is the reference NDVI to which the archive will have to be adapted. OLCI and PROBA-V sensors differ considerably in spectral characteristics: OLCI has several small spectral bands in red and NIR, whereas PROBA-V has only a single broad red and NIR band (see Figure 1). Hence, a combination of the small OLCI bands into single broad red and NIR bands is required in order to be able to reach consistency. Any additional correction that could be required will then be applied on the PROBA-V based NDVI 300m V3.

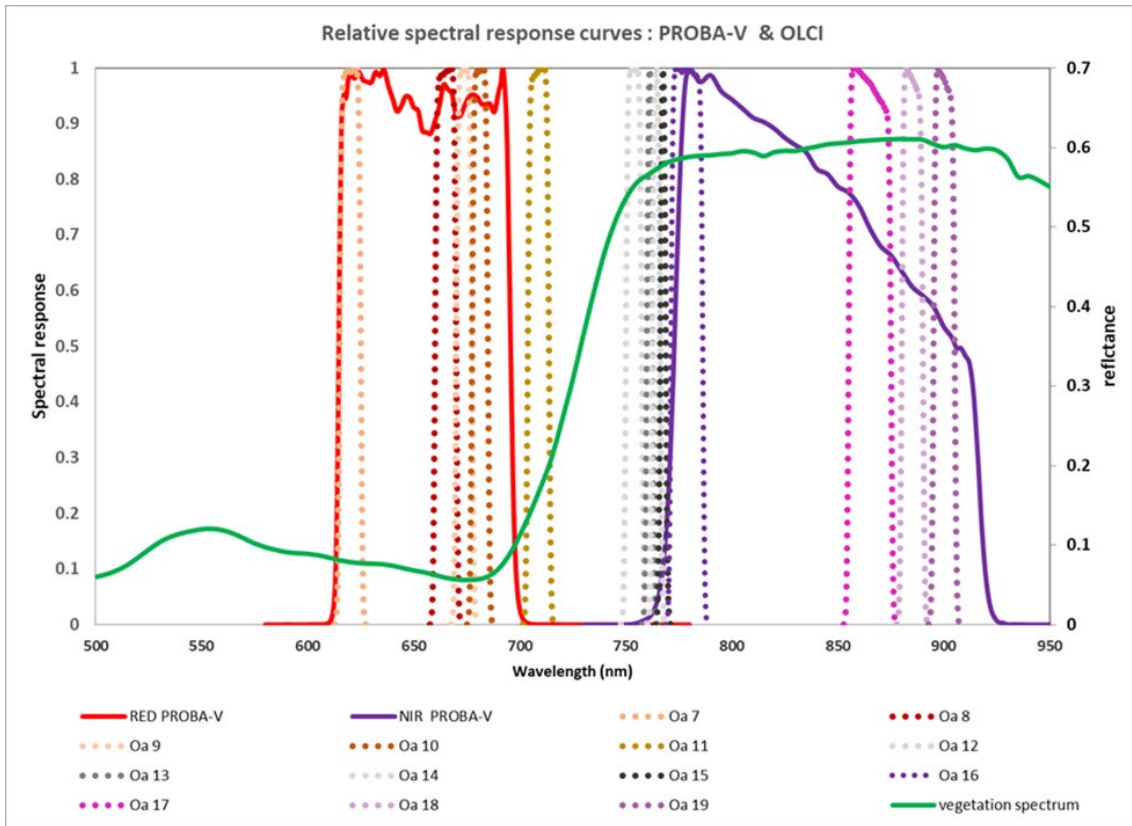


Figure 1: Relative Spectral Response Functions (SRF) of PROBA-V (full lines) and Sentinel-3 OLCI (dotted lines) red and NIR bands, and typical vegetation spectrum (green).

3.2 THE RETRIEVAL ALGORITHM

3.2.1 Outline

Figure 2 shows a flow diagram of the processing scheme for the NDVI 300m Version 3. Following requirements, the production of a BRDF-corrected NDVI product at global scale and a spatial resolution of 300 m is planned to be performed every 10 days. As a first step, daily (or sub-daily if available) Top Of Atmosphere (TOA) reflectances at a subset of OLCI red (Oa07 and Oa08) and NIR (Oa16 and Oa18) bands are converted to Top Of Canopy (TOC) reflectances [see CGLOPS1_ATBD_S3-AC-V1.1]. Next, a time series of observations of the 4 bands are processed sequentially by the REgularized Brdf invErsion for Land Surface reflectances (ReBeLS) code [see CGLOPS1_ATBD_BRDFCorrection300m-V1.6], yielding to a BRDF-corrected TOC reflectance (TOC-r) per band. For NDVI 300m V3, ReBeLS v1.6 is used.

These angular normalized reflectances (TOC-r) in the NIR and red bands are used to compute a BRDF-corrected NDVI product. Prior to NDVI calculation, 2 S3 OLCI red bands and 2 S3 OLCI NIR bands are averaged to a broad red and NIR band.

The same processing scheme is used for the archive PROBA-V data, except that the input data are already atmospherically corrected. The first processing step is the BRDF correction on the data [see CGLOPS1_ATBD_BRDFCorrection300m-V1.6]. Since PROBA-V sensor had only 1 red and 1 NIR band, these bands are used to calculate the NDVI.

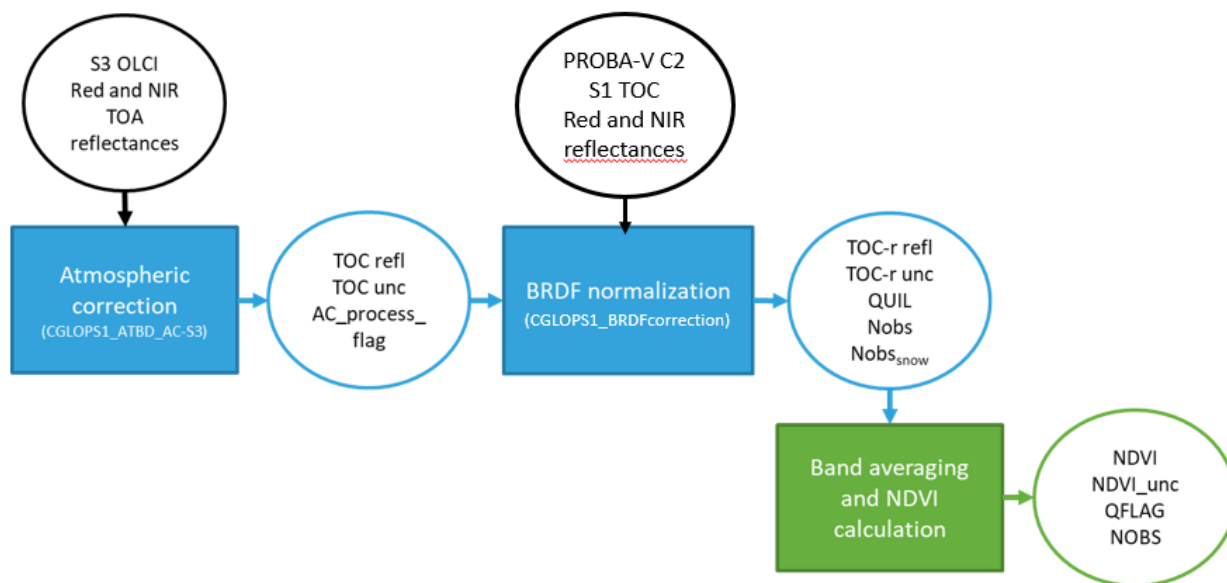


Figure 2: Flow diagram of the NDVI Collection 300m Version 3 algorithm.

The NDVI 300m Version 3 includes the following per-pixel information layers: (i) NDVI, (ii) uncertainty associated to the NDVI (NDVI_unc) (iii) quality flags (QFLAG), and (iv) the number of observations used in the BRDF inversion procedure (NOBS).

3.2.2 Basic underlying assumptions

Healthy vegetation absorbs most of the incident visible light emitted by the Sun, and reflects a large portion of the near-infrared light. Unhealthy (non-green) or sparse vegetation, where the contribution of the soil dominates the signal, reflects more visible light and less near-infrared light. This difference in reflectance for different wavelengths allows remote sensing instruments to measure the relative presence (or absence) of healthy, green vegetation, by simply measuring and comparing the reflectances.

The NDVI can be related to the vegetation photosynthetic activity and was first defined on Advanced Very High-Resolution Radiometer (AVHRR) imagery by Tucker et al. (1981). It is computed from the red and NIR reflectances only. The expression to compute NDVI is as follows:

$$NDVI = \frac{\rho_{(NIR)} - \rho_{(RED)}}{\rho_{(NIR)} + \rho_{(RED)}} \quad \text{Eq. 1}$$

where $\rho_{(RED)}$ and $\rho_{(NIR)}$ are reflectances in the red and NIR spectral band, respectively.

3.2.3 Related and previous applications

3.2.3.1 NDVI 300m products

The differences in algorithms between the NDVI 300m V3 product and the previous versions (V1 and V2) are summarized in Table 1.

The NDVI 300m V1 was derived from the standard PROBA-V 300m 10-daily synthesis (S10) NDVI products, delivered by the PROBA-V ground segment (<http://proba-v.vgt.vito.be/>), with additional application of the status map in the NDVI image. The Global Administrative Unit Layers (GAUL) (<http://www.fao.org/geonetwork>) coastal map was used to distinguish between land and sea. The NDVI 300m V1 was based on the PROBA-V Collection 1 (C1) dataset.

The NDVI 300m V2 dataset was derived from Sentinel-3 OLCI TOA data according to the data flow presented in Figure 2. Atmospheric correction was performed with SMAC (Rahman and Dedieu, 1994), using various sources of ancillary atmospheric parameters for the atmospheric correction [see CGLOPS1_ATBD_S3-AC-V1.1] to generate TOC reflectances V1; the BRDF normalization was applied on the different red and NIR spectral bands [see CGLOPS1_ATBD_BRDFCorrection300m-V1]. Normalized TOC reflectances were generated over land pixels³, that have not been classified as clouds or shadow according to the OLCI IdePix pixel classification processor, using ReBeLS v1.3.

NDVI 300m V3 is derived from Sentinel-3 OLCI TOC reflectance V2.3 input data [see CGLOPS1_PUM_S3-TOC-Reflectance300m-V2.3] and PROBA-V C2 S1 TOC data. A similar BRDF normalization scheme is applied compared to V2, but ReBeLS v1.6 provides improved outlier detection, and filtering of extreme geometries. In NDVI 300m V3, the information contained in the Nobs_{SNOW} BRDF output layer is propagated to the NDVI QFLAG. Moreover, a quality flag is raised when the MCD43P BRDF priors [CGLOPS1_ATBD_BRDFCorrection300m-V1.6] are based on interpolated values.

The NDVI 300m V1, V2 and V3 datasets are not consistent because of the differences in processing approaches, especially the BRDF-normalization.

³ IdePix Land flag is based on a static OLCI land/water mask.

Table 1: Algorithm differences between successive versions of NDVI 300m product

NDVI versions	Algorithm differences
Version 1	Derived from PROBA-V C1 S10 (i.e. directional reflectance) products, with incorporation of the Status Map and land mask.
Version 2	Angular corrected composite over land pixels using ReBeLS v1.3, derived from Sentinel-3 OLCI TOC data, with a 30-days composite window, updated every 10 days using a sliding window. The normalized TOC V1 reflectances from OLCI bands 7, 8, 9 and 10 are averaged to a meanRED reflectance and the OLCI bands 16, 17 and 18 are averaged to a meanNIR reflectance prior to NDVI computation (see Section 3.2.7)
Version 3	BRDF normalization is done on Sentinel-3 TOC V2.3 and PROBA-V C2 S1 TOC data, using ReBeLS v1.6. The number of snow observations in the BRDF compositing window ($N_{obs_{snow}}$) is propagated to the QFLAG. A quality flag is raised when the BRDF priors are based on interpolated values.

3.2.3.2 NDVI 1km products

Next to the NDVI 300m products, there is also the 1km NDVI products. The different versions of the latter are described below (Table 2).

The CLMS NDVI 1km products version 1 was updated every 10 days, with a temporal basis for compositing of 30 days and delivered with a 12 days lag. This NDVI was based on normalized surface reflectances. Its production has been stopped at the end of the SPOT/VGT lifetime (May 2014). It is no longer disseminated.

To comply with the CLMS technical requirements [AD1], the NDVI 1km Version 2 product was derived from the SPOT/VGT Collection 2 (C2, for the period May 1998 – May 2014) and PROBA-V Collection 0 (C0, since October 2013) 10-daily synthesis reflectance values. A spectral harmonization was applied between VGT2 C2 and PROBA-V C0 for NDVI 1km V3. In addition, a bias correction was applied that accounted for remaining systematic differences. This bias correction was based on the observed difference between overlapping PROBA-V and VGT2 images of directional NDVI (i.e., without BRDF correction) and was not representative for the entire time series (1999-2013) for two reasons: (1) the orbital drift of VGT2 in the overlapping period with PROBA-V resulted in different NDVI values for that period, and (2) shortly after this overlapping period (November 2013-May 2014), the calibration of some of the PROBA-V cameras were adjusted to improve inter-camera consistency. As a result, the bias correction proved to impact the consistency

between VGT2 and PROBA-V adversely. No spectral harmonization between VGT1 and VGT2 was performed in the version 2.1 of the NDVI 1km.

The archives of SPOT/VGT and PROBA-V were reprocessed and are referred to as SPOT/VGT Collection 3 (C3) and PROBA-V Collection 1 (C1). The NDVI 1km V2.2 was based on these reprocessed data sets. The NDVI 1km V2.2 also included a spectral harmonization between VGT1 and VGT2. Due to the updated absolute calibration of SPOT/VGT and PROBA-V in the new collections, the bias correction between VGT2 and PROBA-V became obsolete. Furthermore, analysis has showed that spectral harmonization between VGT2 and PROBA-V does not improve the consistency between the two NDVI data sets. Therefore, this correction was not applied anymore. The NDVI 1km V2.2 is provided every 10 days, based on data from these 10 days.

