

# **Copernicus Global Land Operations**

## **“Vegetation and Energy”**

**”CGLOPS-1”**

**Framework Service Contract N° 948120 – IPR - 2023**

### **ALGORITHM THEORETICAL BASIS DOCUMENT**

**BRDF MODEL RETRIEVAL FROM SENTINEL-3 AND PROBA-V**

**VERSION 1.6**

**Issue I1.30**

Organization name of lead contractor for this deliverable: VITO

Book Captain: Jonathan León-Tavares

Contributing Authors: Dominique De Munck

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

## Document Release Sheet

Book captain:	Jonathan León Tavares	Sign	Date 25.09.2025
Approval:		Sign	Date
Endorsement:	Nadine Gobron	Sign	Date
Distribution:	Public		

## Change Record

Date	Page(s)	Description of Change	Release
19.06.2020	All	First issue	I1.00
25.03.2022	14-16 38-39 43, 47, 51	Update after external review	I1.10
22.09.2023	All	Update to reflect v1.6 of the algorithm.	I1.20
25.09.2025	All	Add clarifications about TOC uncertainties and solar zenith angles	I1.30

## TABLE OF CONTENTS

<b>Executive Summary</b> .....	<b>13</b>
<b>1 Background of the document</b> .....	<b>14</b>
<b>1.1 Scope and Objectives</b> .....	<b>14</b>
<b>1.2 Content of the document</b> .....	<b>14</b>
<b>1.3 Related documents</b> .....	<b>14</b>
1.3.1 Applicable documents .....	14
1.3.2 Input.....	14
1.3.3 Output.....	15
1.3.4 External documents .....	15
<b>2 Input data</b> .....	<b>16</b>
<b>2.1 Sentinel-3 data</b> .....	<b>16</b>
<b>2.2 PROBA-V Collection 2 data</b> .....	<b>16</b>
<b>2.3 Auxiliary data</b> .....	<b>16</b>
<b>3 Methodology description</b> .....	<b>20</b>
<b>3.1 History of the algorithm</b> .....	<b>20</b>
<b>3.2 BRDF descriptors retrieval</b> .....	<b>21</b>
3.2.1 Assemblage (A) .....	22
3.2.2 BRDF model (B1).....	25
3.2.3 Inversion (B2).....	26
3.2.4 Quality control (B3).....	33
<b>3.3 BRDF adjusted reflectance (TOCR)</b> .....	<b>36</b>
3.3.1 BRDF adjustment (C1).....	38
3.3.2 Quality control (C2).....	39
<b>3.4 Evaluation of the algorithm performance</b> .....	<b>41</b>
<b>3.5 Difference with previous version v1.3</b> .....	<b>52</b>
<b>3.6 Limitations</b> .....	<b>55</b>
<b>3.7 Risk of failure and mitigation measures</b> .....	<b>56</b>
<b>4 Copernicus BRDF data (CBD) products</b> .....	<b>57</b>
<b>5 References</b> .....	<b>59</b>

## List of Figures

Figure 1: Flow diagram of the BRDF retrieval algorithm correction algorithm. See inner caption for a brief explanation of each stage. It should be noticed that the processing is applied independently to each pixel and spectral band. .... 22

Figure 2: Cross validation function for a pixel near Snargate (see site coordinates at top of Figure 3). The fit provided by a linear interpolation is plotted with dashed line. The cross validation function shown is the logarithm of scaled absolute difference (Sentinel-3 Oa17 ReBeLS predicted - Band2 MODIS MOD09GA) reflectances as a function of the regularisation parameter. .... 31

Figure 3: Top panel: Observed MOD09GA Band2 and ReBeLS Oa17 predicted reflectances for a pixel near Snargate, England. These time series are colour and symbol coded as shown in the legend. Bottom panel: Difference between observed MOD09GA Band2 and ReBeLS Oa17 predicted reflectances. The mean difference is shown with dashed line. Most of differences are within  $\pm 1\sigma$  (yellow band), where  $\sigma$  is the standard deviation..... 32

Figure 4: Continuation of diagram flow shown in Figure 1. Stage TOCR allows to compute BRDF adjusted reflectances (TOCR) based on BRDF descriptors retrieved in stage B3 and solar zenith angle at 12:00 pm local time. .... 36

Figure 5: Diagram flow for the computation of TOCR. Structured layers aim to represent an example where a 3x3 pixel window is processed. The BRDF retrievals (and their variances) are represented as data cubes because there are 3 BRDF descriptors retrieved: kiso, kvol, kgeo with variances  $\sigma_{2kiso}$ ,  $\sigma_{2kvol}$ ,  $\sigma_{2kgeo}$  respectively. The Ross\_thick and Li\_sparse\_reciprocal BRDF kernels for the Sun-viewing common configuration are shown as avol and ageo, respectively. The uncertainty associated to the TOCR estimates is denoted as  $\sigma_{TOCR}$  while QUIL+ is the input QUIL layer with an added bit to identify pixels for which TOCR values are out of a physically believable range (i.e. [0,1]). .... 37

Figure 6: Temporal evolution of retrieved BRDF descriptors (top panel) and BRDF adjusted reflectance (bottom panel) for a pixel near Valencia (this site is also known as Albufera and is a cultivated area), Spain – see geographical coordinates at the top of the figure. The temporal trajectories of both BRDF descriptors and adjusted reflectances are obtained for OLCI spectral band Oa08 (RED spectral range). The bottom panel shows as a reference the MODIS band1 (RED) MCD43A4 (Nadir BRDF adjusted reflectances -- NBAR) time series for the same site. The type of BRDF descriptors retrieved is colour coded as shown in the legend of top panel. The time series of BRDF adjusted reflectances are colour and symbol coded as shown in the legend of the bottom panel. The quality information layer (QUIL – for details see section 3.2.4) for the BRDF retrievals is overlaid on the top panel where corresponding QUIL values can be found in the left y-axis. The latter also applies for the bottom panel, albeit for the TOCR QUIL (see section 3.3.2 for details). The error bars shown in both panels correspond to the uncertainties estimated as described in section 3.2.3 and 3.3.1..... 42

Figure 7: Same as in Figure 6 but for Sentinel-3 OLCI Oa17 spectral band (NIR). The bottom panel shows as a reference the MODIS band2 (NIR) MCD43A4 NBAR time series for the same location..... 43

Figure 8: Same layout as Figure 7 but for a PROBA-V 333m pixel near Starbroek, Belgium – see geographical coordinates at the top of the figure. .... 44

Figure 9: Same layout as in Figure 6 but for a Sentinel-3 pixel near Snargate, England – see geographical coordinates at the top of the figure. .... 45

Figure 10 Temporal evolution of OLCI Oa08 TOC reflectance observed and BRDF adjusted for a pixel near Snargate (England – see Figure 9). The type of reflectance datasets is colour and symbol coded as shown in the legend. .... 46

Figure 11: Same layout as in Figure 6 but for a pixel near Sodankyla, Finland – see geographical coordinates at the top of the figure. .... 47

Figure 12: Layout is the same as in Figure 6 but for a pixel near Gandia, Spain (see geographical coordinates at the top of the figure). On 8<sup>th</sup> of August 2018 a massive burning of vegetation was reported in a region surrounding this pixel. A sharp drop in Oa17 BRDF adjusted reflectance around this date is evident. . 48

Figure 13. Same as Figure 12 but for a PROBA-V pixel. .... 49

Figure 14: RGB image of the Oa17 BRDF descriptors retrieved for 3<sup>rd</sup> June 2019. The colour channels are as follows: R: kiso , G: kvol, B: kgeo. .... 50

Figure 15: Temporal evolution of Oa17 BRDF adjusted reflectance (TOCR) for tile X17Y03. The BRDF adjusted reflectance time series at tile scale follows the expected phenological cycle for this geographical region. .... 51

Figure 16. Same layout as Figure 15 but for PROBA-V data on tile X19Y03. .... 52

Figure 17. BRDF-adjusted surface reflectance temporal evolution for a pixel near station Landval 133. Bottom and top panels show the BRDF-adjusted reflectance obtained from ReBeLS v01.3 and v1.6, respectively. Datasets are colour coded, as shown in the legend. .... 54

Figure 18. Same layout as Figure 17 but for Landval 631 station. .... 55

Figure 1: Flow diagram of the BRDF retrieval algorithm correction algorithm. See inner caption for a brief explanation of each stage. It should be noticed that the processing is applied independently to each pixel and spectral band. .... 22

Figure 2: Cross validation function for a pixel near Snargate (see site coordinates at top of Figure 3). The fit provided by a linear interpolation is plotted with dashed line. The cross validation function shown is the logarithm of scaled absolute difference (Sentinel-3 Oa17 ReBeLS predicted - Band2 MODIS MOD09GA) reflectances as a function of the regularisation parameter. .... 31

Figure 3: Top panel: Observed MOD09GA Band2 and ReBeLS Oa17 predicted reflectances for a pixel near Snargate, England. These time series are colour and symbol coded as shown in the legend. Bottom panel: Difference between observed MOD09GA Band2 and ReBeLS Oa17 predicted reflectances. The mean difference is shown with dashed line. Most of differences are within  $\pm 1\sigma$  (yellow band), where  $\sigma$  is the standard deviation. .... 32

Figure 4: Continuation of diagram flow shown in Figure 1. Stage TOCR allows to compute BRDF adjusted reflectances (TOCR) based on BRDF descriptors retrieved in stage B3 and solar zenith angle at 12:00 am local time. .... 36

Figure 5: Diagram flow for the computation of TOCR. Structured layers aim to represent an example where a 3x3 pixel window is processed. The BRDF retrievals (and their variances) are represented as data cubes because there are 3 BRDF descriptors retrieved: kiso, kvol, kgeo with variances  $\sigma_{2kiso}$ ,  $\sigma_{2kvol}$ ,  $\sigma_{2kgeo}$  respectively. The Ross\_thick and Li\_sparse\_reciprocal BRDF kernels for the Sun-viewing common configuration are shown as avol and ageo, respectively. The uncertainty associated to the TOCR estimates is denoted as  $\sigma_{TOCR}$  while QUIL+ is the input QUIL layer with an added bit to identify pixels for which TOCR values are out of a physically believable range (i.e. [0,1]). ..... 37

Figure 6: Temporal evolution of retrieved BRDF descriptors (top panel) and BRDF adjusted reflectance (bottom panel) for a pixel near Valencia (this site is also known as Albufera and is a cultivated area), Spain – see geographical coordinates at the top of the figure. The temporal trajectories of both BRDF descriptors and adjusted reflectances are obtained for OLCI spectral band Oa08 (RED spectral range). The bottom panel shows as a reference the MODIS band1 (RED) MCD43A4 (Nadir BRDF adjusted reflectances -- NBAR) time series for the same site. The type of BRDF descriptors retrieved is colour coded as shown in the legend of top panel. The time series of BRDF adjusted reflectances are colour and symbol coded as shown in the legend of the bottom panel. The quality information layer (QUIL – for details see section 3.2.4) for the BRDF retrievals is overlaid on the top panel where corresponding QUIL values can be found in the left y-axis. The latter also applies for the bottom panel, albeit for the TOCR QUIL (see section 3.3.2 for details). The error bars shown in both panels correspond to the uncertainties estimated as described in section 3.2.3 and 3.3.1. .... 42