Finally, NDVI 1km V3 is based on BRDF normalized surface reflectances from SPOT/VGT C3 and PROBA-V C1. TOC reflectances were accumulated over a sliding window of maximum 16 days. The NDVI Collection 1km Version 3 includes a spectral harmonization between VGT1 and VGT2 and is distributed as 10-daily global images. The following layers are included: (i) NDVI, (ii) uncertainty associated to NDVI estimation (iii) quality, (iv) number of observations used in the BRDF inversion procedure and (v) the median date of observations used in the BRDF inversion.

Table 2: Algorithm differences between successive versions of NDVI 1km product

NDVI versions	Algorithm differences
Version 1	Derived from SPOT/VGT TOA C2 products, normalized surface reflectance, 30-days composite, updated every 10 days using a sliding window
Version 2.0	Maximum value 10-days composite derived from SPOT/VGT C2 and PROBA-V C0 S10 products, with incorporation of the Status Map and land mask.
Version 2.1	Same as Version 2.0 with a spectral harmonization and a bias correction between VGT2 and PROBA-V. No spectral harmonization between VGT1 and VGT2.
Version 2.2	Maximum value 10-days composite derived from SPOT/VGT C3 and PROBA-V C1 S10 products, with incorporation of the Status Map and land mask. A spectral harmonization between VGT1 and VGT2 is performed.
Version 3	Derived from SPOT/VGT C3 TOA segments and PROBA-V C1 TOA data, normalized surface reflectance, 10-days composite window (extendable to 16 days), updated every 10 days using a sliding window. A spectral harmonization between VGT1 and VGT2 is performed.

3.2.4 Alternative methodologies currently in use

For several decades now, vegetation status is commonly monitored by using near-infrared (NIR) and red reflectances in different combinations (Tucker, 1979). Vegetation indices are arithmetic combinations of surface reflectance from a number of spectral bands that enhance and express the degree of greenness of the land surface. While NDVI is the most widely used band combination, other similar indices are used: e.g. the simple NIR/red ratio (Jordan, 1969), the Soil-Adjusted Vegetation Index (Huete, 1988), the MODIS-specific Enhanced Vegetation Index (Huete et al., 2002), EVI2 (Jiang et al., 2008), the AVHRR-specific Global Environment Monitoring Index (Pinty and Verstraete, 1992), Wide Dynamic Range VI (Gitelson, 2004) and Visible Atmospherically Resistant Index (Gitelson et al., 2002; Hunt et al., 2013). The Plant Phenology Index (Jin and Eklundh, 2014) was designed specifically to monitor vegetation phenology at high northern latitudes.

3.2.5 Input data

The input data for the NDVI calculation are global 10-daily BRDF normalized surface reflectances (TOC-r) derived from 4 Sentinel-3 OLCI bands (Oa7, Oa8, Oa16 and Oa18) and the red and NIR bands of PROBA-V C2 S1 TOC data. More details on the PROBA-V data can be found in the PROBA-V C2 PUM for the general data description and use [PROBA-V C2 PUM], and the ATBD of atmospheric correction of PROBA-V C2 [PROBA-V C2 ATBD AC]. More details about the atmospheric correction applied on S3 data can be found in the ATBD [CGLOPS1_ATBD_S3-AC-V1.1]. The BRDF correction applied to reflectances of both sensors is described in the ATBD [CGLOPS1_ATBD_BRDFCorrection300m-V1.6].

The following layers are used from the TOC-r data files for each of the spectral bands:

- the normalized surface reflectance (TOC-r),
- its associated uncertainty (TOC-r_unc)
- the number of clear observations in the dekad time window (Nobs)
- the number of clear observations in the dekad time window classified as snow (Nobs_{snow})
- and the quality information layer (QUIL) which provides information on the quality of the BRDF correction. The QUIL indicates the following:
 - whether the retrieval is based on observations or not,
 - whether the inversion was successful,
 - the quality of the BRDF inversion based on an estimation of the goodness of fit,
 - whether the retrieved TOC-r is out of range (i.e. $\text{TOC-r} < 0$ or $\text{TOC-r} > 1$).

TOC-r is only available for pixels classified as land. The land/water classification is based on the OLCI IdePix land mask, which is a static layer (see Figure 3).

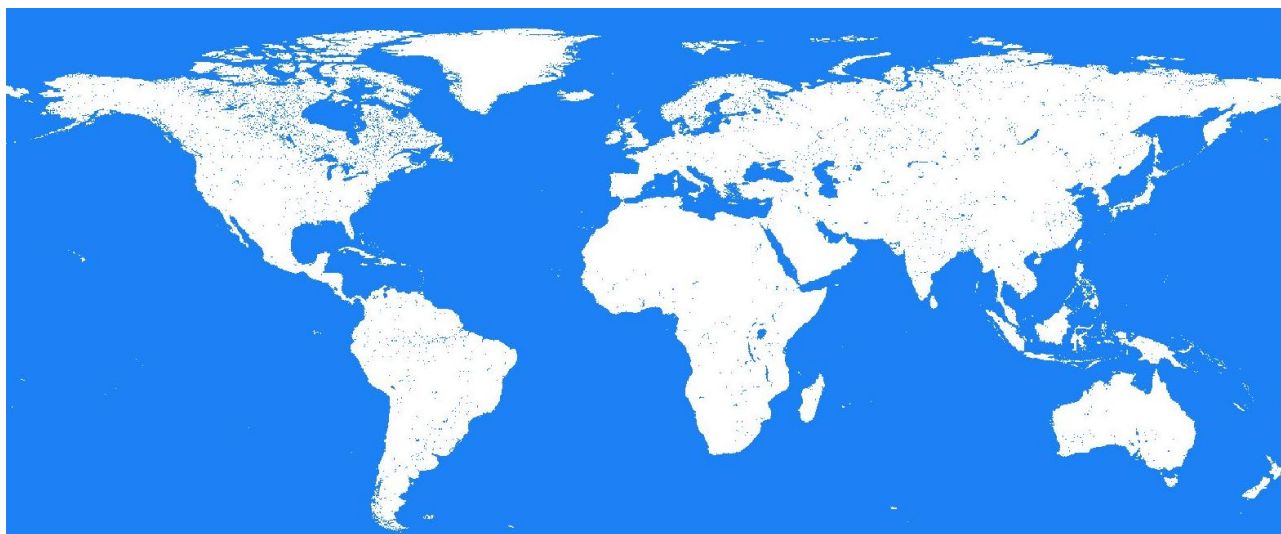


Figure 3: No TOC-r input is available over water pixels, indicated in blue in the OLCI land mask

3.2.5.1 Ancillary layers

PROBA-V C2 AOT masks

The PROBA-V C2 dataset exhibits an artefact where high AOT was used in the atmospheric correction (https://proba-v.vgt.vito.be/sites/probavgt/files/PROBA-V_C2_TN_AOT_masks_V1.0.pdf). To solve this issue, an additional quality mask (AOT mask) is provided that allows masking out these areas. For NDVI, all pixels for which the AOT value used in the atmospheric correction is larger than 0.8 are masked out. This is done prior to the BRDF correction.

BRDF prior quality masks

The BRDF inversion uses a climatology of BRDF descriptors, referred as MCD43P, derived from MODIS MCD43 products (see CGLOPS1_ATBD_BRDFCorrection300m-V1.6). The assembled MCD43P climatology (with weekly cadence) is gap filled by means of a linear interpolation. In order to avoid spurious effects of the gap filled MCD43P BRDF priors, especially on tiles located at high latitudes and in winter periods, a series of 36 10-daily boolean masks were generated that indicate whether the MCD43P is gap filled or not (see example in Figure 4).

In order to generate these masks, per time step t_i the MCD43P was compared to t_{i-1} and t_{i+1} . The resulting weekly masks were translated into 10-daily masks by comparing the day-of-year of the weekly masks and the 10-daily periods and by combining the closest matches.

The masks are used to raise a quality flag (QFLAG bit 7) (Table 5), and for pixels located above 55° latitude, when there are no clear observations in the compositing period, the NDVI and NDVI_unc are not calculated, but replaced by a flag value instead (see §3.2.7.3).

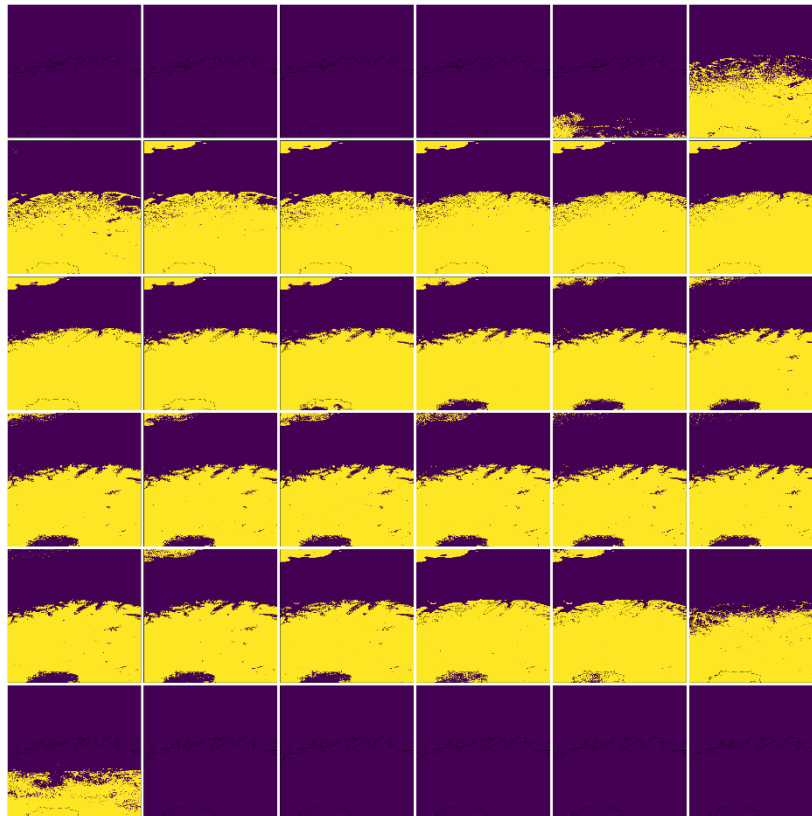


Figure 4: Example of 36 10-daily masks (January-December) to indicate whether the MCD43P BRDF priors are gap filled. Tile located in Northern Finland (65°-75°N, 20°-30°E). Dark purple areas are flagged (see §3.2.7.3).

3.2.6 Output product

The NDVI V3 product is associated to per-pixel information layers as follows:

- NDVI: NDVI value estimated from angular normalized reflectances to a common Sun-sensor geometry (i.e. nadir viewing and Sun zenith angle at 10:00 am local time) (see Section 3.2.7.1)
- NDVI_unc: Uncertainty in the angular normalized NDVI estimate (see Section 3.2.7.2).
- QFLAG: quality flag (describing BRDF inversion quality in both bands, indicating whether (snow) observations are present, and whether the MCD43P BRDF priors are interpolated) (for more details, see Section 3.2.7.3),
- NOBS: number of observations used in the BRDF inversion procedure, propagated from the quality information layer of the TOC-r (see Section 3.2.7.4)

3.2.7 Methodology

The processing of NDVI Version 3 comprises three main steps (see Figure 2) for S3 OLCI and 2 main steps for PROBA-V data. For S3 OLCI, the atmospheric correction is first applied to the TOA observations. This step yields Top-of-Canopy reflectances for the 4 OLCI bands used. The PROBA-V input data are already atmospherically corrected. As a second step, the BRDF correction is performed individually for each pixel of the red and NIR OLCI or PROBA-V TOC reflectances. The BRDF model is used to estimate normalized (to a common Sun-sensor geometry) TOC-r reflectances, which are used, in a third step, to compute the NDVI.

The first step is discussed in detail in [CGLOPS1_ATBD_S3-AC-V1.1].

The general method of the second step is explained in [CGLOPS1_ATBD_BRDFCorrection300m-V1.6]. The input for the BRDF-correction differs for NRT and archive processing. The first step of ReBeLS is a filtering of the data to remove outliers. These outliers can originate e.g. from unidentified cloudy observations. The filtering is performed on the time series of a pixel. The longer the time series, the better the filtering of spurious observations in the time series, but the longer the processing time. For archive processing, an entire year of TOC reflectance with 1 month before and 1 month after (i.e. 14 months) is used as input for ReBeLS. The BRDF-corrected TOC reflectance is then calculated for each of the 10-day periods within that year. In contract, for NRT processing, only 30 days of TOC reflectance are used as input for ReBeLS, and only the BRDF-corrected TOC reflectance of the last 10-day period is kept as output.

The third step is described below. The choice of the S3 OLCI bands was made to maximize the consistency between the resulting NDVI of S3 OLCI and PROBA-V. The approach is described in the Annex: selection of OLCI red and NIR spectral bands.

3.2.7.1 NDVI

Prior to calculation of OLCI NDVI, the 2 narrow red TOC-r bands and the 2 narrow NIR TOC-r bands are converted to a broad red and NIR band by averaging using Eq.2 and Eq.3.

Calculate meanRED and meanNIR reflectances from the TOC-r.

$$\mathit{meanRED} = (B7 + B8)/2 \quad \text{Eq. 2}$$

$$\mathit{meanNIR} = (B16 + B18)/2 \quad \text{Eq. 3}$$

With B_x is the TOC-r reflectance of band x .

Then, the NDVI is calculated using the meanRED and meanNIR bands.

$$NDVI = \frac{meanNIR - meanRED}{meanNIR + meanRED} \quad \text{Eq. 4}$$

For PROBA-V data, the NDVI is calculated in the same way based on the available red and NIR bands. The NDVI from PROBA-V is corrected by 4.5% to agree better the S3-based NDVI (see Annex: selection of OLCI red and NIR spectral bands).

$$NDVI = \frac{NIR - RED}{NIR + RED} \cdot 1.045 \quad \text{Eq. 5}$$

Finally, the NDVI is rescaled from float to byte. The physical range of [-0.08, 0.92] is retained and rescaled to the Digital Number (DN) range of [0, 250] using Eq.6.

$$\begin{aligned} \text{If } NDVI < -0.08 &\rightarrow NDVI = -0.08 \\ \text{If } NDVI > 0.92 &\rightarrow NDVI = 0.92 \\ DN &= (NDVI + 0.08)/0.004 \end{aligned} \quad \text{Eq. 6}$$

The NDVI is calculated for all land pixels (Figure 3), except in a few cases. In these cases, the pixel value in the NDVI layer is set to a flag value (see Table 3), according to the following priority scheme. Firstly, water pixels are flagged directly in the NDVI layer (DN=254). Secondly, the QUIL layer of the input is checked: when there is no TOC-r input for at least one of the input bands (see section 3.2.7.3), or when the TOC-r of one of the input bands is out of range (see section 3.2.7.3), the NDVI is not calculated. These two cases are directly flagged in the NDVI layer as ‘missing’ (DN=255). When half or more than half of the recent valid observations⁴ are classified as snow, the NDVI layer is flagged as ‘snow’ (DN=253). Finally, the NDVI is also flagged (DN=252) for pixels with latitude above 55°N when the MCD43P prior information in the BRDF inversion is gap filled (see §3.2.5.1) and there are no recent valid observations. This is summarized in Table 3.

The NDVI is calculated for all other pixels, including in the following cases:

- When the BRDF-retrieval of at least one band is not based on input data for the compositing window, i.e. Nobs=0: QFLAG =1

⁴ Nobs refers to the number of clear observations in dekad time window [t0, t0+10days] -- where t0 is the date of the dekad provided, i.e. the availability of recent clear observations.

- When the BRDF-inversion for at least one red band has a quality warning (i.e. QUIL=8): QFLAG=4
- When the BRDF-inversion for at least one red band has an extreme quality warning (QUIL=16): QFLAG=8
- When the BRDF-inversion for at least one NIR band has a quality warning (i.e. QUIL=8): QFLAG=16
- When the BRDF-inversion for at least one NIR band has an extreme quality warning (QUIL=16): QFLAG=32

Table 3: Flag values in the NDVI layer

Flag value	Flag name	Description
252	Unknown	NOBS = 0 and the BRDF priors are interpolated (QFLAG = 128, see QFLAG Table 5). This flag value only occurs above 55°N.
253	Snow	NOBS > 0 and NOBS_SNOW ≥ ½ NOBS
254	Water	Water
255	Missing	Where TOC-r is out of range (QFLAG = 64, see Table 5) or where no TOC-r for at least one of the red or NIR bands is available

3.2.7.2 NDVI uncertainty (NDVI_unc)

The uncertainty of the NDVI is calculated by error propagation of the TOC-r uncertainty layers that are delivered with each spectral reflectance. No additional uncertainty is added by calculating the NDVI, since NDVI is calculated using merely arithmetic expressions.

The NDVI uncertainty (Δ NDVI) is calculated from the uncertainties associated with the TOC-r layers (Δ B7, etc.) according to Eq.7, Eq.8, Eq.9 and Eq.10.

meanRED uncertainty

$$\Delta_{meanRED} = \frac{1}{2} \sqrt{\Delta B7^2 + \Delta B8^2} \quad \text{Eq. 7}$$

meanNIR uncertainty

$$\Delta_{meanNIR} = \frac{1}{2} \sqrt{\Delta B16^2 + \Delta B18^2} \quad \text{Eq. 8}$$

NDVI uncertainty

$$\Delta NDVI = \frac{\sqrt{\text{meanNIR}^2 \Delta \text{meanRED}^2 + \text{meanRED}^2 \Delta \text{meanNIR}^2}}{(NIR + RED)^2} \quad \text{Eq. 9}$$

With ΔX is the uncertainty of X . It is considered that the uncertainties on red and NIR are not correlated.

For PROBA-V, the uncertainty is derived from the uncertainty of the red and NIR bands as follows

$$\Delta NDVI = \frac{\sqrt{NIR^2 \Delta RED^2 + RED^2 \Delta NIR^2}}{(NIR + RED)^2} \quad \text{Eq. 10}$$

Finally, the NDVI uncertainty is rescaled from float to integer (DN) using Eq.11

$$DN = \Delta NDVI * 1000 \quad \text{Eq. 11}$$

Similar to NDVI, certain pixels are flagged directly in the NDVI_unc layer (see Table 4).

Table 4: Flag values in the NDVI_unc layer.

Flag value	Flag name	Description
-2	Water	Water (NDVI = 254)
-1	Invalid	Where NDVI = 252 or NDVI = 253 or NDVI = 255 (see Table 3)

3.2.7.3 Quality flags (QFLAG)

The quality flag of the NDVI V3 is a bitwise map that propagates information of each TOC-r input band (QUIL, Nobs and Nobs_{snow}, see §3.2.5) and indicates for all land pixels:

- whether the BRDF inversion for the compositing period is based on recent valid observations (Nobs > 0),
- whether recent observations are classified as snow (Nobs_{snow} > 0),
- the quality of the BRDF inversion (based on QUIL),
- whether the retrieved TOC-r is out of range (i.e. TOC-r < 0 or TOC-r > 1)
- whether MCD43P BRDF priors are based on linearly interpolated (gap filled) values.

The different bits are described in detail below (and summarized in Table 5):

- Bit 0 = 1 (QFLAG = 1): if, at least, for one of the input bands for NDVI calculation, no observations were found within the compositing window. This means that the NDVI is based

on a TOC-r value based on prior information only for at least one of the input bands. The NDVI should be treated with caution.

- Bit 1 = 1 (QFLAG = 2): at least one of the observations in the compositing window for any of the TOC-r input bands is classified as 'snow'. If half, or more than half, of the observations in the compositing window are classified as 'snow', the NDVI and NDVI_unc are not calculated, and a flag value (DN=253 for NDVI, DN=-1 for NDVI_unc) is added in these layers (see Table 3 and Table 4).
- Bit 2 = 1 (QFLAG = 4): at least one of the red TOC-r input bands has a quality 'warning' (i.e. QUIL=8) [CGLOPS1_ATBD_BRDFCorrection300m-V1]. It means that the goodness of fit estimation between observations and model is adequate, but results should be taken with caution.
- Bit 3 = 1 (QFLAG = 8): at least one of the red TOC-r input bands has a quality 'extreme warning' (i.e. QUIL=16) [CGLOPS1_ATBD_BRDFCorrection300m-V1]. It means that the goodness of fit estimation between observations and model is not adequate.
- Bit 4 = 1 (QFLAG = 16): at least one of the NIR TOC-r input bands has a quality 'warning' (i.e. QUIL=8) [CGLOPS1_ATBD_BRDFCorrection300m-V1]. It means that the goodness of fit estimation between observations and model is adequate, but results should be taken with caution.
- Bit 5 = 1 (QFLAG = 32): at least one of the NIR TOC-r input bands has a quality 'extreme warning' (i.e. QUIL=16) [CGLOPS1_ATBD_BRDFCorrection300m-V1]. It means that the goodness of fit estimation between observations and model is not adequate.
- Bit 6 = 1 (QFLAG = 64): at least one of the input TOC-r values was out of range (TOC-r < 0 or TOC-r > 1). Also, here, the NDVI and NDVI_unc are not calculated, and a flag value (DN=255) is added in these layers (see Table 3 and Table 4).
- Bit 7 = 1 (QFLAG = 128): the MCD43P climatology (BRDF priors) are gap filled by means of a linear interpolation (see CGLOPS1_ATBD_BRDFCorrection300m-V1). If NOBS = 0 and the pixel is located > 55°N, the NDVI and NDVI_unc are not calculated, and a flag value (DN=252 for NDVI, -1 for NDVI_unc) is added in these layers (see Table 3 and Table 4).

Table 5: Bit number, description and value of the quality flags.

Bit	Description	Value
0	No observations found in the compositing window in, at least, one of the red or NIR bands	1
1	At least one of the observations in the compositing window is flagged as ‘snow’	2
2	At least one TOC-r input band for red has quality ‘warning’	4
3	At least one TOC-r input band for red has quality ‘extreme warning’	8
4	At least one TOC-r input band for NIR has quality ‘warning’	16
5	At least one TOC-r input band for NIR has quality ‘extreme warning’	32
6	TOC-r out of range (TOC-r < 0 TOC-r > 1) for at least one band	64
7	The BRDF MCD43P priors are gap filled	128

3.2.7.4 Number of observations (NOBS)

Each input normalized TOC reflectance band has associated Nobs and Nobs_{snow} layers (see §3.2.5). The Nobs is propagated to the NDVI NOBS layer, by taking the minimum value of the 4 OLCI or 2 PROBA-V Nobs layers, one per spectral band, for that pixel (see §3.2.5). When NOBS equals zero, QFLAG bit 0 is set to 1.

Also, information contained in the Nobs_{snow} layer is propagated into the NDVI chain, by taking the maximum value of the available Nobs_{snow} layers, resulting in NOBS_SNOW. The NOBS_SNOW layer is not included in the output product. However, when NOBS_SNOW is larger than zero, QFLAG bit 1 is set. When NOBS is larger than 0 and $NOBS_SNOW \geq \frac{1}{2} NOBS$, no NDVI or NDVI_{unc} is calculated and instead a flag value is set (DN=253 for NDVI, DN=-1 for NDVI_{unc}).

3.2.8 Limitations

All reported limitations of the atmospheric correction and the BRDF correction are also applicable to the NDVI as far as they concern the 4 OLCI or 2 PROBA-V input bands used for the NDVI calculation. These limitations are described in detail in the ATBDs [CGLOPS1_ATBD_S3-AC-V1.1 (only for S3 OLCI) and CGLOPS1_ATBD_BRDFCorrection300m-V1 (for both sensors)]. A short summary is given below. Since the PROBA-V data are atmospherically corrected using the same model as for S3 OLCI [PROBA-V C2 ATBD AC], the same limitations are valid.

Limitations related to the atmospheric correction:

- SMAC is a parameterization of the radiative transfer model 6S (Vermote et al., 1997). For certain conditions, e.g. anisotropic surfaces, the SMAC approximations could lead to an inaccuracy of several percent, especially for high atmospheric turbidity.

- Neither adjacency effects nor terrain slope correction is considered. These effects are, however, secondary at the spatial scale of 300 meters.

Limitations related to the BRDF correction:

- The quality of BRDF descriptor retrievals is fully dependent on the quality of the atmospheric correction and cloud-shadow-snow pixel identification. Although a robust outlier detection is part of the ReBeLS processor, its performance is significantly diminished in periods with a high frequency of cloud occurrence.
- The MCD43P dataset that is used as prior input for the BRDF inversion does not make a distinction for snow and snow-free pixels.
- BRDF descriptors and BRDF adjusted reflectances (TOC-r) estimates are provided each dekad even if no observations were available within that dekad (and thus NOBS=0). These estimates are significantly dominated by the MCD43P prior of BRDF descriptors (based on MODIS MCD43A1 and MCD43A2 products) used by ReBeLS. In NDVI V3, a quality flag is raised when the MCD43P are gap filled by means of a linear interpolation (see §3.2.7.3), and the NDVI is flagged when this is the case for pixels $> 55^{\circ}\text{N}$ and when NOBS=0.

Limitations related to the input data:

- Clear-sky snow observations are considered valid inputs to the BRDF inversion, which results in snow contamination in the NDVI outputs. To mitigate this, in NDVI 300m V3 the information on Nobs_{snow} is propagated. Nevertheless, the snow identification in S3 OLCI data is known to underperform, and clear-sky snow is often misclassified as cloud by the pixel identification scheme [see CGLOPS1_QAR_S3-CloudMask]. The snow identification of PROBA-V was much improved in C2, but has still limitations.

3.3 EVALUATION OF ALGORITHM PERFORMANCE

3.3.1 Consistency analysis of NDVI 300m V3

A test dataset was generated for the year 2019. Both the PROBA-V and OLCI NDVI datasets were generated for this period. These datasets were intercompared based on a global systematic subsample. The systematic subsample was taken as the 15th pixel in x- and y-direction in a window of 51 by 51 pixels. The sample is independent from the sample that is used for the definition of the method.

The scatterplot between the Sentinel-3 OLCI and PROBA-V-based NDVI 300m V3 is presented in Figure 5. It shows a linear relationship between the two data sets with high R^2 of 0.96 and an

orthogonal geometric mean regression equation close to the 0-1 line. The correction of 4.5% is applied on the PROBA-V data (Figure 5 right) and results in a good consistency between the two datasets.

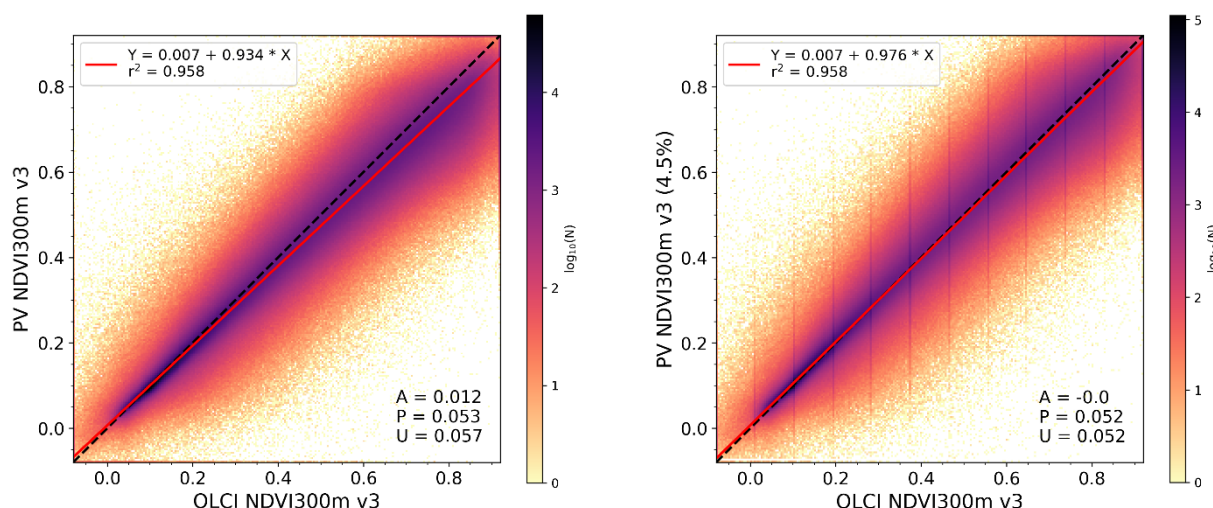


Figure 5: Scatterplot between the Sentinel-3 OLCI-based (X) and the PROBA-V-based NDVI 300m V3 (Y), before (left) and after (right) the 4.5% correction.