Figure 7: Same as in Figure 6 but for Sentinel-3 OLCI Oa17 spectral band ( NIR). The bottom panel shows as a reference the MODIS band2 (NIR) MCD43A4 NBAR time series for the same location. .... 43

Figure 8: Same layout as Figure 7 but for a PROBA-V 333m pixel near Starbroek, Belgium – see geographical coordinates at the top of the figure. .... 44

Figure 9: Same layout as in Figure 6 but for a Sentinel-3 pixel near Snargate, England – see geographical coordinates at the top of the figure. .... 45

Figure 10 Temporal evolution of OLCI Oa08 TOC reflectance observed and BRDF adjusted for a pixel near Snargate (England – see Figure 9). The type of reflectance datasets is colour and symbol coded as shown in the legend. .... 46

Figure 11: Same layout as in Figure 6 but for a pixel near Sodankyla, Finland – see geographical coordinates at the top of the figure. .... 47

Figure 12: Layout is the same as in Figure 6 but for a pixel near Gandia, Spain (see geographical coordinates at the top of the figure). On 8<sup>th</sup> of August 2018 a massive burning of vegetation was reported in a region surrounding this pixel. A sharp drop in Oa17 BRDF adjusted reflectance around this date is evident. . 48

Figure 13. Same as Figure 12 but for a PROBA-V pixel. .... 49

Figure 14: RGB image of the Oa17 BRDF descriptors retrieved for 3<sup>rd</sup> June 2019. The colour channels are as follows: R: kiso , G: kvol, B: kgeo. .... 50

Figure 15: Temporal evolution of Oa17 BRDF adjusted reflectance (TOCR) for tile X17Y03. The BRDF adjusted reflectance time series at tile scale follows the expected phenological cycle for this geographical region..... 51

Figure 16. Same layout as Figure 15 but for PROBA-V data on tile X19Y03. .... 52

Figure 17. BRDF-adjusted surface reflectance temporal evolution for a pixel near station Landval 133. Bottom and top panels show the BRDF-adjusted reflectance obtained from ReBeLS v01.3 and v1.6, respectively. Datasets are colour coded, as shown in the legend..... 54

Figure 18. Same layout as Figure 17 but for Landval 631 station..... 55

## List of Tables

Table 1: Layers of MCD43P files. The mean and variances ( $\sigma^2$ ) are computed from a MCD43A1 and MCD43A2 MODIS climatology assembled for a period between 01Jan2013 and 31Dec2019. ....	18
Table 2: Characteristics of the MCD43P files.....	18
Table 3. Goodness of fit status .....	34
Table 4. QUIL (quality information layer) encoding. The dekad time window is defined as [t0, t0+10days] where t0 is the date of the dekad provided. ....	34
Table 5: Layers provided as output of the ReBeLS BRDF processor.....	35
Table 6: QUIL for TOCR.....	40
Table 7: Layers provided as output of the ReBeLS TOCR processor.....	41
Table 8: Information on the ReBeLS BRDF (CBD_K) product files. ....	57
Table 9. Information on the ReBeLS TOCR (CBD_TOCR) product files .....	58

### List of Acronyms

AC	Atmospheric Correction
AD	Applicable Document
AM	Ante Meridian
ATBD	Algorithm Theoretical Basis Document
BRDF	Bidirectional Reflectance Distribution Function
CBD	Copernicus BRDF Data
CBD_K	BRDF descriptors product
CBD_TOCR	BRDF adjusted reflectances
CGLOPS	Copernicus Global Land Operations
CLMS	Copernicus Land Monitoring Service
ESA	European Space Agency
GEOTIFF	Geospatial Tagged Image File Format
MCD43A1	MODIS Terra+Aqua BRDF/Albedo Model Parameters Daily Product
MCD43A2	MODIS Terra+Aqua BRDF/Albedo Quality Daily Product
MCD43A4	MODIS Terra+Aqua Nadir BRDF-Adjusted Reflectance Daily Product
MCD43P	ReBeLS assembled prior based on MCD43A1 and MCD43A2
MOD09GA	MODIS/Terra Surface Reflectance Daily Product
MODIS	Moderate Resolution Imaging Spectroradiometer
NBAR	Nadir BRDF Adjusted Reflectance
NDVI	Normalized Difference Vegetation Index
NETCDF	Network Common Data Format
NRT	Near Real Time
OLCI	Ocean and Land Colour Instrument
PUM	Product User Manual
QAR	Quality Assessment Report
QUIL	Quality Index Layer

---

ReBeLS	Regularised BRDF inversion for Land Surface
RGB	Red Green Blue
S3	Sentinel-3
SAA	Sun Azimuth Angle
SLSTR	Sea and Land Surface Temperature Radiometer
SZA	Sun Zenith Angle.
TOA	Top Of Atmosphere
TOC	Top Of Canopy
TOCR	BRDF adjusted TOC reflectance
VAA	Viewing Azimuth Angle
VZA	Viewing Zenith Angle.
VITO	Vlaamse Instelling Voor Technologisch Onderzoek
WGS	World Geodetic System

## 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.

Since land surface reflectance is not isotropic, differences in observing and illumination conditions yield an impact on the measured land surface reflectance values from space observations. The consequence of this is the presence of spurious deviations in atmospherically corrected surface reflectance time series which may hamper significantly a further analysis. Modelling the anisotropy of the land surface reflectance is needed to remove the above mentioned directional effects from Top-Of-Canopy (TOC) reflectance data. The anisotropy of the land surface is described by its Bidirectional Reflectance Distribution Function (BRDF). The usage of semi empirical kernel-driven models to approximate the BRDF of land surface targets is a widely accepted approach.

This Algorithm Theoretical Basis Document (ATBD) describes the second release (v1.6) of the Copernicus Land Monitoring Service algorithm to obtain BRDF model retrievals from Sentinel-3 and PROBA-V land surface TOC reflectances. The methodology to use the outputs of this algorithm to estimate BRDF adjusted (to a common Sun-sensor configuration) reflectances is also described in this document.

## 1 BACKGROUND OF THE DOCUMENT

### 1.1 SCOPE AND OBJECTIVES

This document provides a description of the algorithm implemented to retrieve BRDF descriptors from Sentinel-3/OLCI and PROBA-V Collection 2 (C2) observations. The retrieved BRDF descriptors allow computing BRDF adjusted TOC reflectances. The later methodology is also described in this ATBD.

Note: In the CLMS context, these algorithms were designed and fine-tuned for the visible and NIR spectral bands of OLCI and PROBA-V, which are used for the calculation of the NDVI and Land Surface Phenology (LSP) products. The design and fine-tuning for other OLCI spectral bands as well as the spectral bands of the Sea and Land Surface Temperature Radiometer (SLSTR) was performed in the context of the Copernicus Climate Change Service in order to calculate the albedo.

### 1.2 CONTENT OF THE DOCUMENT

This document is structured as follows:

- A brief description of the input data is given in Chapter 2.
- Chapter 3 describes the retrieval methodology.
- Details on the output products are listed in Chapter 4

### 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, 19<sup>th</sup> 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 data
CGLOPS1_QAR_S3-CloudMask	Quality Assessment Report of Sentinel-3 OLCI and SLSTR cloud, cloud shadow and snow detection

Available on <https://land.copernicus.eu/en/technical-library>

### 1.3.3 Output

Document ID	Descriptor
CGLOPS1_ATBD_NDVI300m-V3	Algorithm Theoretical Basis Document of the NDVI 300mVersion3.
CGLOPS1_PUM_NDVI300m-V3	Product User Manual of the NDVI 300m Version 3
CGLOPS1_QAR_NDVI300m-V3	Quality Assessment Report of the NDVI 300mVersion 3

Available on <https://land.copernicus.eu/en/technical-library>

### 1.3.4 External documents

PROBAV\_PUM\_C2                      PROBA-V Collection 2 Products User Manual v1.0, 27 March 2023

Available                      at                      [https://proba-v.vgt.vito.be/sites/probavvgt/files/downloads/PROBA-V\\_C2\\_Products\\_User\\_Manual.pdf](https://proba-v.vgt.vito.be/sites/probavvgt/files/downloads/PROBA-V_C2_Products_User_Manual.pdf)

ATBD GlobAlbedo                      GlobAlbedo Algorithm Theoretical Basis Document, version 4.12, 7<sup>th</sup> July 2013

[http://www.globalbedo.org/docs/GlobAlbedo\\_Albedo\\_ATBD\\_V4.12.pdf](http://www.globalbedo.org/docs/GlobAlbedo_Albedo_ATBD_V4.12.pdf) (accessed 16.10.2023)

## 2 INPUT DATA

The CLMS BRDF retrieval algorithm, known as ReBeLS, was initially designed to retrieve BRDF descriptors from atmospherically corrected Sentinel-3 surface reflectance datastreams (Léon-Tavares et al., 2024). However, the updated version of the algorithm now enables processing of atmospherically corrected data from the PROBA-V mission as well. As shown in the following sections, the ReBeLS algorithm can ingest datastreams from two wide imaging sensors (i.e. Sentinel-3 and PROBA-V). Therefore, hereafter we describe the methodology of the ReBeLS algorithm in a sensor agnostic fashion, by simply referring to datastreams from a wide imaging-swath sensor (**WIS**).

General details about the WIS datastreams that ReBeLS v1.6 can process are shown in the following subsections.

### 2.1 SENTINEL-3 DATA

Atmospherically corrected visible and NIR reflectances derived from OLCI measurements on-board of Sentinel-3A and Sentinel-3B satellites are the input for the BRDF descriptors retrieval methodology described in Chapter 3.

Full details on how the OLCI measurements are processed into Top of Canopy (TOC) reflectances can be found in the ATBD of Atmospheric Corrections [CGLOPS1\_ATBD\_S3-AC-V1.1].

### 2.2 PROBA-V COLLECTION 2 DATA

The most recent reprocessing of the datasets provided by the PROBA-V mission is used to retrieve BRDF descriptors. Full details on the atmospherically corrected surface reflectance data of PROBA-V collection 2 (C2) can be found in PROBAV\_PUM\_C2. ReBeLS ingests PROBA-V 333m data and hereafter we refer to the later as PROBA-V datasets.