Figure 6 shows the bias histogram between the two data sets. The peak is clearly centered around 0 and the histogram is almost symmetrical at both sides of the peak. A total of 84.2 % of the pixels analyzed are within the range [-0.05, 0.05], and 65.4 % within the range [-0.025, 0.025] after the 4.5% correction. Before this correction, these numbers are respectively 82.2% and 63.9%.

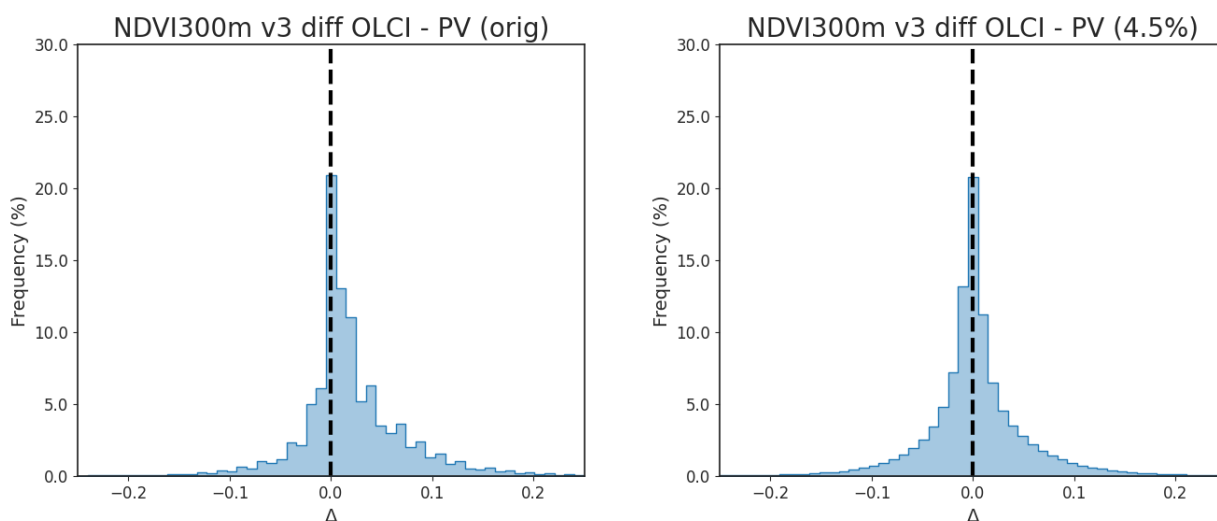


Figure 6: Bias histogram between the S3- and PROBA-V-based NDVI 300m V3, before (left) and after (right) the 4.5% correction.

The results suggest that a good consistency between S3 and PROBA-V based NDVI 300m V3 is obtained, especially after the 4.5% correction of the PROBA-V NDVI 300m v3 (Figure 7, right).

3.4 RISK OF FAILURE AND MITIGATION MEASURES

In case one of the Sentinel-3A or -3B satellites or OLCI sensors fails, the NDVI can still be derived from the remaining OLCI sensor. This will evidently impact the accuracy and the uncertainty of the NDVI because the accuracy of the BRDF-normalization is related to the number of observations that are available for model inversion. The launch of Sentinel-3C is foreseen for 2025. From then on, sufficient observations would be available again.

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5 ANNEX: SELECTION OF OLCI RED AND NIR SPECTRAL BANDS

5.1 INTRODUCTION

This annex describes the analysis performed to establish the band selection of S3 OLCI red and NIR bands so that the OLCI NDVI 300m V3 is as consistent as possible with the PROBA-V NDVI 300m V3.

When looking at the spectral response functions (SRFs) of OLCI and PROBA-V (Figure 1), it is clear that the shape of the SRFs are very different. PROBA-V has single red and NIR bands that are much broader than the various small red and NIR bands of OLCI. There are 4 red bands of OLCI (Oa07, Oa08, Oa09, Oa10) and 3 NIR bands (Oa16, Oa17 and Oa18) that overlap with the PROBA-V red and NIR bands. A combination of OLCI bands is therefore necessary to reach consistency between the NDVI of both sensors.

To evaluate the different band combinations, we started from simulated spectra that were generated for the related S3 OLCI and PROBA-V red and NIR bands, and verified the combinations on a sample of global data of 2019 which is the overlap year between PROBA-V and OLCI life time. In the following sections, the input data is described, the analysis method is explained and the results are discussed.

5.2 INPUT DATA

5.2.1 Simulations

Hyperspectral reflectances were simulated using the Coupled Soil-Leaf-Canopy (SLC) model (Verhoef and Bach, 2007). The SLC model is a combination of a modified version of the Hapke soil BRDF model (Hapke, 1981), PROSPECT (Jacquemoud and Baret, 1990) and 4SAIL2 based on SAIL (Verhoef, 1984) and is available on github (<https://github.com/ajwdewit/pyslc>). The definition of the minimum and maximum values of the soil, leaf and canopy parameters is based on values found in literature ((Darvishzadeh et al., 2008; Gonsamo and Chen, 2013; Mousivand et al., 2014). The sampling scheme is using Latin hypercube sampling, which aims to spread the sample points evenly across all possible values.

These simulations are then convoluted with the PROBA-V red and NIR Spectral Response Functions (SRFs) and those of the S3 OLCI bands Oa07, Oa08, Oa09, Oa10, Oa16, Oa17 and Oa18.

5.2.2 Satellite data

One year (2019) of BRDF-normalized data TOC reflectance data from PROBA-V and Sentinel-3 OLCI were used. A global subsample of the data was used by taking only good quality pixels for each center pixel in a window of 51 by 51 pixels.

Because the final Sentinel-3 OLCI TOC reflectance products (v2.3) were not available at the time of this analysis, an evaluation was done on the final data once it was available (§ 5.4.3).

5.3 APPROACH AND METHOD

The approach to establish the combination of OLCI bands to have the best agreement with the PROBA-V NDVI V2 is done in different steps.

1. Separate bands comparison: A comparison is done between each single S3 OLCI band and its corresponding PROBA-V band. This is done on the simulations and on the satellite data.
2. Evaluation of various band combinations: We start the evaluation using all S3 OLCI bands on the real data and on the simulations. Next, various band combinations are evaluated on the simulations and a selection is made. This selection is then evaluated on real data. Here, not only the agreement for red and NIR bands are investigated, but also the NDVI.

In terms of methods, scatterplots and bias histograms are used as well as metrics to derive APU statistics: Accuracy (mean bias (B)), Precision (standard deviation of the bias (STD)) and Uncertainty (root mean squared difference (RMSD)). Spatial plots of the APU metrics are also generated to evaluate the impact spatially.

5.4 RESULTS

5.4.1 Separate band comparisons

The scatterplots between the simulated TOC reflectance of the PROBA-V red band against every overlapping S3 OLCI band (Oa07, Oa08, Oa09 and Oa10) is shown in Figure 7. The same graphs, but for the real satellite data, are presented in Figure 8. There is no single band that has an unbiased relationship with the PROBA-V red band. S3 OLCI band Oa07 has opposite behaviour than Oa08, Oa09 and Oa10. Similar behaviour can be observed in the real satellite data presented in Figure 8. The contrasting behaviour of band Oa07 suggests that this band should be selected together with at least one of the other OLCI bands to obtain a closer agreement between the S3 OLCI and PROBA-V red reflectances.

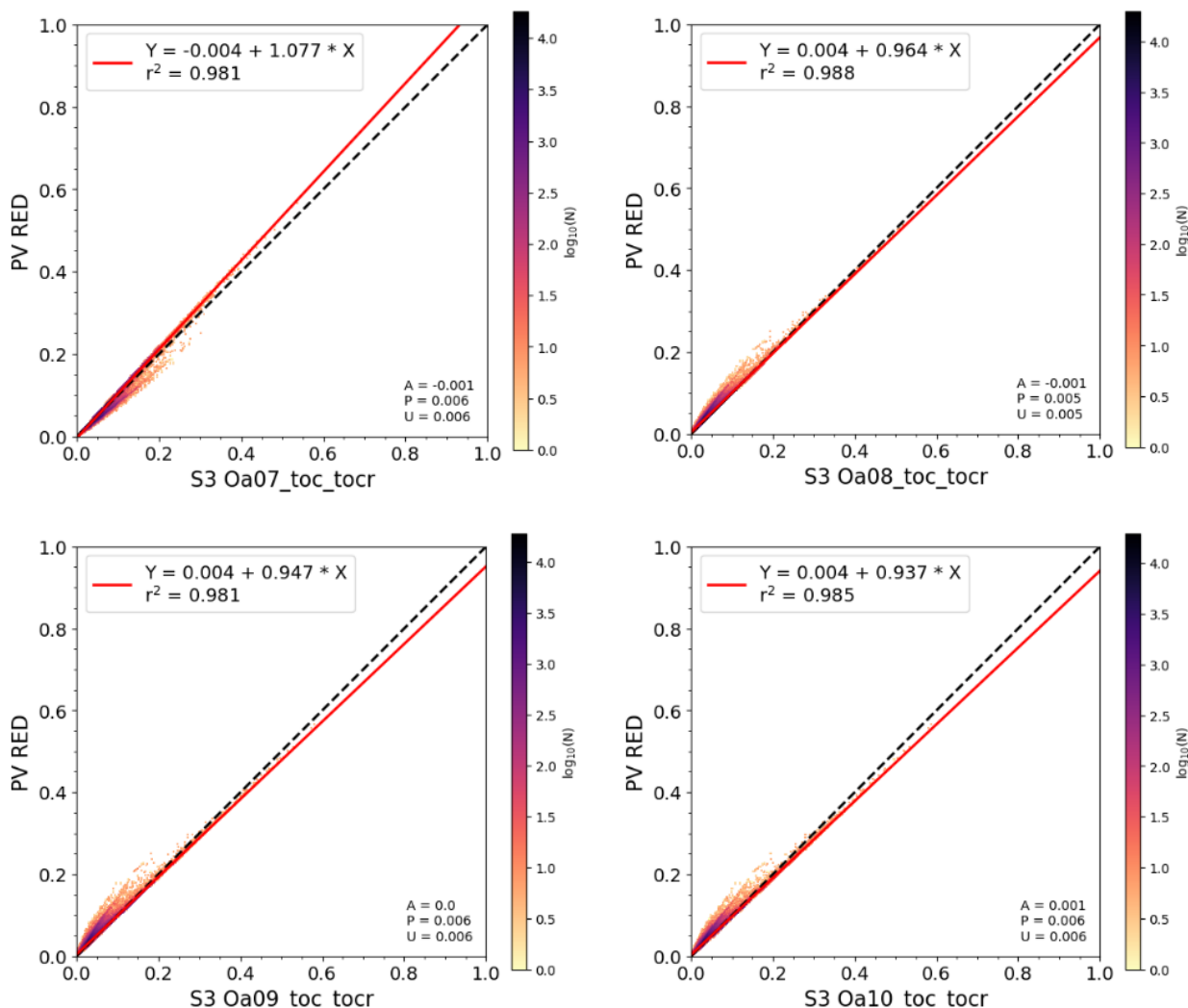


Figure 7: Scatterplots between simulated PROBA-V red and the simulated overlapping S3 OLCI bands (Oa07: top-left, Oa08: top-right, Oa09: bottom-left, Oa10: bottom-right) TOC reflectances.