### 2.3 AUXILIARY DATA

The approximation of the BRDF for land surface is achieved by numerical inversion of kernel-driven semi-empirical models (for a review, see Roujean et al., 2018b). BRDF inversion methods are known for being ill-posed problems, meaning that the least-square inversion solution can turn out to be unstable and physically unacceptable (e.g. BRDF retrieved descriptors [parameters] yielding to negative or out of range BRDF adjusted reflectances).

Thus, to constraint the results of the BRDF descriptors retrievals in a realistic fashion, the present algorithm uses a climatology of BRDF descriptors ( $k_{iso}$  - Isotropic kernel weight;  $k_{vol}$  – Volumetric

kernel weight;  $k_{geo}$  – Geometric kernel weight) built from MODIS MCD43A1<sup>1</sup> and MCD43A2<sup>2</sup> products version V006 (Schaaf et al., 2011, 2002; Wang et al., 2018). The assembled climatology is referred through this document as **prior** or **MCD43P** (see Figure 1). In the current version of the algorithm, the MCD43P dataset associated to a WIS tile is assembled as follows:

- For each Monday of the period between 01Jan2013 and 31Dec2019<sup>3</sup>, all MCD43A1 and MCD43A2 MODIS tiles that spatially intersect the corresponding WIS TOC tile are downloaded from <https://e4ftl01.cr.usgs.gov/MOTA/>.
- Conversion of MCD43A1 and MCD43A2 tiles from MODIS (sinusoidal) to the WISTOC grid projection (the two WIS datastreams that ReBeLS can process are in Plate-Carree projection) and extent (10 degrees by 10 degrees in both MODIS and WISTiles). It is worth noticing that some inherent alteration might have been introduced by reprojecting and resampling MODIS MCD43A1 and MCD43A2 products from 500m to 333m spatial resolution. However, by visual inspection of the MCD43P dataset, no systematic artefacts likely introduced by reconciling the spatial mismatch between datasets were found.
- Good quality BRDF descriptors screening by decoding BRDF\_AlbedoLandWaterType and BRDF\_Albedo\_Band\_Quality (for all bands) layers in MCD43A2 product.
- Computation of mean and variance for the whole dataset as in GlobAlbedo<sup>4</sup> (Lewis et al., 2012; Muller et al., 2011). See subsection 32.4 in section D of GlobAlbedo ATBD [ATBD GlobAlbedo]
- The MCD43P climatology (weekly cadence) is gap filled by means of a linear interpolation. It should be noticed that this last step is applied to all tiles, albeit impacting mostly to tiles located at high latitudes.

A MCD43P file associated to a WIS tile contains the layers listed in Table 1. MCD43P tiles are generated for each week of a climatology year and are saved in GEOTIFF format (Table 2).

---

<sup>1</sup> <https://lpdaac.usgs.gov/products/mcd43a1v006/>

<sup>2</sup> <https://lpdaac.usgs.gov/products/mcd43a2v006/>

<sup>3</sup> The beginning of this period coincides with the year when PROBA-V 300m TOC time series became available. The last date in the period was chosen to have full years to assemble the prior.

<sup>4</sup> <http://www.globalbedo.org/>

**Table 1: Layers of MCD43P files. The mean and variances ( $\sigma^2$ ) are computed from a MCD43A1 and MCD43A2 MODIS climatology assembled for a period between 01Jan2013 and 31Dec2019.**

Number of layer	MCD43P layer
1	Mean $k_{iso}$
2	Mean $k_{vol}$
3	Mean $k_{geo}$
4	$\sigma_{k_{iso}}^2$
5	$\sigma_{k_{vol}}^2$
6	$\sigma_{k_{geo}}^2$

**Table 2: Characteristics of the MCD43P files**

<b>Number of layers</b>	6
<b>Data format</b>	GEOTIFF
<b>Cadence</b>	Weekly (each Monday)
<b>Projection and Grid information</b>	Coordinate System is: GEOGCS["WGS 84", DATUM["WGS_1984", SPHEROID["WGS 84",6378137,298.257223563, AUTHORITY["EPSG","7030"]], AUTHORITY["EPSG","6326"]], PRIMEM["Greenwich",0], UNIT["degree",0.0174532925199433], AUTHORITY["EPSG","4326"]]

Even though the MCD43A1(2) products are generated and distributed daily, the MCD43P dataset has a weekly cadence. The latter responds to the fact that downloading and storing all daily MCD43A1 and MCD43A2 products generated over six years would quickly amount to

significantly large storage capacity unavailable when developing the ReBeLS processor. Therefore, a weekly cadence (Mondays) for the MCD43P dataset arose as a tradeoff between the daily temporal resolution (offered by the MCD43 V006 suite of products) and the dekadal and five-day frequencies at which the NDVI and LSP products are envisaged, respectively.

Moreover, the discerning reader might ask: why select Mondays and not another day of the week? The adoption of Mondays merely follows the approach used in the operational BOKU NDVI product – based on MODIS (Klisch and Atzberger, 2016), providing Monday images in near real-time with a seven-day update interval. Thus, the assumption that the temporal variability of the BRDF kernel weights can be adequately sampled each Monday for NDVI purpose studies finds support in the methodology implemented by the BOKU's MODIS processing chain (Klisch and Atzberger, 2016), delivering an NDVI product that can be considered robust, and used for operational vegetation assessment purposes (Meroni et al., 2019).

In addition, it should be noted that during the assemblage of the MCD43 dataset, a spectral band adjustment between MODIS and the WIS datastreams has not been attempted. The uncertainties in the ReBeLS BRDF retrievals introduced by using the MODIS MCD43 product as an auxiliary dataset are largely dominated by the uncertainties associated with the MCD43P prior kernel weights. Thus, given that the uncertainties due to WIS and MODIS spectral bands mismatch are significantly smaller than those associated with the MCD43P product, the inclusion of a spectral harmonization shall not significantly impact the current BRDF retrievals or their uncertainties. The characterization of spectral differences can be informative, in any case, and potential evolutions of the BRDF-adjusted surface reflectance product based on Sentinel-3 OLCI should consider such harmonization between MODIS and Sentinel-3 OLCI spectral bands.

Finally, although the MCD43A2 product contains information about the snow pixel classification, for this version of the MCD43P dataset, we have not considered it. The latter is motivated by the assumption that computing the mean and variance of a dataset comprising snow and snow-free pixels shall reflect the large variability of kernel weights. Thus, a large variance can significantly relax the prior constraints imposed in the inversion, allowing the BRDF parameters' temporal evolution to vary accordingly. Unfortunately, such an assumption has not been verified in the current version of the ReBeLS processor because of the severe limitations of the cloud mask identification inherent to the OLCI TOC input data [CGLOPS1\_QAR\_S3-CloudMask]. Even for geographical regions characterized by a persistent presence of snow, these snow pixels are confused with clouds, rejecting them from any further treatment. An updated version of the Sentinel-3 OLCI TOC reflectances shall allow us to test the assumption mentioned above, and if it does not hold, the generation of an MCD43P dataset for snow and snow-free pixels should be performed instead.

### 3 METHODOLOGY DESCRIPTION

Since observed land surface reflectance is highly anisotropic, spurious deviations and large scatter in TOC reflectance time series are usually associated to directional effects.

Therefore, TOC surface reflectances obtained after correction of atmospheric effects, should be “adjusted” to a common illumination and observing geometry before interpretation or to assess their temporal evolution.

In the following sections, we describe the methodology to retrieve land surface reflectance BRDF descriptors which shall be used to adjust (usually called “BRDF correction”) WIS TOC reflectances to a common viewing (nadir) and illumination (local noon, 12pm) configuration.

Before delving into the details of the algorithm, in section 3.2, we briefly review the history of the processor development to provide the reader a sense of how ReBeLS has evolved to assess the limitations found in its original version, v1.3.

#### 3.1 HISTORY OF THE ALGORITHM

ReBeLS v1.3 has been used to generate the CLMS Sentinel-3 NDVI 300m Version 2 product. Due to its versatility, the ReBeLS algorithm was selected as the processor to facilitate the retrieval of multi-spectral Sentinel-3 BRDF descriptors, which enabled the computation of the Copernicus Climate Change Service surface albedo product<sup>5</sup> (Sanchez-Zapero et al., 2023). One of the main limitations of the latter product pertained to the faulty snow mask identification (i.e., erroneous identification of snow pixels as clouds) in the Sentinel-3 TOC datasets that serve as inputs. To bypass the afore mentioned issue, a decision rule has been designed for identifying snow pixels within the Copernicus Climate Change Service. This rule relied on a Normalised Difference Snow Index (NDSI) threshold and was implemented within ReBeLS v1.4 as a provisional solution to mitigate the underperforming snow-mask identification layer in the S3 TOC datasets.

An updated version of ReBeLS (v1.6) has been further developed to allow output product generation from PROBA-V data streams at any cadence the user selects. This was explicitly useful to support subsidiary CLMS products (i.e. LSP). In addition, the outlier identification procedure was further refined, and a filter to extreme SZA was implemented before computing BRDF-corrected TOC

---

<sup>5</sup> [https://datastore.copernicus-climate.eu/documents/satellite-albedo/C3S\\_COP\\_059\\_D-02\\_ATBD\\_CDR-ICDR\\_SA\\_SENTINEL3\\_v3.0\\_PRODUCTS\\_v1.1.pdf](https://datastore.copernicus-climate.eu/documents/satellite-albedo/C3S_COP_059_D-02_ATBD_CDR-ICDR_SA_SENTINEL3_v3.0_PRODUCTS_v1.1.pdf)

reflectances. Details on the former and later changes can be found in sections 3.2.1.4 and 3.3.2, respectively.

### 3.2 BRDF DESCRIPTORS RETRIEVAL

The land surface reflectance varies with the observation and illumination geometry (defined by the sensor and Sun positions) and wavelength. The BRDF quantifies the reflectance anisotropy and it can be approximated by means of a kernel-driven semi-empirical BRDF linear model with three parameters, commonly known as BRDF parameters or descriptors. After the BRDF descriptors are found via an inversion method (with regularisation for the presented algorithm), the directional signature of the natural targets is obtained.

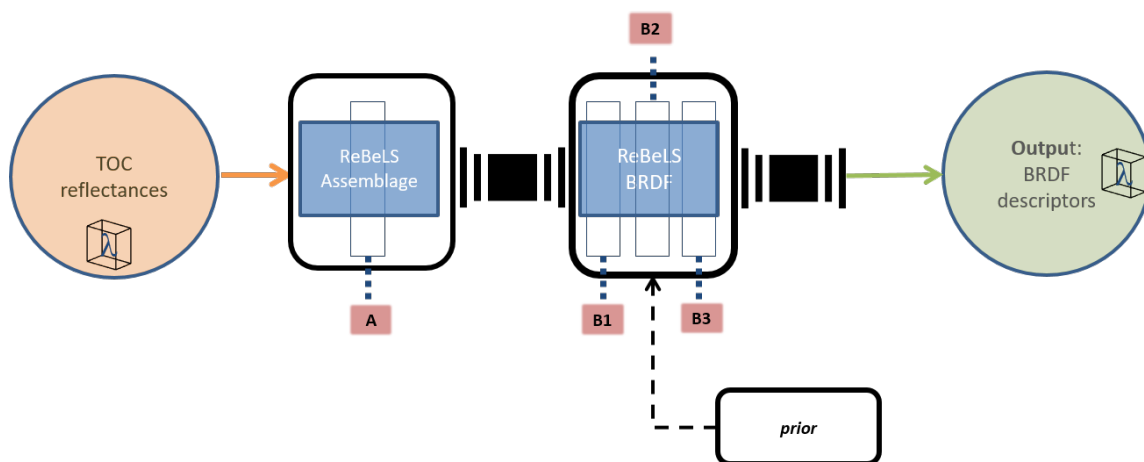
Figure 1 shows a flow diagram of the processing scheme for the retrieval of BRDF descriptors from WIS TOC observations. As shown in Figure 1, the BRDF retrieval algorithm comprises three main stages: A (Assemblage), B1 (BRDF model), B2 (Inversion) and B3 (Quality control). It should be noticed that the algorithm is pixel based and runs for each spectral band independently. In addition, a prior of BRDF descriptors, the MCD43P climatology assembled as described in subsection 2.3, is required to run B2 stage.

Details on the processing blocks (A, B1, B2 and B3) sketched in Figure 1 are presented in the following subsections. The BRDF descriptors retrieval is achieved by using the ReBeLS (Regularised Brdf inversion for Land Surface reflectances) processor written in Python3.6 and developed on a virtual machine of the Mission Exploitation Platform (MEP)<sup>6</sup> / Terrascope<sup>7</sup>.

---

<sup>6</sup> <https://proba-v-mep.esa.int/>

<sup>7</sup> <https://terrascope.be/en>



- **A – Assemblage:** Accumulation of observations over a selected period of time. Using information from quality indicators, only clear observations are retained for further processing.
- **B1 – BRDF model:** Kernels from a semi-empirical BRDF model are computed for each observation
- **B2 – Inversion:** BRDF descriptors that best represent the ensemble of observations are found by solving an inverse problem with the addition of regularisation (prior).
- **B3 – Quality control:** A quality information layer is assembled to reflect availability of observations and whether (or not) the BRDF model inversion was successful.

**Figure 1: Flow diagram of the BRDF retrieval algorithm correction algorithm. See inner caption for a brief explanation of each stage. It should be noticed that the processing is applied independently to each pixel and spectral band.**

### 3.2.1 Assemblage (A)

The orchestration of the assemblage stage follows the steps below:

#### 3.2.1.1 Accumulation

TOC reflectance observations along with their associated uncertainties, corresponding geometry (solar viewing angle, solar azimuth angle, viewing zenith angle and viewing azimuth angle) and quality layers are accumulated over a predefined period of time (e.g.. 30 days and 365 days for near-real time (NRT) and back processing products, respectively).

#### 3.2.1.2 Clear observations screening

The rejection of pixels classified as clouds or shadows are summarised next:

- Sentinel-3:
  - OLCI spectral bands. Following the encoding of the pixel\_classif\_flags [Figure 1 in CGLOPS1\_QAR\_S3-CloudMask], we select pixels classified as land but that

have not been classified as clouds neither as shadow. In addition, decoding of quality\_flags<sup>8</sup> layer allows us to remove bad quality (saturated) pixels.

- SLSTR spectral bands. Based on cloud\_an layer, pixels classified as clouds are rejected.
  - The AC\_process\_flag is a quality layer which aims to provide information on the reliability of the atmospheric correction [CGLOPS1\_ATBD\_S3-AC-V1.1]. However, the AC\_process\_flag is not used because we found it too conservative – by decoding AC\_process\_flag, a significant number of observations will be left out while their values fit the temporal evolution of a one-year TOC time series.
- PROBA-V: To select clear pixels associated with land, we decode the status map of the PROBA-V quality layer, following the the guidelines in Table 13 of the PROBAV\_PUM\_C2.

### 3.2.1.3 *Outlier screening*

After applying the clear observation filter described above, it is likely to find undetected clouds and shadows in the ensemble of clear TOC observations (due to limitations of the Sentinel-3 cloud and cloud shadow detection methods: for details see CGLOPS1\_QAR\_S3-CloudMask). Since these outliers can severely bias the inversion results, an outlier screening is needed. We make use of the BRDF descriptors prior assembled (see section 2.3) to predict reflectances based on the WIS solar and sensor geometry of observations. Clear observations accumulated are compared against predicted reflectances by means of z-score computations.

The absolute value of the z-score indicates how many standard deviations the observed Sentinel-3 TOC reflectance value departs from the predicted TOC reflectance values (based on prior BRDF descriptors). Absolute values of z-score higher than 2 can be considered significant. Thus, initially, all observations with an absolute value of z-score higher than 2 are identified as potential outliers. To make sure that those deviations are not associated to real changes on the surface (e.g. those introduced by fires or snow melt), we analyse the temporal evolution of the z-score trajectories over the accumulation period.

The later allows us to identify persistent deviations which are likely associated to real changes on the surface. Observations identified as systematic deviations (z-score > 2 repeatedly occurring in a predefined observation window) are not further considered as outliers and since are likely to be associated to real changes on the surface, these observations are processed.

---

<sup>8</sup> See <https://sentinel.esa.int/documents/247904/1872756/Sentinel-3-OLCI-Product-Data-Format-Specification-OLCI-Level-1> page 47-50

### 3.2.1.4 Synthetic uncertainty

The estimation of uncertainties associated to S3 TOC reflectances is described in [CGLOPS1\_ATBD\_S3-AC-V1.1]. As stated in the afore-mentioned document, the uncertainty associated to TOA reflectances has been assumed to be 2% of the TOA reflectance value for the SLSTR bands. This can result in an under estimation of the uncertainty associated to TOC reflectances. Consequently, the TOC reflectance uncertainties estimated in this way show a significant dependence with their TOC reflectance values (the lower the TOC reflectance value, the lower its uncertainty associated). The latter can significantly bias the BRDF modelling, especially when a non-detected outlier (e.g. undetected shadow) has a very small uncertainty associated.

This means that the Sentinel-3 TOC reflectance uncertainties have their limitations. Moreover, as the TOC input data streams from PROBA-V are supplied without an explicit estimation of uncertainty, we make the conservative assumption that the uncertainties associated with TOC are 5% of their value. ReBeLS thus introduces an additional concept of synthetic uncertainties.

For both WISs, we derive approximate (synthetic) uncertainties as follows:

1. The 95<sup>th</sup> percentile of the TOC uncertainties related to the atmospheric correction process is calculated and subsequently employed as a criterion to filter out observations with uncertainties exceeding this threshold. This approach implemented in ReBeLS results in the exclusion of observations for which the uncertainties linked to the atmospheric correction procedure indicate their unsuitability for further analysis.
2. An estimate of the mean TOC reflectance uncertainty is obtained ( $\sigma_{oTOC}$ ). The mean is computed over the period used in the accumulation of TOC reflectance.
3. An air mass factor (amf) based on the solar and viewing zenith angle of each observation is computed as:

$$\text{amf} = \frac{1}{\cos(\theta_{SZA})} + \frac{1}{\cos(\theta_{VZA})}$$

Where  $\theta_{SZA}$  and  $\theta_{VZA}$  are the solar and viewing zenith angles, respectively. The air-mass factor is larger for observations acquired at higher viewing and solar zenith angles.

4. The synthetic TOC reflectance uncertainty is thus obtained as:

$$\sigma_{TOC} = \sigma_{oTOC} \times \text{amf}$$

Then, an ensemble of clear TOC reflectance observations along with their uncertainties is the input for the ReBeLS processor which is responsible to assemble and solve an inverse problem (with regularisation) allowing for the retrieval of the BRDF descriptors within the period considered.

### 3.2.2 BRDF model (B1)

We make use of a kernel-based semi-empirical model to approximate the WIS TOC reflectances as a sum of three angular functions (BRDF kernels --  $\mathbf{a}_0, \mathbf{a}_1, \mathbf{a}_2$  ) weighted by coefficients (BRDF descriptors --  $\mathbf{k}_0, \mathbf{k}_1, \mathbf{k}_2$ ) as in expression below:

$$\rho(\theta_s, \theta_v, \phi_r) = \mathbf{k}_0 \mathbf{a}_0(\theta_s, \theta_v, \phi_r) + \mathbf{k}_1 \mathbf{a}_1(\theta_s, \theta_v, \phi_r) + \mathbf{k}_2 \mathbf{a}_2(\theta_s, \theta_v, \phi_r) \quad \text{Eq. 1}$$

where  $\theta_s$  and  $\theta_v$  are the Sun and viewing (sensor) zenith angles, respectively. The relative azimuth angle ( $\phi_r = \phi_v - \phi_s$ ) is the difference between viewing azimuth angle ( $\phi_v$ ) and Sun azimuth angle ( $\phi_s$ ). The BRDF kernels  $\mathbf{a}_0, \mathbf{a}_1$  and  $\mathbf{a}_2$  are angular functions describing in a simplified way the elementary properties of the matter and photon interaction (Roujean et al., 2018b). It is now widely accepted that kernel-driven semi-empirical BRDF models can adequately represent the directional signature of most of natural targets (Breon and Maignan, 2017; Bréon and Vermote, 2012; Claverie et al., 2015; Franch et al., 2014; Lucht et al., 2000; North et al., 2005; Roujean et al., 1992; Roujean et al., 2018a; Roy et al., 2016; Schaaf et al., 2002; Vermote et al., 2009; Wanner et al., 1995).

The Roujean (Roujean et al., 1992) and RossThick-LiSparse (Wanner et al., 1995) models are the most popular kernel-driven semi-empirical models to approximate the BRDF of land surface and have been successfully implemented in operational data processing chains (Baret et al., 2013, Geiger et al., 2008; Lucht et al., 2000; Roujean et al., 2018a; Schaaf et al., 2002). The MODIS operational BRDF product has provided BRDF descriptors (MCD43A1<sup>9</sup> and MCD43A2<sup>10</sup>), surface albedo estimates (MCD43A3<sup>11</sup>) and nadir BRDF adjusted reflectances (MCD43A4<sup>12</sup>) based on MODIS satellite observations acquired since February 2000 to date. It is thus remarkable the high archival value of the MCD43 product allowing us to assemble BRDF prior descriptor climatologies -- as described in section 2.3 -- which are needed for the optimal estimation framework presented in this ATBD.