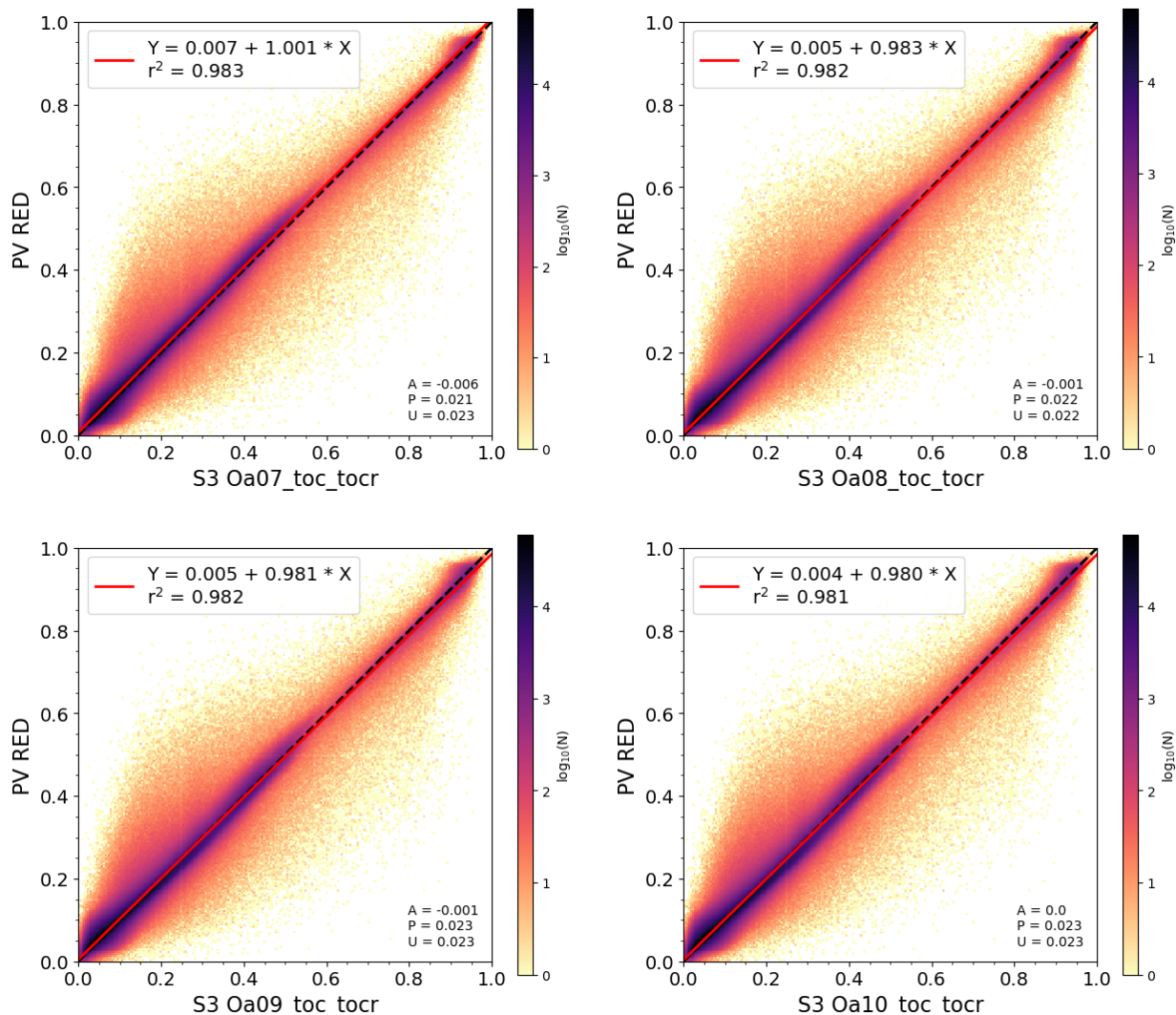


Figure 8: Scatterplots between BRDF-normalized TOC reflectances of PROBA-V red and overlapping S3 OLCI bands (Oa07: top-left, Oa08: top-right, Oa09: bottom-left, Oa10: bottom-right).

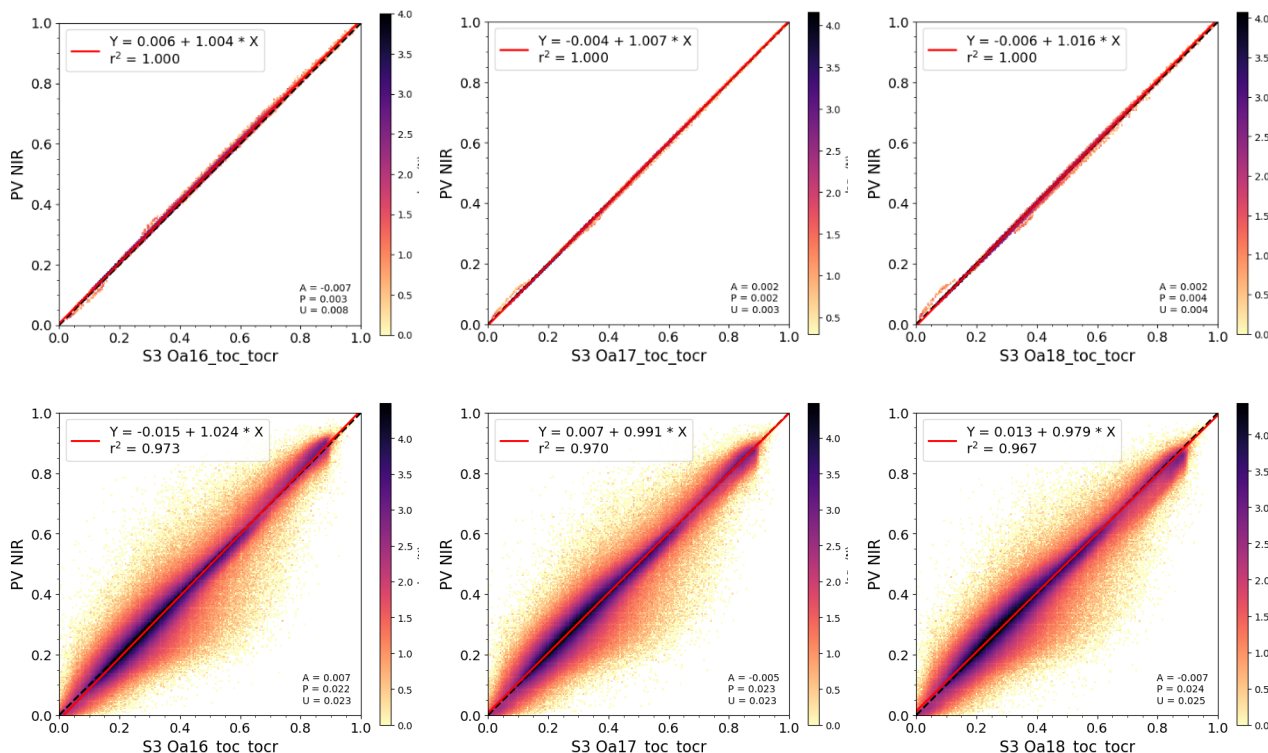


Figure 9: Scatterplots between PROBA-V NIR and overlapping S3 OLCI bands for simulated TOC reflectances (top row) and BRDF-normalized TOC reflectances (bottom row).

Figure 9 shows the same analysis, but for the agreement between PROBA-V NIR and S3 OLCI bands Oa16, Oa17 and Oa18. From the BRDF-normalised TOC reflectance data, it appears that band Oa16 should be combined with at least one of the other OLCI bands to obtain a better agreement with PROBA-V NIR. This does not seem to be supported by the simulated data as the slope of the gm regression line is always higher than 1. But visually on the graph, we see that for Oa16, OLCI>PV for TOC<0.2 and OLCI<PV for TOC>0.2. This seems to be the opposite for Oa17 and Oa18. So, the behaviour of Oa16 is also different in simulated data.

5.4.2 Evaluation of various band combinations

5.4.2.1 Evaluation of using all S3 red and NIR bands

The NDVI300 V2 uses the average of the 4 S3 OLCI red bands (Oa07, Oa08, Oa09 and Oa10) and the 3 NIR bands (Oa16, Oa17 and Oa18) as input for the NDVI. When this approach was established, the Rebels BRDF-method was not yet available for PROBA-V data, and the PROBA-V Collection 1 was used. The same approach is now tested on the Rebels BRDF-normalized TOC reflectances using PROBA-V Collection 2 as input. The results are presented in Figure 10. The average OLCI red reflectance is higher than that of PROBA-V, but the averaged NIR band is corresponding well to the

PROBA-V NIR data. The resulting OLCI NDVI is therefore higher than the PROBA-V NDVI. This can be seen from the simulated data as well as from the satellite data. Therefore, other band combinations are investigated.

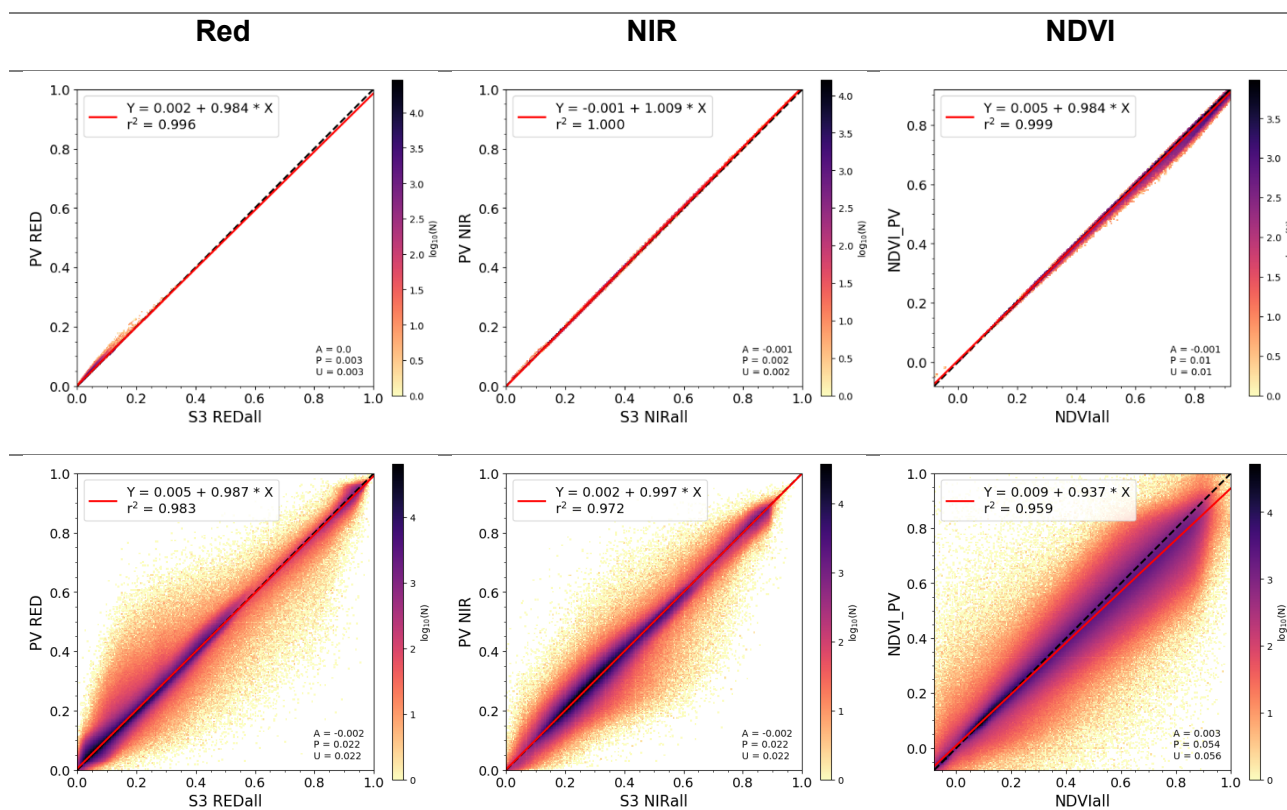


Figure 10: Scatterplots between PROBA-V and S3 OLCI using the average of 4 red bands (REDall) and 3 NIR bands (NIRall) as input, as well as the NDVI derived from these averaged bands (NDVIall). Results are given for red (left), NIR (middle) and NDVI (right) for simulated reflectances (top) and real satellite data (bottom).

Figure 11 shows the bias histograms between the same datasets for red, NIR and NDVI, both simulated data and satellite data. The bias histograms are skewed towards positive difference between S3 NDVI and PROBA-V, meaning that the former has higher values. Again, similar results are obtained for the simulated data and the real satellite data.

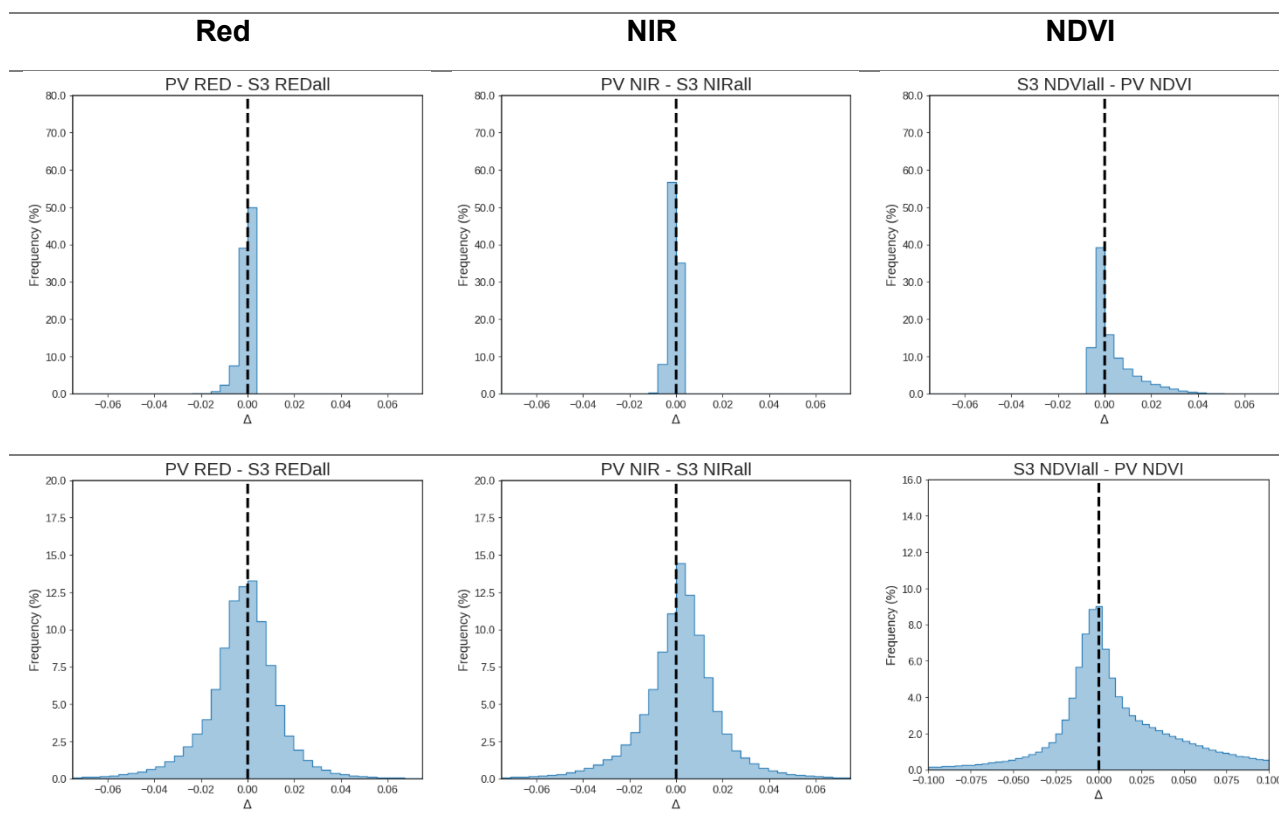


Figure 11: Bias histograms between PROBA-V and S3 OLCI using the average of 4 red bands (REDall) and 3 NIR bands (NIRall) as input, as well as the NDVI derived from these averaged bands (NDVIall). Results are given for red (left), NIR (middle) and NDVI (right) for simulated reflectances (top) and real satellite data (bottom).