Thus, the decision to use the same kernel-driven semi-empirical BRDF model as the MODIS MCD43 product (i.e. RossThick-LiSparseReciprocal) is solely motivated by the possibility to assemble a BRDF descriptor climatology based on a long-term archive. This approach has been also followed in the GlobAlbedo<sup>13</sup> project ( Lewis et al., 2012; Muller et al., 2011). While the latter choice is merely

---

<sup>9</sup> <https://lpdaac.usgs.gov/products/mcd43a1v006/>

<sup>10</sup> <https://lpdaac.usgs.gov/products/mcd43a2v006/>

<sup>11</sup> <https://lpdaac.usgs.gov/products/mcd43a3v006/>

<sup>12</sup> <https://lpdaac.usgs.gov/products/mcd43a4v006/>

<sup>13</sup> <http://www.globalbedo.org/>

pragmatic, several studies have shown that most of the directional signatures can be captured properly by both BRDF models (Maignan et al., 2004). The selection of using the RossThick-LiSparse semi-empirical model is in line with operational BRDF data streams currently operating (e.g. MODIS, Copernicus Climate Change Service surface albedo<sup>14</sup>).

After selecting the semi-empirical model, Eq. 1 can be re-written as:

$$\rho(\theta_s, \theta_v, \phi_r) = k_{iso} a_{iso}(\theta_s, \theta_v, \phi_r) + k_{vol} a_{vol}(\theta_s, \theta_v, \phi_r) + k_{geo} a_{geo}(\theta_s, \theta_v, \phi_r) \quad \text{Eq. 2}$$

Where  $a_{iso}$  is an isotropic function accounting for bidirectional reflectance with nadir viewing and the overhead sun ( $a_{iso} = 1$ ).  $a_{vol}$  is a function that simulates the volume scattering properties of the surface and  $a_{geo}$  is a geometric function accounting for the effects of shadows and the geometrical structure of protuberances on the surface. Full expression for each of the kernels mentioned above can be found in (Lucht et al., 2000; Roujean et al., 1992) and in section 31.3 of section D of GlobAlbedo ATBD[ATBD GlobAlbedo].

The volumetric and geometric kernels are computed for the stream of data coming out of stage A (see Figure 1). The computation of these angular functions requires four layers of data:

1. Solar zenith angle (SZA)
2. Solar azimuth angle (SAA)
3. Sensor viewing angle (VZA)
4. Sensor azimuth angle (VAA)

and is performed only for those pixels classified as clear in stage A.

The wavelength dependent kernel weights ( $k_{iso}$ ,  $k_{vol}$ ,  $k_{geo}$ ) from Eq. 2 are then found via a BRDF inversion which is described in the next section.

### 3.2.3 Inversion (B2)

Given a set of  $n$  surface reflectance observations acquired by the sensor under varying illumination and viewing conditions, what is the BRDF model that best represent the multi-angular observed reflectances? This forms the BRDF inverse problem and its solution involves the finding of wavelength dependent BRDF descriptors ( $k_{iso}$ ,  $k_{vol}$ ,  $k_{geo}$  in Eq. 2) via an optimal estimation

---

<sup>14</sup> <https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-albedo?tab=overview>

framework. Thus, based on an ensemble of  $n$  observations obtained from the assemblage stage (block labelled as A in Figure 1), each surface reflectance observation can be written in a generalised form of Eq. 2 as:

$$\begin{aligned} \rho_j(\theta_{s_j}, \theta_{v_j}, \phi_{r_j}) = & \mathbf{a}_{iso_j}(\theta_{s_j}, \theta_{v_j}, \phi_{r_j}) \mathbf{k}_{iso_j} + \\ & \mathbf{a}_{vol_j}(\theta_{s_j}, \theta_{v_j}, \phi_{r_j}) \mathbf{k}_{vol_j} + \\ & \mathbf{a}_{geo_j}(\theta_{s_j}, \theta_{v_j}, \phi_{r_j}) \mathbf{k}_{geo_j} \end{aligned} \quad \text{Eq. 3}$$

Where  $j = 1, \dots, n$ . Thus, for the ensemble of clear surface reflectance observations, the expression above returns an equation system which can be written as follows:

$$\boldsymbol{\rho} = \mathbf{K}\mathbf{f} \quad \text{Eq. 4}$$

Where  $\mathbf{K}$  is a matrix containing the three RossThick-LiSparse kernels (angular functions --  $\mathbf{a}_{iso}, \mathbf{a}_{vol}, \mathbf{a}_{geo}$ ) for the ensemble of  $n$  observations. The  $\mathbf{f}$  vector contains the wavelength dependent BRDF descriptors (kernel weights --  $\mathbf{k}_{iso}, \mathbf{k}_{vol}, \mathbf{k}_{geo}$ ) and  $\boldsymbol{\rho}$  is a vector with observed reflectances.

Thus, the solution of Eq. 4 obtained by minimizing the square norm of residuals (least-squares solution) yields to:

$$\mathbf{f} = (\mathbf{K}^T \mathbf{C}_{obs}^{-1} \mathbf{K})^{-1} \mathbf{K}^T \mathbf{C}_{obs}^{-1} \boldsymbol{\rho} \quad \text{Eq. 5}$$

where  $\mathbf{C}_{obs}$  is the observation covariance matrix -- squared uncertainties (variances) of observed reflectances populate the diagonal of  $\mathbf{C}_{obs}$  -- and  $\mathbf{C}_{obs}^{-1}$  denotes its inverse.  $\mathbf{K}^{-1}$  and  $\mathbf{K}^T$  are the inverse and transpose of  $\mathbf{K}$  matrix. Eq. 5 is applied to an ensemble of clear surface reflectance observations accumulated over a predefined period. By doing so, an implicit assumption is being made: The land surface does not undergo significant changes across the time window used to accumulate observations. Thus, the retrieved BRDF descriptors are representative of the selected accumulation period.

According to Gao et al. (2002), BRDF model inversions typically fail because of the following two reasons: (i) Lack of information (scarce number of clear reflectance observations gathered over the accumulation period and/or poor angular sampling) and (ii) low information to noise ratio.

The lack of information issue pointed out in the paragraph above, is related to the later assumption. Gathering observations over a long-time period (e.g. > 30 days) would increase the number of observations to be used in the inversion (positively influencing the quality of BRDF descriptor retrievals).

However, the BRDF approximated would represent an average surface state over the period considered – smoothing out rapid (e.g. < 30 days) variations that could tell about vegetation dynamics. On the other hand, if a short accumulation period is retained, the risk exists for not being able to collect enough observations to yield a successful BRDF model inversion.

To overcome the lack of clear observations issue, an optimal accumulation time window should be used. This is not a straight forward task because it depends on cloud coverage (associated to geographical regions) and viewing-illumination conditions of the sensor. Nevertheless, a 16 day accumulation time window has been used for MODIS MCD43 products (Schaaf et al., 2002; Wang et al., 2018).

BRDF model inversion is known to be an ill-posed problem -- there is no unique set of BRDF descriptors that can solve Eq. 5. Therefore, noisy data (surface reflectance observations for which atmospheric effects were not properly removed) can bias the BRDF descriptor retrievals showing physically unacceptable variations (i.e. significant BRDF descriptors variations over a short [e.g. < 10 days] period) hampering the temporal evolution of retrieved BRDF descriptors time series.

Since significant variations of the surface BRDF shape parameters over a short time scale due to changes in surface cover are usually not expected, an approach to ensure a constrained evolution of the retrieved BRDF descriptors uses prior information obtained from previous BRDF inversions (Geiger et al., 2008; Hagolle et al., 2004; Pokrovsky et al., 2003; Roujean et al., 2018).

Nonetheless, the approach above has a strong dependence on the quality of BRDF descriptors retrievals obtained in previous processing steps. If the most recent retrieved BRDF descriptors were noisy (e.g. due to processing of undetected clouds and/or poor angular and temporal sampling), previous retrievals with low information to noise ratio will serve as prior constraint to the next step, which in turn can result in non-adequate temporal trajectories of retrieved BRDF descriptors.

Thus, the instability in solving Eq. 4 via the well-known least-squares inversion solution is unavoidable because of the ill-conditioned BRDF kernel matrix  $K$ . Therefore, to circumvent the instability in solving Eq. 5, some additional constraints to the matrix system can be attached. Quaife and Lewis (2010) impose conditions on temporal smoothness to constrain linear BRDF model inversion via a Lagrange multiplier.

As shown in Quaife and Lewis (2010), their proposed methodology allows the retrieval of BRDF descriptors with physically acceptable (i.e. sharp changes occurred in short time scales are suppressed) temporal evolutions. Moreover, the methodology presented in Quaife and Lewis (2010) does not require a fix accumulation window (16 days time window for MCD43: Lucht et al., 2000;

Schaaf et al., 2002, 2011; Wang et al., 2018) to perform the BRDF model inversion. On the other hand, the Quaife and Lewis (2010) approach accumulates surface reflectance observations over an arbitrary period of time (in their article is 1 year) and BRDF descriptors retrievals can be obtained for an arbitrary cadence (e.g. daily, each dekad etc.) while the BRDF descriptors retrieved are not representative of the full accumulation period but for the date where the retrieval is obtained. The latter has the advantage of attempting BRDF retrievals at times and regions characterised by a high frequency of cloud occurrence. Using a Kalman filter formulation for the BRDF inverse problem, an equivalent approach has been presented in Samain et al., (2008).

The BRDF model inversion described in this ATBD follows the methodology presented in Quaife and Lewis (2010), albeit a climatology prior of BRDF descriptors (currently based on MODIS MCD43 product Schaaf et al., 2002; Wang et al., 2018) is added to the inversion problem statement. Full details on the derivation of the matrix system stating the BRDF model inversion can be found in Quaife and Lewis (2010). Thus, the BRDF model inversion problem using a Lagrangian multiplier and a BRDF descriptors prior climatology to constraint the inversion can be stated as follows:

$$(\mathbf{K}^T \mathbf{C}_{obs}^{-1} \mathbf{K} + \mathbf{C}_{prior}^{-1} + \gamma \mathbf{D}) \vec{\mathbf{x}} = \mathbf{K}^T \mathbf{C}_{obs}^{-1} \boldsymbol{\rho} + \mathbf{C}_{prior}^{-1} \vec{\boldsymbol{\mu}} \quad \text{Eq. 6}$$

where  $\mathbf{K}$  is a matrix of kernel values (we use the RossThick-LiSparse BRDF kernels in consistency with the MODIS product MCD43),  $\boldsymbol{\rho}$  and  $\mathbf{C}_{obs}$  are the observed reflectance vector and covariance matrix, respectively.  $\vec{\boldsymbol{\mu}}$  and  $\mathbf{C}_{prior}$  are the mean and covariance matrix of the prior BRDF descriptors, respectively. Details on the assembling of the BRDF descriptors prior used in this algorithm can be found in section 2.2.

The temporal smoothness matrix ( $\mathbf{D}$ ) encodes the first order differences of BRDF descriptors between adjacent days – see expression 8 in Quaife and Lewis (2010). The Lagrangian multiplier ( $\gamma$ ) is an adjustable trade-off parameter that represents our confidence on the smoothness (first order differences) constraint. The vector  $\vec{\mathbf{x}}$  is the solution containing the retrieved BRDF descriptors.

The solution of the inverse problem stated in Eq. 6 is performed for a daily grid with the extent of the accumulation period (near-real time mode: 30 days, back-processing mode: 365 days). In other words, BRDF descriptors are retrieved for each day of the accumulation period. The variances of the BRDF descriptors retrieved are estimated (assuming uncorrelated errors<sup>15</sup>) as the diagonal elements of the inverse of  $(\mathbf{K}^T \mathbf{C}_{obs}^{-1} \mathbf{K} + \mathbf{C}_{prior}^{-1} + \gamma \mathbf{D})$ . ReBeLS does not compute the full inverse of  $(\mathbf{K}^T \mathbf{C}_{obs}^{-1} \mathbf{K} + \mathbf{C}_{prior}^{-1} + \gamma \mathbf{D})$  to obtain the variances of BRDF descriptors retrieved but rather solves

---

<sup>15</sup> The same approach has been used in other operational data processing chains providing uncertainties associated to BRDF descriptors (Geiger et al., 2008).

for the diagonal elements of the covariance matrix only for the dates of interest. The latter is due to the fact that inverting the matrix above is very time consuming.

The BRDF descriptors retrieved along with their variances are provided as independent layers. Thus, the output products of the presented algorithm will have, at this stage, 6 layers:  $\mathbf{k}_{iso}$ ,  $\mathbf{k}_{vol}$ ,  $\mathbf{k}_{geo}$  and their respective variances  $\sigma^2_{k_{iso}}$ ,  $\sigma^2_{k_{vol}}$ ,  $\sigma^2_{k_{geo}}$  (see Table 8).

### 3.2.3.1 Selection of regularisation parameter

The regularisation parameter  $\gamma$  in Eq. 6 is an adjustable trade-off parameter that represents our confidence on the smoothness constraint (first order differences) applied to the temporal evolution of BRDF retrievals to obtain. Thus, if  $\gamma$  is too high, too much regularisation is imposed on the solution, then it will not fit the observed TOC reflectances and -- for the stated inverse problem (Eq. 6) -- the solution will be dominated by the prior. Consequently, the residual computed as the difference between the model fitted and observed reflectances will be too large.

On the other hand, if  $\gamma$  is too small too little regularisation is imposed on the solution; then the fit will be good, but the solution will be dominated by the contribution from the data errors which will results in low residuals and unstable (rapid and step temporal variations that are physically unacceptable) BRDF retrievals trajectories.

Although the  $\gamma$  parameter plays an important role in the solution of Eq. 6, there is not a general consensus on how to determine it (Quaife and Lewis, 2010; Samain et al., 2008; Wang et al., 2007). The finding of the regularisation parameter in an inverse problem can be often regarded as matter of art, although it can be guided by some heuristics (Valentine and Sambridge, 2018). Within ReBeLS, the determination of the regularisation parameter follows a posteriori choice method for which the solutions of the inverse problem are obtained for a grid (sequence) of  $\gamma$  values.

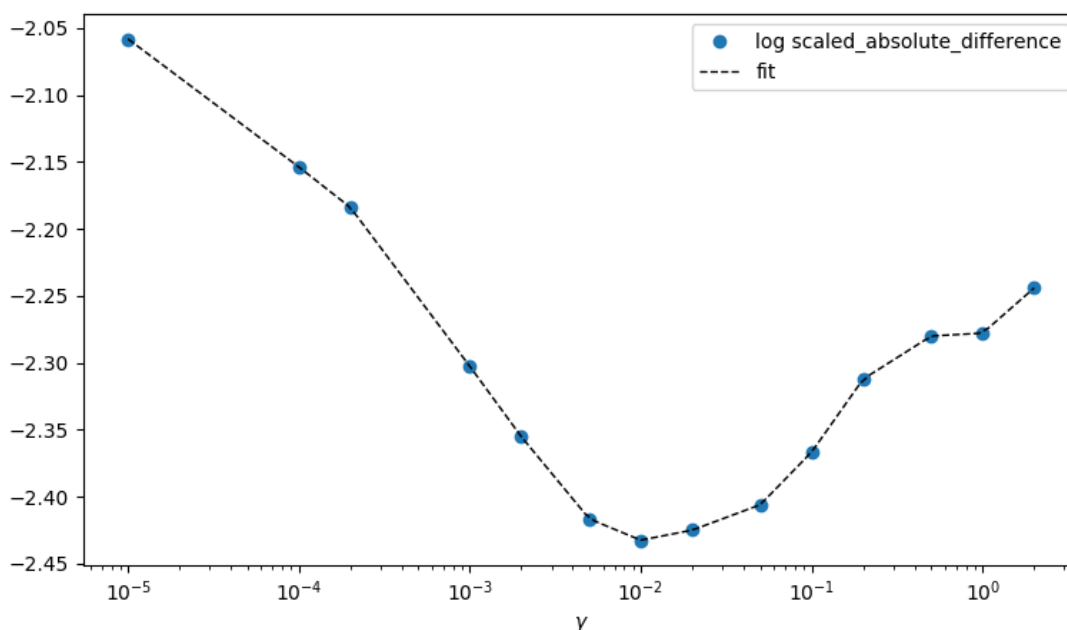
Then, BRDF retrievals obtained with each  $\gamma$  parameter in the above-mentioned grid are used in the BRDF forward model to yield predicted reflectances (computed by plugging the BRDF descriptors retrieved into Eq. 2, along with the BRDF kernels computed for a reference dataset observation acquisition geometry). The residuals (difference between predicted reflectance and reference reflectance dataset) are computed and the regularisation parameter that produces the lowest residuals is considered as the most adequate. We make use of the MODIS MOD09GA (MODIS Terra surface reflectance daily<sup>16</sup>) product as the reference reflectance dataset to compute the residuals. This approach is inspired by the cross validation analysis done in Lewis et al., (2012), albeit their inverse problem is stated for a different context.

---

<sup>16</sup> -- <https://lpdaac.usgs.gov/products/mod09gav006/>

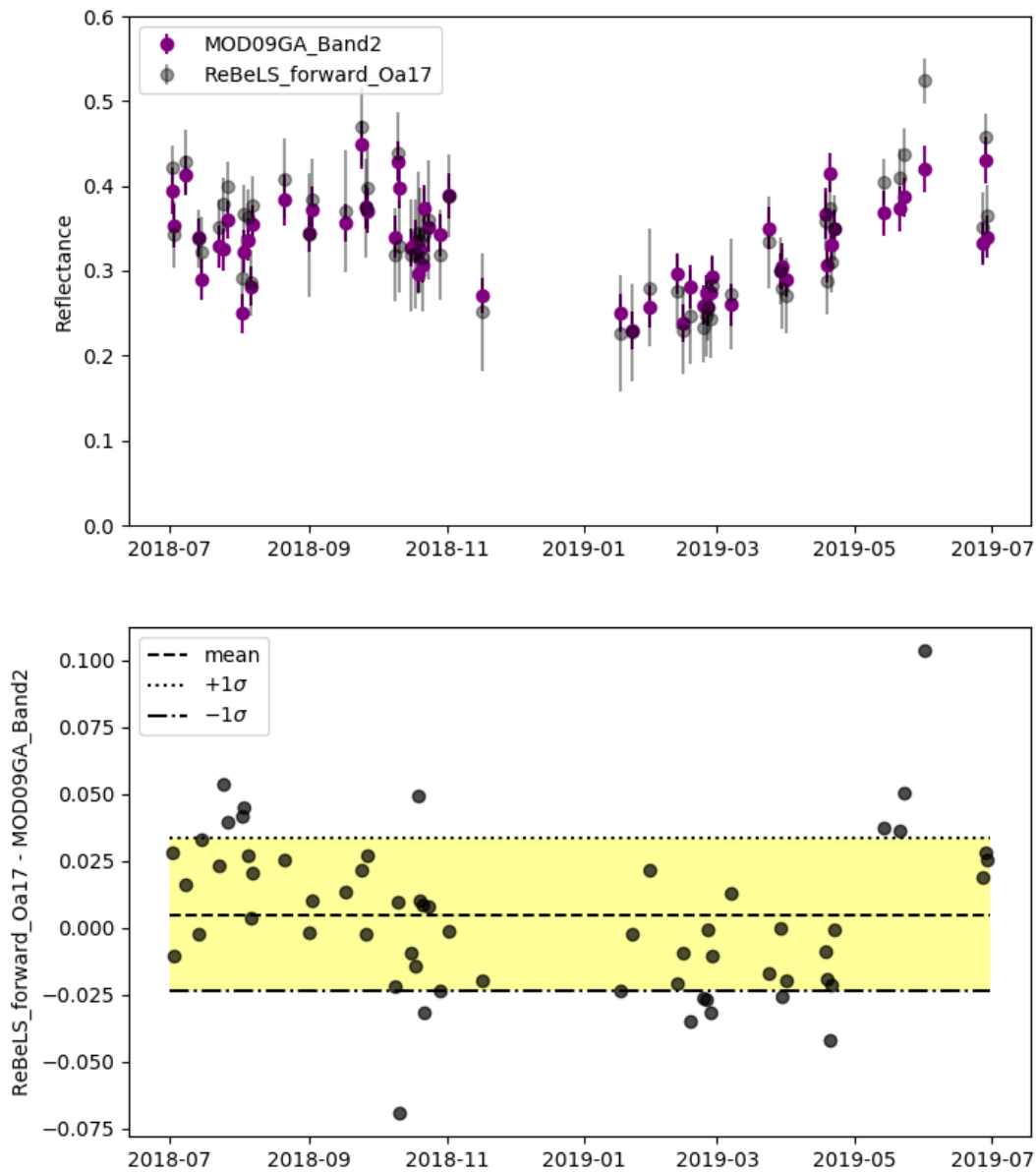
The Band2 from MODIS MOD09GA and Oa17 band from Sentinel-3 TOC reflectances are selected to perform the cross-validation exercise delineated above. The criteria to perform this exercise in the NIR spectral regime follows the fact that NIR TOC reflectances are less likely to show inaccuracies introduced after (or due to an inadequate) atmospheric correction. Nevertheless, the regularisation parameter found as described above shall be used for all Sentinel-3 and PROBA-V spectral bands.

As an example of the cross validation strategy above described, Figure 2 shows the cross validation function -- scaled absolute difference between ReBELS Oa17 predicted (ReBeLS forward) and Band2 MODIS MOD09GA reflectances as a function of the regularisation parameter  $\gamma$  -- for a pixel near Snargate (see site coordinates at top of Figure 3), England. From the cross validation function shown in Figure 2 is evident a rather broad minimum which suggests that a range of values of  $\gamma$  can yield to BRDF retrievals allowing an adequate prediction of MOD09GA Band2 surface reflectances for the pixel and over the period of time considered (1 year for this cross validation exercise).