5.4.2.2 Simulations

Since there is a close agreement between the results of the simulated data and the real satellite data, the selection of the band combinations is predominantly done on the simulated data to select a few candidate band combinations. The criteria for the selection are that the relationship should be linear, the precision should be the highest (lowest standard deviation of the bias, meaning lowest scatter around the gm regression line), the uncertainty should be the lowest (lowest RMSD) and the accuracy (A) should be the highest (lowest bias). In addition, the best solution with the lowest number of bands is preferred to limit the processing time. The best results are obtained by the following band combinations:

- Red: Oa07 and Oa10, NIR: Oa16 and Oa17 (“NDVI7-10not18”)
- Red: Oa07 and Oa08, NIR: Oa16 and Oa17 (“NDVI7-8not18”)
- Red: Oa07 and Oa08, NIR: Oa16 and Oa18 (“NDVI7-8not17”)

Figure 12 shows the scatterplots and bias histograms between PROBA-V and S3 OLCI for the band

combinations listed above. When comparing the results with those for NDVI in Figure 10 and Figure 11, it is clear that there is much less bias when using these band combinations than when using the NDVI based on all the OLCI bands that overlap with the PROBA-V red and NIR bands. Also, the relationship in the scatterplot is closer to the 0-1 line, but most importantly, there is less scatter (higher precision (P) due to lower standard deviation of the bias (STD) and lower uncertainty (U)).

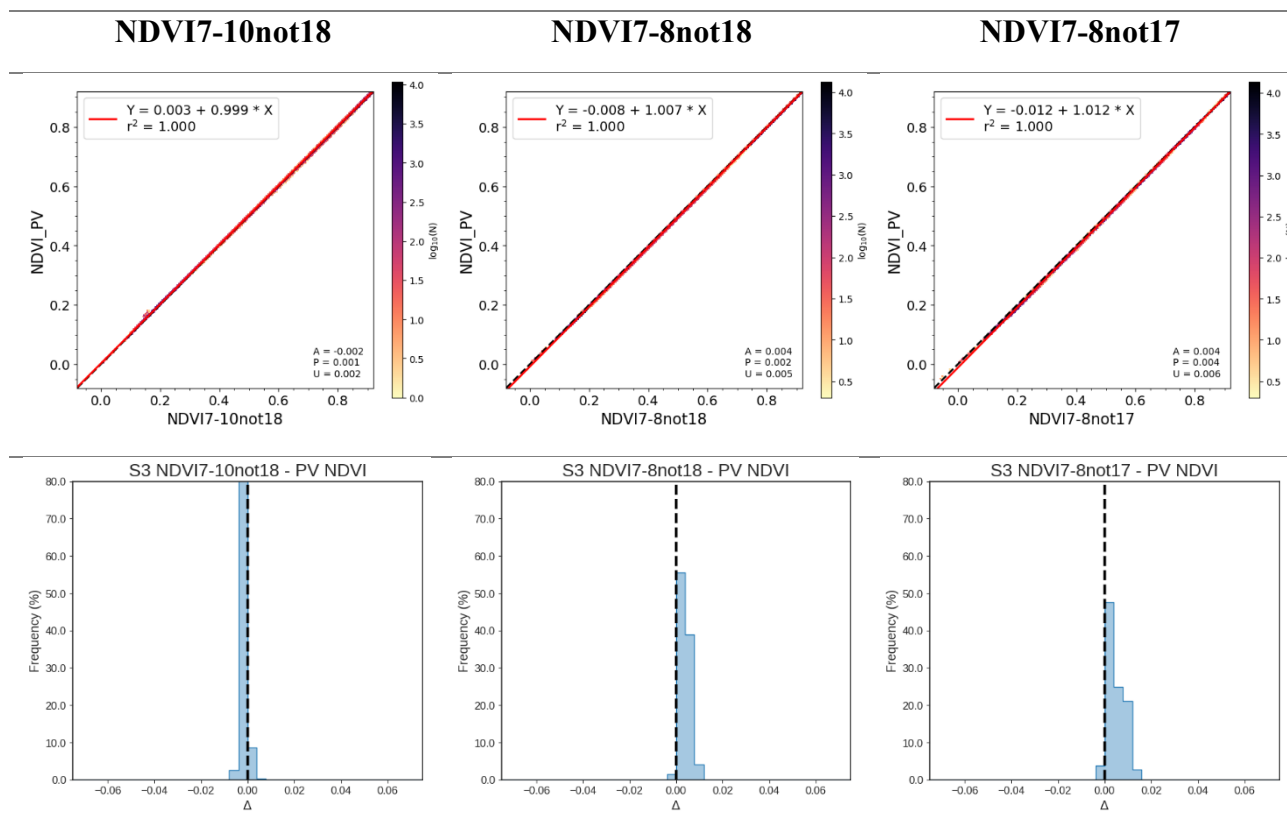


Figure 12: Scatterplots (top) and bias histograms (bottom) between PROBA-V NDVI and S3 OLCI NDVI based on the different band combinations of simulated reflectances: OA07, Oa10, Oa16 and Oa17 (left), Oa07, Oa08, Oa16 and Oa17 (middle) and Oa07, Oa08, Oa16 and Oa18 (right).

5.4.2.3 Evaluation of selected band combinations on satellite data

Figure 13 shows the scatterplots and bias histograms of PROBA-V-based NDVI300 V3 and the 3 candidate band combinations for S3 OLCI based NDVI300 V3. The scatterplots show a clear linear relationship, with a smaller bias with the 0-1 than when using all available red and NIR OLCI bands for the NDVI (see Figure 10). Not only the slope of the regression line is closer to 1, but also the offset is closer to 0. The bias histograms are much less skewed, but not entirely centered around 0, meaning that there is still a remaining bias between the two NDVI300 V3 data sets.

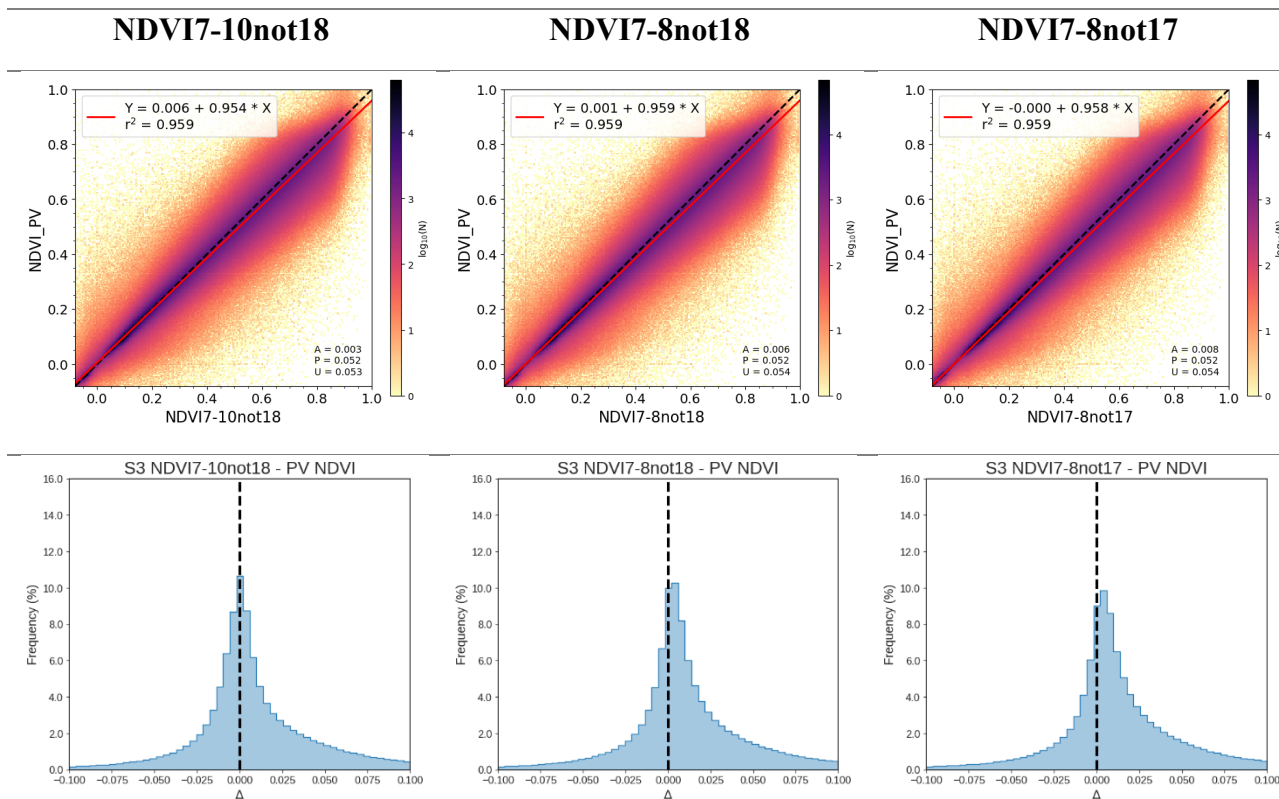


Figure 13: Scatterplots (top) and bias histograms (bottom) between PROBA-V-based NDVI300 V3 and S3 OLCI NDVI300 V3 based on the different band combinations of satellite reflectances: Oa07, Oa10, Oa16 and Oa17 (left), Oa07, Oa08, Oa16 and Oa17 (middle) and Oa07, Oa08, Oa16 and Oa18 (right).

Figure 14 presents the spatial plots of the bias, uncertainty (RMSD) and precision (standard deviation of the bias) calculated between the PROBA-V-based NDVI300 V3 and the 3 candidate band combinations for S3 OLCI based NDVI300 V3. The bias plots confirm the bias to higher values of S3 OLCI based NDVI300 V3 candidate band combinations. The patterns of the bias are slightly different between the various band combinations, but the precision and uncertainty are similar.

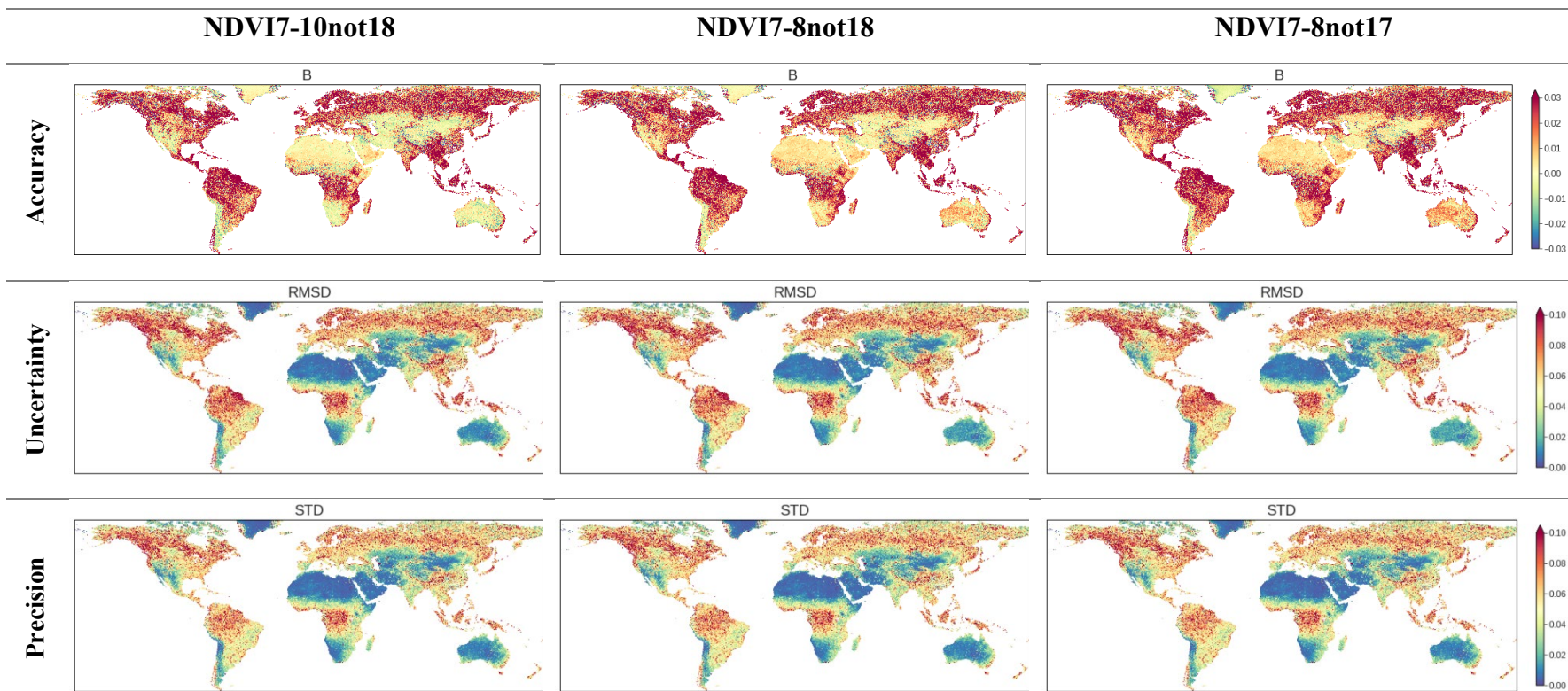


Figure 14: Spatial plots of Accuracy (top), Uncertainty (middle) and Precision (bottom) between PROBA-V-based NDVI300 V3 and the 3 candidate S3 OLCI NDVI300 V3 based on different band combinations.