**Figure 2: Cross validation function for a pixel near Snargate (see site coordinates at top of Figure 3). The fit provided by a linear interpolation is plotted with dashed line. The cross validation function shown is the logarithm of scaled absolute difference (Sentinel-3 Oa17 ReBeLS predicted - Band2 MODIS MOD09GA) reflectances as a function of the regularisation parameter.**

Snargate (51.009913, 0.0828825)



**Figure 3: Top panel: Observed MOD09GA Band2 and ReBeLS Oa17 predicted reflectances for a pixel near Snargate, England. These time series are colour and symbol coded as shown in the legend. Bottom panel: Difference between observed MOD09GA Band2 and ReBeLS Oa17 predicted reflectances. The mean difference is shown with dashed line. Most of differences are within  $\pm 1\sigma$  (yellow band), where  $\sigma$  is the standard deviation.**

The temporal evolution of Band 2 MOD09GA and ReBeLS Oa17 predicted reflectances for a pixel near Snargate are shown in the top panel of Figure 3. These time series are colour and symbol coded as shown in the legend. The ReBeLS Oa17 predicted reflectances plotted in the top panel of Figure 3 are computed by plugging the BRDF descriptors retrieved with the gamma value associated to the minimum of the cross validation function (see Figure 2 -- for this pixel is 0.009) along with the BRDF kernels computed with the observation acquisition MOD09GA geometry.

From a visual inspection of the top panel of Figure 3, it appears that the optimal (minimum of the cross validation function shown in Figure 2) regularisation parameter found (following the approach above described) permits the retrieval of BRDF descriptors that allow a good prediction of the MOD09GA observed reflectances. The agreements are evident at reflectance level and for reflectance temporal trajectories. This is confirmed by the inspection of residuals shown in the bottom panel of Figure 3. The standard deviation of residuals is around 0.02 which is comparable to the expected uncertainty in surface reflectance observations in the NIR spectral regime. The latter (together with the discussion presented in section 3.4) adds confidence in the BRDF descriptors retrieval methodology presented in this ATBD.

The cross-validation methodology described above was applied at tile scale resulting in optimal regularisation parameters for the 12 Sentinel-3 TOC tiles ( $10^\circ \times 10^\circ$ ) available at the time of releasing ReBeLS v1.3. Since the cross-validation approach should be applied globally, in this version of the processor, we adopt an average optimal regularisation parameter based on the 12 regularisation parameter tiles mentioned above. Thus, an average regularisation parameter ( $\gamma = 5 \times 10^{-3}$ ) is used as default in the current configuration of the ReBeLS processor. It has been verified that this pragmatic decision yields to adequate results derived from Sentinel-3 and PROBA-V datasets as can be seen in section 3.4.

### 3.2.4 Quality control (B3)

After solving Eq. 6, an output control is performed to assess whether the BRDF descriptors retrievals are within a range of physically acceptable values [0.01, 3] obtained from statistics of the BRDF descriptors prior climatology assembled and their corresponding variances are limited to [ $1e^{-5}$ , 0.5] – the lower limit is related to datatype used in scaled values provided in final products. If a BRDF descriptor value lies above (below) the corresponding ranges, its value indicates an unsuccessful inversion (is replaced by the lower limit overrun).

To assess the quality of the BRDF descriptor retrievals, the algorithm computes a mean z-score between predicted (reflectances obtained by running the BRDF model in forward mode using the BRDF descriptors retrieved) and observed reflectances. A quantitative estimate of goodness of fit is provided according to Table 3. The quality of the model fit provided is obtained by means of the mean z-score computed with all observations accumulated in the corresponding dekad (it should be

noticed that for some regions the frequency of observations is sub daily), regardless of the output cadence selected.

To summarize the output control described above, a quality information layer (QUIL - Table 4) is provided as an independent extra layer. To further assess the retrievals, the algorithm counts the number of observations identified as clear (and snow) that are used in the inversion. Thus, all the layers provided in the output product of the BRDF retrieval algorithm are shown in Table 5. For details on the output product files see Table 8.

**Table 3. Goodness of fit status**

<b>Best</b>	$z_{score} \leq 2$
<b>Warning</b>	$2 < z_{score} \leq 3$
<b>Extreme warning</b>	$z_{score} > 3$

**Table 4. QUIL (quality information layer) encoding. The dekad time window is defined as [t0, t0+10days] where t0 is the date of the dekad provided.<sup>17</sup>**

Bit	State	Value	Description
<b>0</b>	No observations found in a predefined time window <sup>18</sup>	1	If bit0 is 1 then no clear observations were found in the predefined time window
<b>1</b>	No ReBeLS data (unsuccessful inversion)	2	If bit1 is 1 then no ReBeLS data is provided (meaning that the BRDF descriptors were out of range, unsuccessful inversion)
<b>2</b>	Quality of BRDF inversion: Best -- $z_{score} \leq 2$	4	If bit 2 is 1 then an estimation of goodness of fit (z-score within a predefined time window) indicates that the agreement between observations and model fit can be considered as best

<sup>17</sup> Warning (QUIL=8) does not necessarily mean that the model fit has been degraded. Sometimes when rapid reflectance changes take place in a dekad QUIL can take 8 (or 16 – see Figure 12) values. The latter is of course pixel and temporal dependent.

<sup>18</sup> 10 and 5 days for NDVI and LPS products, respectively.

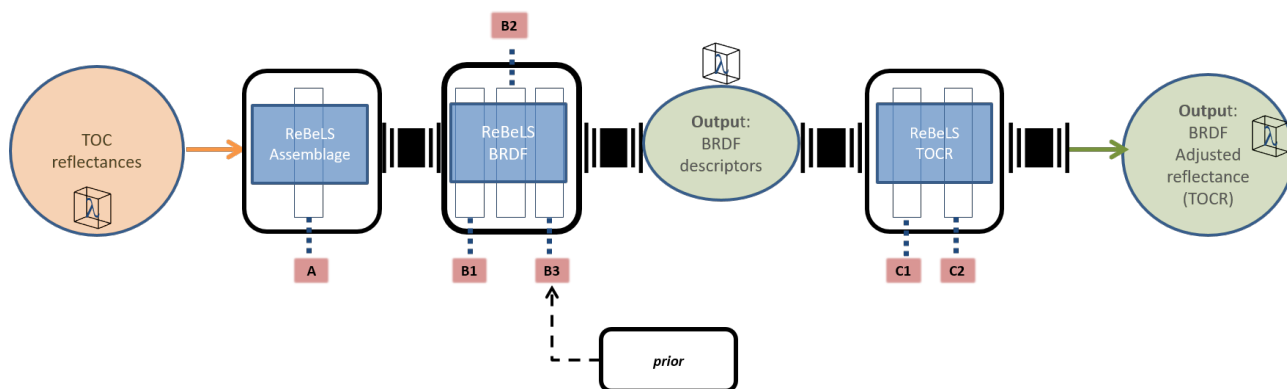
3	Quality of BRDF inversion: Warning -- $2 < z_{score} \leq 3$	8	If bit 3 is 1 then an estimation of goodness of fit (z-score within the dekad time window) indicates that the agreement between observations and model fit is adequate, albeit results should be taken with caution.
4	Quality of BRDF inversion: Extreme warning -- $z_{score} > 3$	16	If bit 4 is 1 then an estimation of goodness of fit (z-score within the dekad time window) indicates that the agreement between observations and model fit cannot be considered adequate.

**Table 5: Layers provided as output of the ReBeLS BRDF processor.**

Number of layer	ReBeLS BRDF	Description
1	$k_{iso}$	Isotropic BRDF descriptor
2	$k_{vol}$	Ross-thick BRDF descriptor
3	$k_{geo}$	Li-sparse BRDF descriptor
4	$\sigma_{k_{iso}}^2$	Variance of isotropic BRDF descriptor
5	$\sigma_{k_{vol}}^2$	Variance of Ross-thick BRDF descriptor
6	$\sigma_{k_{geo}}^2$	Variance of Li-sparse BRDF descriptor
7	QUIL	Quality information layer -- see Table 4 for details on encoding.
8	$N_{obs}$	Number of clear observations in a predefined time window and used throughout the inversion.
9	$N_{obs_{snow}}$	Number of clear observations used throughout the inversion classified as snow <sup>19</sup> in a predefined time window

<sup>19</sup> Based on pixel\_classif\_flags layer provided in the Sentinel-3 TOC datasets [CGLOPS1\_QAR\_S3-CloudMask] or by using the snow patch introduced during the development of the Copernicus Climate Change Services surface albedo product – for details we refer the reader to Sanchez-Zapero et al. (2023) and specifically to their Figure 1.