Although the three candidate band combinations perform well, a bias of about 4% remains as can be seen from the slope of the gm regression line. In general, S3-based NDVI300 V3 is higher than the PROBA-V-based one. This difference can be due to differences in absolute calibration of both sensors. S3 OLCI bands are brighter than PROBA-V bands. This is a difference that cannot be attributed to the SRFs. Therefore, an empirical correction of 4% should be applied on the data, in order to have the smallest bias when changing from PROBA-V to S3-based NDVI300 V3.

The results of the intercomparison of the 3 candidate band combinations with the PROBA-V based NDVI300 V3 after the 4% correction applied on the PROBA-V NDVI on are shown in Figure 15 (scatterplots and bias histograms) and Figure 16 (spatial plots of accuracy, precision and uncertainty). The band combination using Oa7, Oa08, Oa16 and Oa18 (NDVI7-8not17) shows a good agreement in the scatterplot, with the best accuracy (A=0). The bias histogram is symmetrically centered around 0, and the spatial plot of the bias (Accuracy) shows the most improvement compared to the original data without application of the 4% correction (Figure 14). Therefore, this band combination is selected for the processing of the NDVI300 V3.

The 4% correction was evaluated on the final dataset (see section 5.4.3), and slightly adapted.

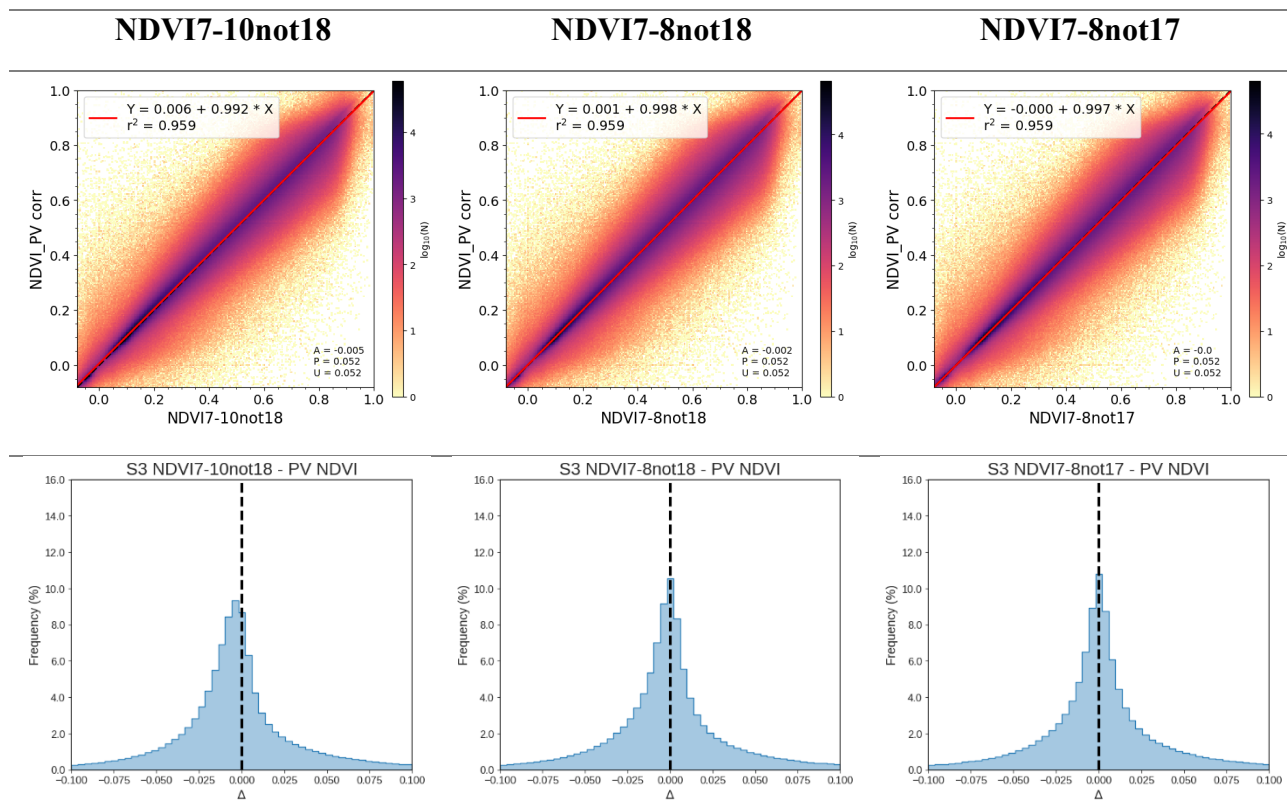


Figure 15: Scatterplots (top) and bias histograms (bottom) between PROBA-V-based NDVI300 V3 after correction and S3 OLCI NDVI300 V3 based on the different band combinations of satellite reflectances: Oa07, Oa10, Oa16 and Oa17 (left), Oa07, Oa08, Oa16 and Oa17 (middle) and Oa07, Oa08, Oa16 and Oa18 (right).

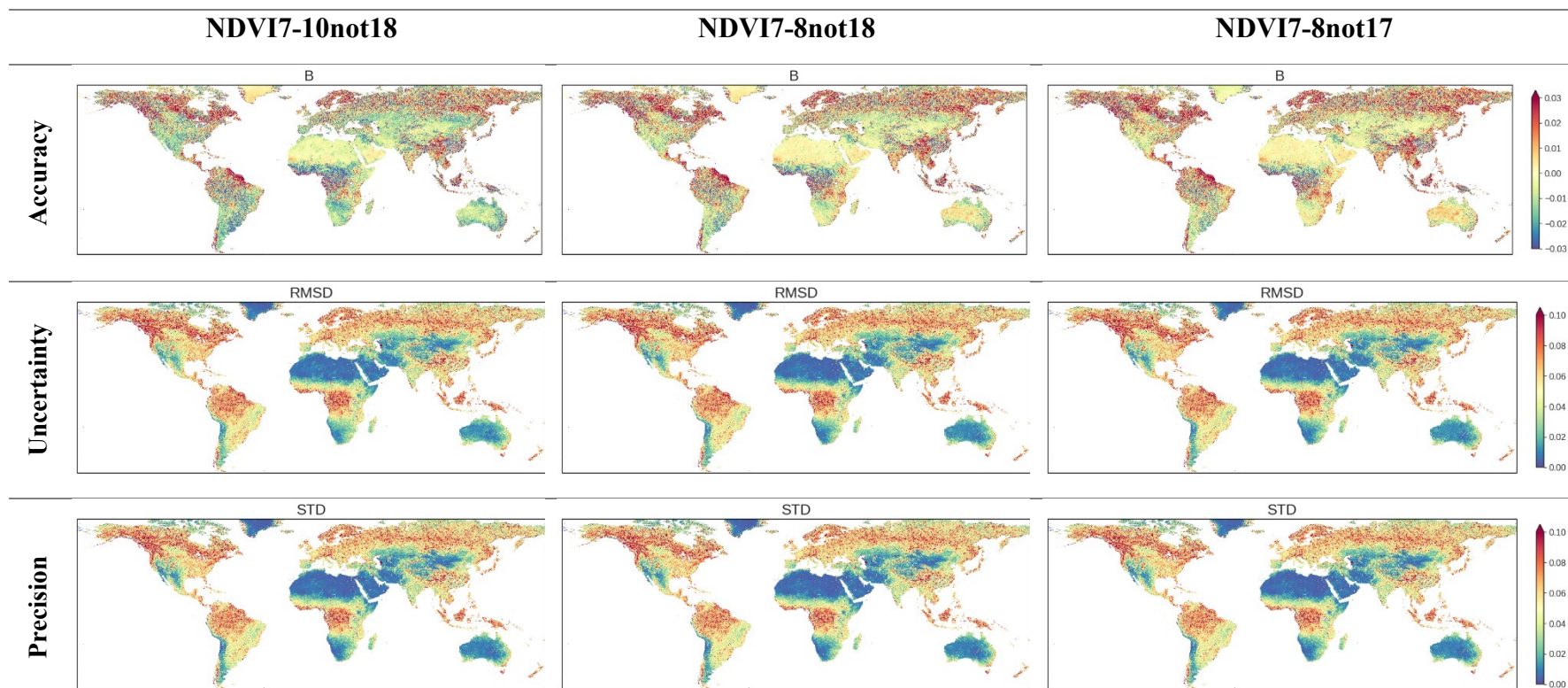


Figure 16: Spatial plots of Accuracy (top), Uncertainty (middle) and Precision (bottom) between PROBA-V-based NDVI300 V3 and the 3 candidate S3 OLCI NDVI300 V3 based on different band combinations after additional correction.

5.4.2.4 Consistency check with NDVI Collection 1km V3

In order to verify if the 4% correction should be applied on the OLCI- or PROBA-V-based NDVI300 V3, a comparison is done with the NDVI 1km V3 product. An overall large statistical and spatial consistency was found between S3/OLCI NDVI300 V2 and the BRDF-corrected PROBA-V NDVI 1km V3 [see CGLOPS1_QAR_NDVI300m_V3]. So, in order to keep this consistency, an intercomparison with the NDVI300 V3 from PROBA-V and OLCI is done. This is performed by comparing the NDVI for the LANDVAL sites (Fuster et al., 2020) at 1 km spatial resolution. The mean NDVI of the NDVI300 V3 is calculated in a window of 3 x 3 pixels if 75% of the pixels is of good quality. The analysis is based on the selected combination NDVI7-8not17.

Figure 17 presents the results of the comparison of the PV- and OLCI- based NDVI V3 with the NDVI 1 km V3 (scatterplots and histograms). It is clear that the latter is in between the values of both NDVI300 V3 datasets. Therefore, it is equally good to apply the correction on either of them. In order to have S3/OLCI as reference, the choice is made to apply the 4% correction on the PROBA-V based NDVI300 V3. The results obtained after applying this correction are shown in Figure 18.

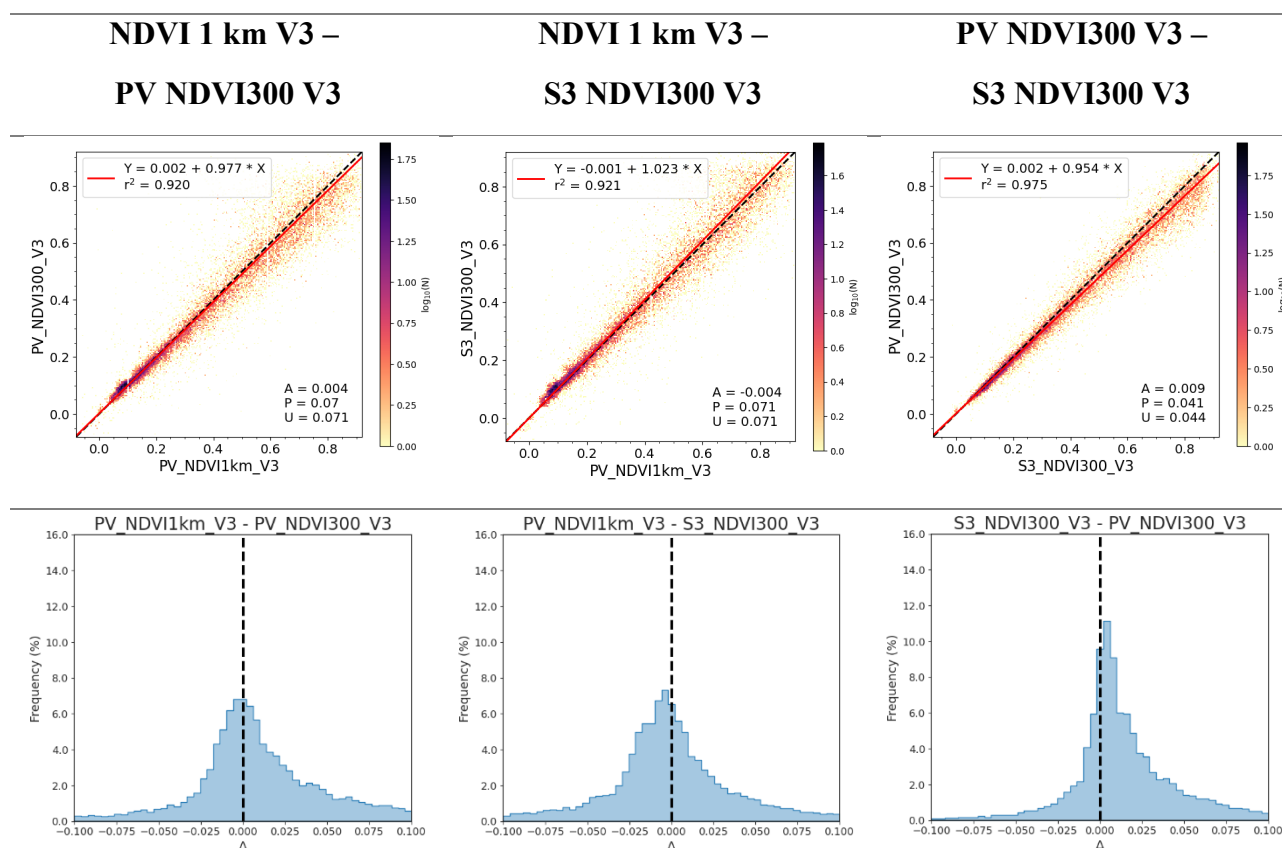


Figure 17: Scatterplots and bias histograms between all combinations of the PROBA-V and OLCI based NDVI V3 and the NDVI 1km V3 without correction applied.

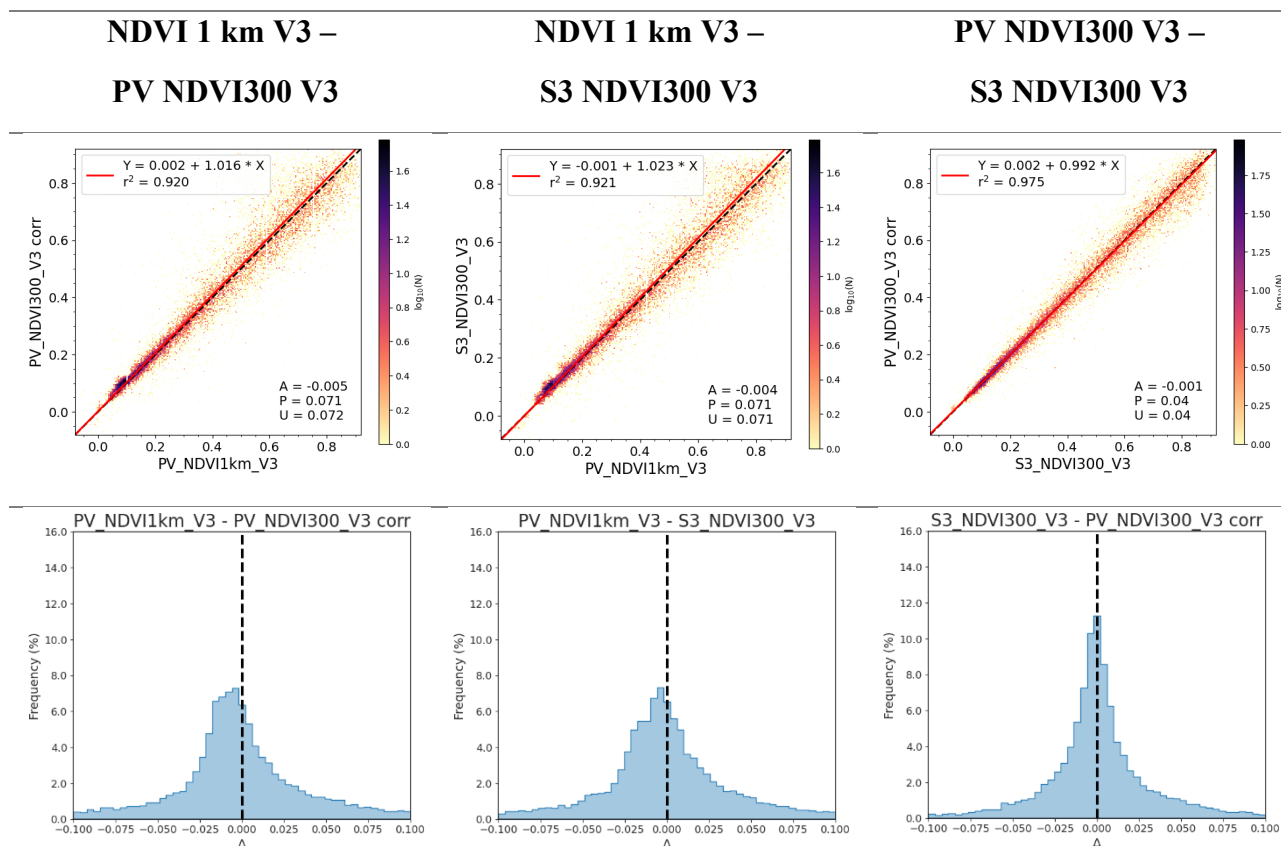


Figure 18: Scatterplots and bias histograms between all combinations of the PROBA-V and OLCI based NDVI V3 and NDVI 1km V3 after applying the correction on PROBA-V based NDVI300 V3.

5.4.2.5 Intermediate conclusions

The S3 bands Oa07 and Oa08 are selected for the red reflectance and Oa16 and Oa18 for NIR. This band combination results in the best agreement with the PROBA-V NDVI. A systematic bias is observed, and a correction of 4% applied on PROBA-V NDVI is suggested.

5.4.3 Evaluation of the correction factor on the final NDVI V3 product

The final Sentinel-3 OLCI NDVI V3 is derived from the Sentinel-3 OLCI TOC reflectance V2.3 [CGLOPS1_PUM_S3-TOC-Reflectance300m-V2.3] based on the reprocessed archive of Sentinel-3 OLCI acquisitions, which was not available at the time of the optimal band combination evaluation. As the proposed 4% correction was not based on the final NDVI V3 dataset, this was evaluated anew when it was available. A systematic subsample of a full year (2019) of overlapping PROBA-V and Sentinel-3 OLCI based NDVI 300m V3 was compared.

Figure 19 shows the scatterplots (top) and bias histograms (bottom) calculated between the NDVI V3

derived from Sentinel-3 and PROBA-V. The left plots show the results of the uncorrected dataset, and the middle plots after application of the 4% correction, as suggested in section 5.4.2. The results indicate a slightly larger difference between the two datasets after the reprocessing of the OLCI archive. A correction of 4.5% results in a more symmetrical bias histogram, and a closer agreement in the scatterplot (slope closer to 1 and mean bias (A) = 0).

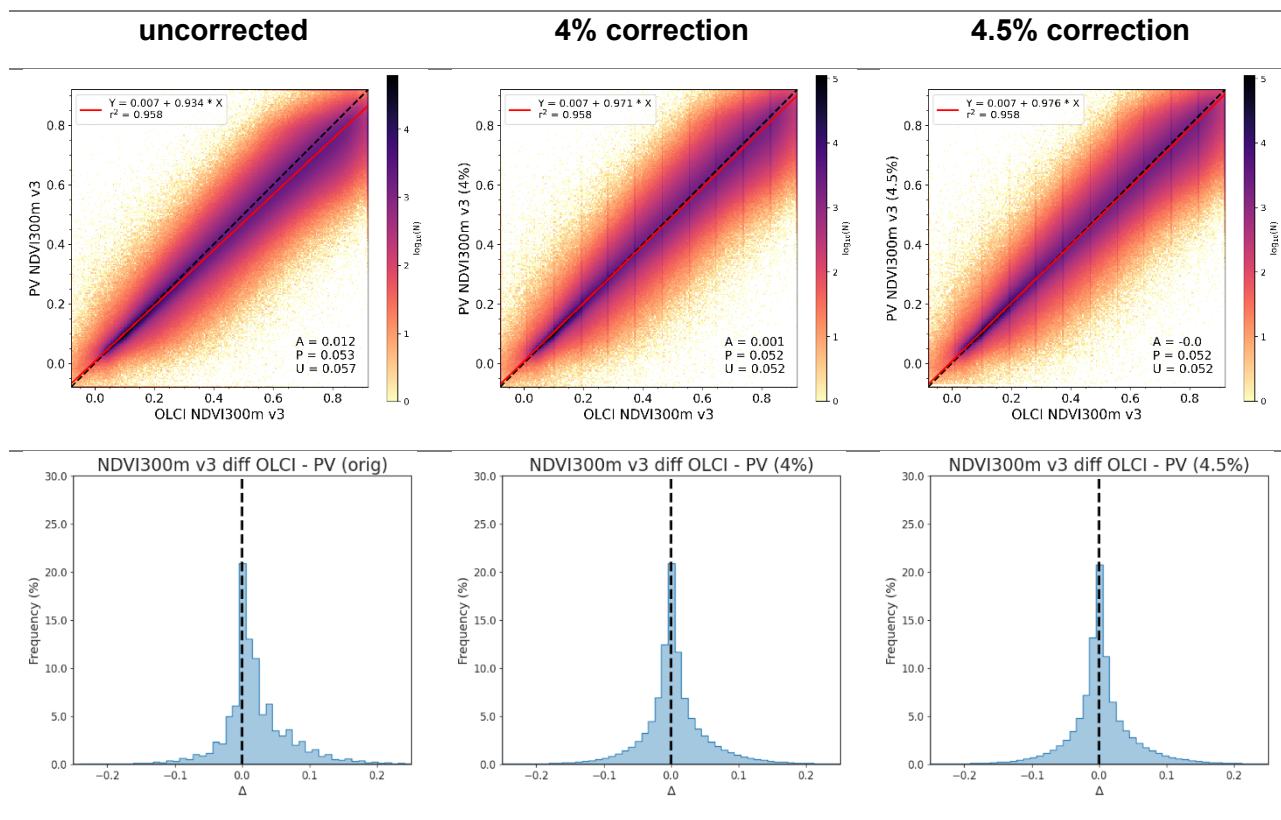


Figure 19: Scatterplots (top) and bias histograms (bottom) between PROBA-V-based NDVI300 V3 before correction (left), after 4% correction (middle), and after 4.5% correction (right).

The spatial analysis of accuracy, uncertainty, and precision provides a comprehensive understanding of the effects of the different corrections applied to the NDVI300 V3 dataset. Figure 20 shows the spatial plots of accuracy (top), uncertainty (middle), and precision (bottom) for the dataset before correction (left), after a 4% correction (middle), and after a 4.5% correction (right). The 4.5% correction demonstrates a better balance in positive and negative biases in Figure 20. These results are in line with the more symmetrical bias histogram shown in Figure 19. This correction brings the slope of the scatterplot closer to 1, indicating an improved agreement between the NDVI values derived from Sentinel-3 and PROBA-V. The spatial analysis of accuracy, uncertainty, and precision reveals that there is no significant impact on precision and uncertainty.

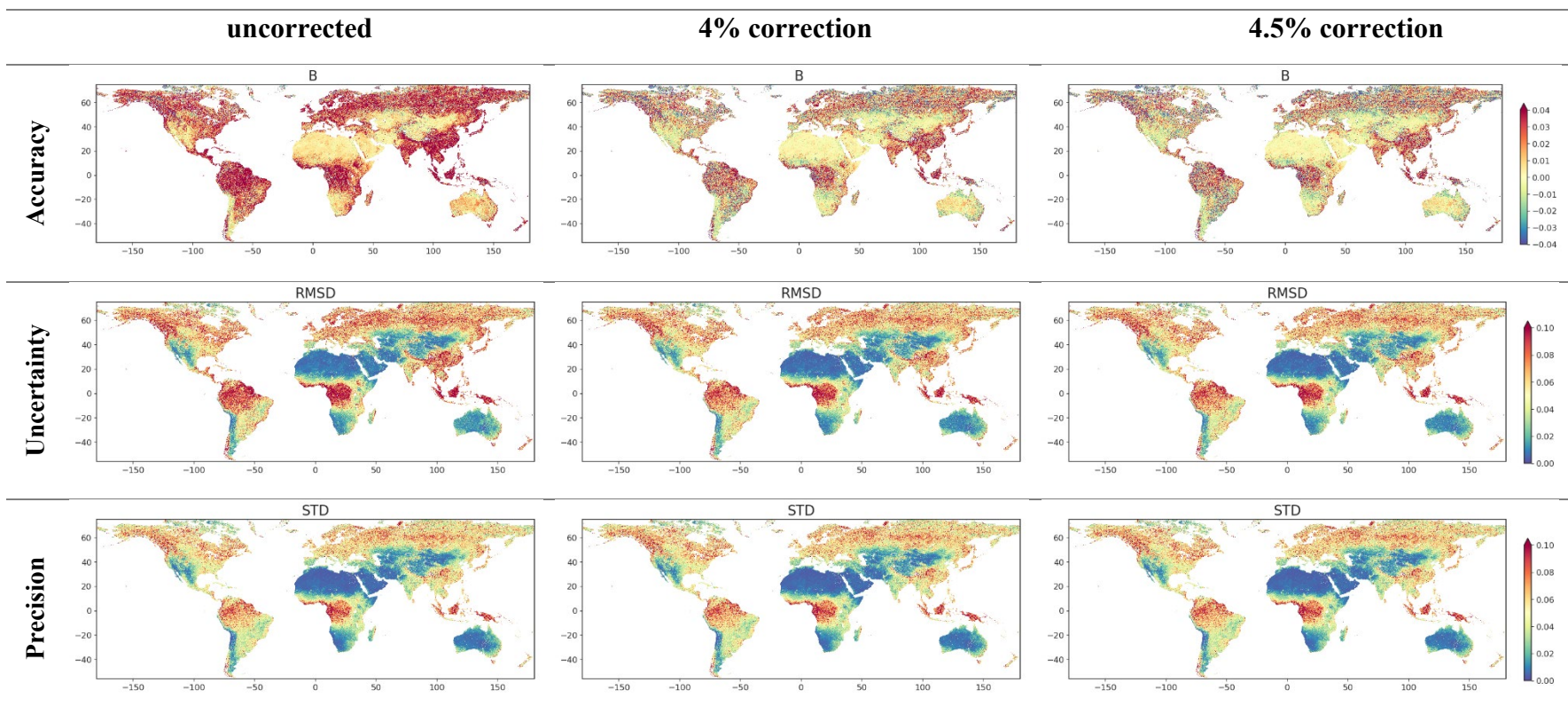


Figure 20: Spatial plots of Accuracy (top), Uncertainty (middle) and Precision (bottom) between PROBA-V-based NDVI300 V3 and S3 OLCI NDVI300 V3 before correction (left), after 4% correction (middle), and after 4.5% correction (right).

The slight increase of the empirical correction from 4% to 4.5% does not affect the consistency with the NDVI 1km V3 dataset, because the correction is applied on the PROBA-V dataset. The results on the consistency between the NDVI 1km V3 and the NDVI300m V3 based on Sentinel-3 shown in Figure 18 remains valid.

5.5 CONCLUSIONS

The NDVI300 V3 time series is made of two components: products based on PROBA-V and products based on S3 OLCI. In order to have the most consistent dataset over the full period (2014 to the present), an analysis was done to define the optimal band combination of S3 OLCI bands. Use was made of the real satellite data, but also simulated data to better capture the impact of the differences in SRFs of the spectral bands.

The S3 OLCI bands Oa7, Oa8 for red and Oa16, Oa18 for NIR showed the best results in the agreement with the PROBA-V based NDVI300 V3. A remaining bias was observed for which is corrected empirically. The 4.5% correction is applied to the PROBA-V based NDVI300 V3, such that the OLCI-based NDVI serves as the reference. It was checked that the correction does not decrease the consistency between the NDVI 300 m products and the PROBA-V NDVI 1km V3.