### 3.3 BRDF ADJUSTED REFLECTANCE (TOCR)



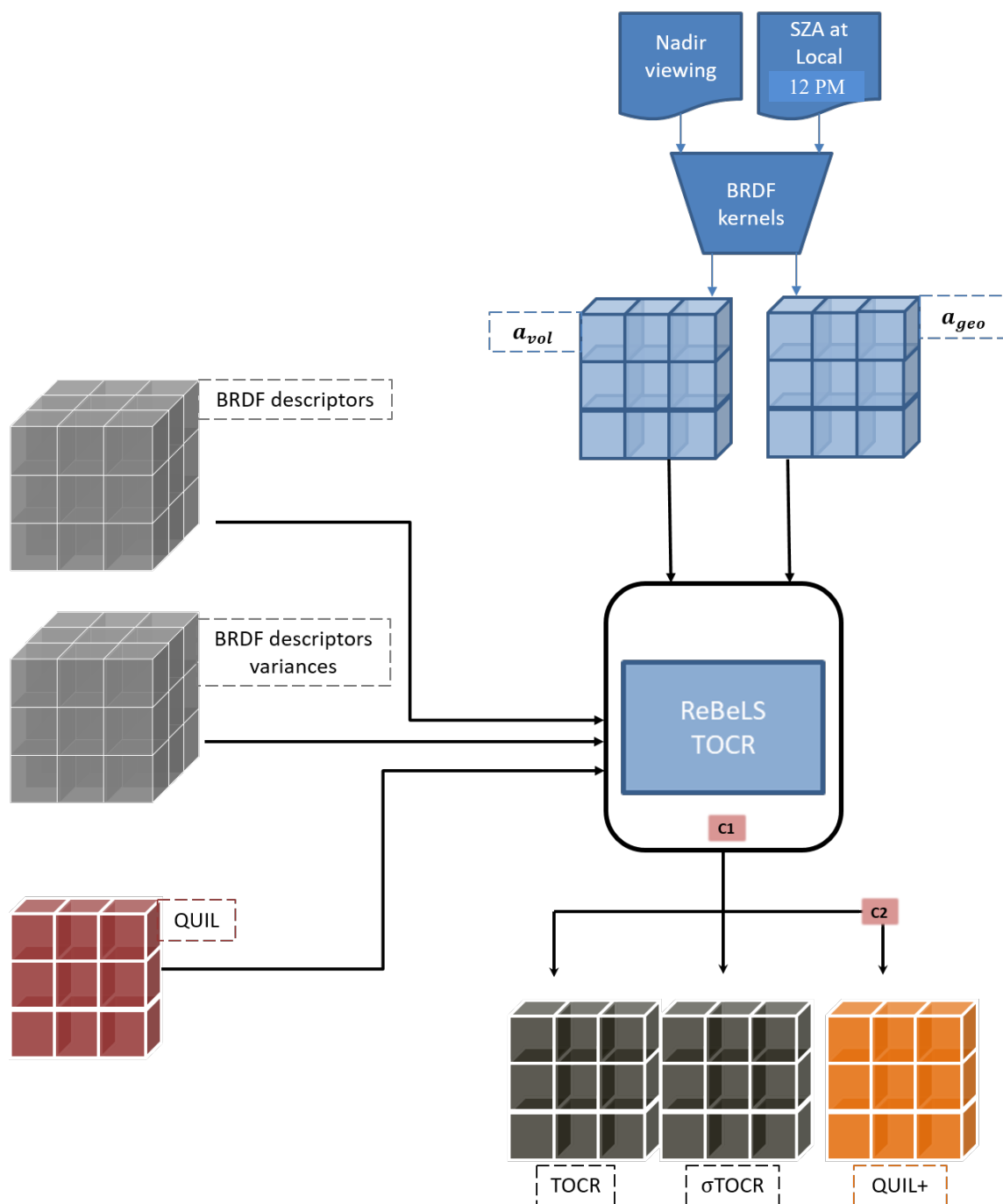
- **A – Assemblage:** Accumulation of observations over a selected period of time. Using information from quality indicators, only clear observations are retained for further processing.
- **B1 – BRDF model:** Kernels from a semi-empirical BRDF model are computed for each observation
- **B2 – Inversion:** BRDF descriptors that best represent the ensemble of observations are found by solving an inverse problem with the addition of regularisation (prior).
- **B3 – Quality control:** A quality information layer is assembled to reflect availability of observations and whether (or not) the BRDF model inversion was successful.
- **C1 – BRDF adjustment:** Accumulation of observations over a selected period of time. Using information from quality indicators, only clear observations are retained for further processing.
- **C2 – Quality control:** The quality information layer from the BRDF retrieval is propagated and a bit is added to indicate whether the BRDF adjusted reflectances values are physically unacceptable.

**Figure 4: Continuation of diagram flow shown in Figure 1. Stage TOCR allows to compute BRDF adjusted reflectances (TOCR) based on BRDF descriptors retrieved in stage B3 and solar zenith angle at 12:00 pm local time.**

The solution of the inverse BRDF problem stated in the previous section together with BRDF kernels allow us to predict the surface reflectance of a region (i.e. pixel) under any observing and illumination conditions. Thus, computed reflectances as mentioned above are known as BRDF adjusted reflectances -- these are also commonly known as BRDF corrected reflectances.

Figure 4 shows the continuation of the processing with ReBeLS to compute a BRDF adjusted reflectance based on the BRDF descriptors retrieved as described in section 3.2.3. An additional stage (ReBeLS TOCR) is shown in Figure 4 ingesting the BRDF descriptors retrieved in ReBeLS BRDF stage to compute a BRDF adjusted surface reflectance. Hereafter, the BRDF adjusted reflectance is also referred as TOCR -- this naming aims to keep consistency with previous Copernicus Global Land

Service BRDF adjusted reflectances such as the 1km spatial resolution TOCR<sup>20</sup> based on SPOT-VGT and PROBA-V data which is currently discontinued<sup>21</sup>.



**Figure 5: Diagram flow for the computation of TOCR. Structured layers aim to represent an example where a 3x3 pixel window is processed. The BRDF retrievals (and their variances) are represented as**

<sup>20</sup> <https://land.copernicus.eu/global/products/toc-r>

<sup>21</sup> <https://land.copernicus.eu/global/content/toc-r-1km-discontinued>

data cubes because there are 3 BRDF descriptors retrieved:  $k_{iso}$ ,  $k_{vol}$ ,  $k_{geo}$  with variances  $\sigma^2_{k_{iso}}$ ,  $\sigma^2_{k_{vol}}$ ,  $\sigma^2_{k_{geo}}$  respectively. The Ross\_thick and Li\_sparse\_reciprocal BRDF kernels for the Sun-viewing common configuration are shown as  $a_{vol}$  and  $a_{geo}$ , respectively. The uncertainty associated to the TOCR estimates is denoted as  $\sigma_{TOCR}$  while QUIL+ is the input QUIL layer with an added bit to identify pixels for which TOCR values are out of a physically believable range (i.e. [0,1]).

The ReBeLS TOCR stage comprises two steps: BRDF adjustment (C1) and quality control (C2) and, in the following sections, details on the processing blocks of the ReBeLS TOCR stage are given.

### 3.3.1 BRDF adjustment (C1)

Given the processing framework outlined in Figure 4, for the reader convenience, Figure 5 shows the diagram flow for the computation of TOCR detached from the overall processing. The data structures (layers) shown in Figure 5 represent an example where a 3x3 pixel window is processed. The BRDF retrievals and their variances are represented as data cubes because there are 3 BRDF descriptors retrieved:  $k_{iso}$ ,  $k_{vol}$ ,  $k_{geo}$  with variances  $\sigma^2_{k_{iso}}$ ,  $\sigma^2_{k_{vol}}$ ,  $\sigma^2_{k_{geo}}$ , respectively. Following Figure 5, the ReBeLS TOCR processor is fed with BRDF descriptors (their variances and quality information layer) that have been retrieved by the ReBeLS BRDF processor. It should be noticed that it is not mandatory for the ReBeLS BRDF and ReBeLS TOCR to run sequentially. Moreover, the ReBeLS TOCR processor runs independently for each spectral band.

The task was to provide BRDF adjusted reflectances at nadir viewing and solar zenith angle at local 12 PM. Thus, as shown in the top right of Figure 5, the BRDF kernels for the requested Sun-viewing configuration (i.e. SZA corresponding to 12:00 PM local time, VZA= 0° -- nadir -- and relative azimuth angle  $\phi_r = 0^\circ$ ) are computed for each pixel. It is important to note that the SZA for local 12PM shows variations along the latitude axis. In other words, the SZA at local 12PM for the top row of a tile (10° × 10°) will be different from the bottom row of the tile.

Once the BRDF kernels for the common Sun-viewing configuration have been computed and the BRDF descriptors (along with their variances and quality information layer) have been fed into the ReBeLS TOCR processor, the BRDF model runs forward outputting two layers: TOCR, and TOCR uncertainty ( $\sigma_{TOCR}$  in Figure 5). TOCR is computed as follows:

$$TOCR = k_{iso} + k_{vol}a_{vol}(\theta_{S12PM}, 0,0) + k_{geo}a_{geo}(\theta_{S12PM}, 0,0) \quad \text{Eq. 7}$$

The uncertainty of the TOCR computed is estimated by propagating the BRDF retrievals variances through the TOCR computations resulting in the following expression:

$$\sigma TOCR = \sqrt{\sigma^2_{k_{iso}} + \sigma^2_{k_{vol}} a_{vol}^2(\theta_{S12PM}, 0, 0) + \sigma^2_{k_{geo}} a_{geo}^2(\theta_{S12PM}, 0, 0)} \quad \text{Eq. 8}$$

### 3.3.2 Quality control (C2)

As shown in Figure 5, four layers are the output of the ReBeLS TOCR processor. Those related to the TOCR numerical values are estimated as described in the previous section. The *QUIL+* layer is basically an augmented version of QUIL (Table 4) (output of ReBeLS BRDF processor) where an extra bit has been added to identify TOCR values with unrealistic values.

The determination of the extra bit added to QUIL is as follows: If the BRDF descriptors retrieved when plugged into Eq. 7 yield to a reflectance value outside a physically unacceptable range (i.e. [0, 1]), the extra bit is set to 1. Otherwise, it is set to 0.

Then, the structure of QUIL+ takes the form as shown in Table 6 .

Thus, all the layers provided in the output product of the TOCR retrieval algorithm are shown in Table 7. Nobs is the result of screenings described in section 3.2.1.2, section 3.2.1.3 and section 3.2.1.4. For details on the output product files see Table 9.

It is important to note that the illumination conditions associated with acquisitions in the northernmost regions during wintertime can be exceptionally extreme. In such cases,  $\theta_{S12PM}$  is very large, yielding to singularities in the BRDF kernels analytical expressions and the derived surface reflectance model becomes unreliable. Therefore, ReBeLS restricts the computation of TOCR to instances where  $\theta_{S12PM}$  is less than 90 degrees. As a special case, when the scene is in darkness, no data value for TOCR is provided and this is signalled by activating QUIL's bit 0 and 5, yielding to a QUIL value of 33. It is worth noticing that such illumination conditions are predominantly occurring at northernmost regions during periods of persistent darkness which have an infrequent incidence in the global context.

**Table 6: QUIL for TOCR<sup>22</sup>**

Bit	State	Value	Description
0	No observations found in a predefined time window	1	If bit0 is 1 then no clear observations were found in the dekad time window
1	No ReBeLS data (unsuccessful inversion)	2	If bit1 is 1 then no ReBeLS data is provided (meaning that the BRDF descriptors were out of range, unsuccessful inversion)
2	Quality of BRDF inversion: Best -- $z_{score} \leq 2$	4	If bit 2 is 1 then an estimation of goodness of fit (z-score within the predefined time window) indicates that the agreement between observations and model fit can be considered as best
3	Quality of BRDF inversion: Warning -- $2 < z_{score} \leq 3$	8	If bit 3 is 1 then an estimation of goodness of fit (z-score within the predefined time window) indicates that the agreement between observations and model fit is adequate, albeit results should be taken with caution.
4	Quality of BRDF inversion: Extreme warning -- $z_{score} > 3$	16	If bit 4 is 1 then an estimation of goodness of fit (z-score within the predefined time window) indicates that the agreement between observations and model fit cannot be considered adequate.
5	TOCR out of range	32	If bit 5 is 1, then the BRDF adjusted reflectance is out of range (either negative or higher than one)

<sup>22</sup> Warning (QUIL=8) does not necessarily mean that the model fit has been degraded. Sometimes when rapid reflectance changes take place in a dekad QUIL can be 8 (or 16 – see Figure 12). The latter is of course pixel and temporal dependent

**Table 7: Layers provided as output of the ReBeLS TOCR processor**

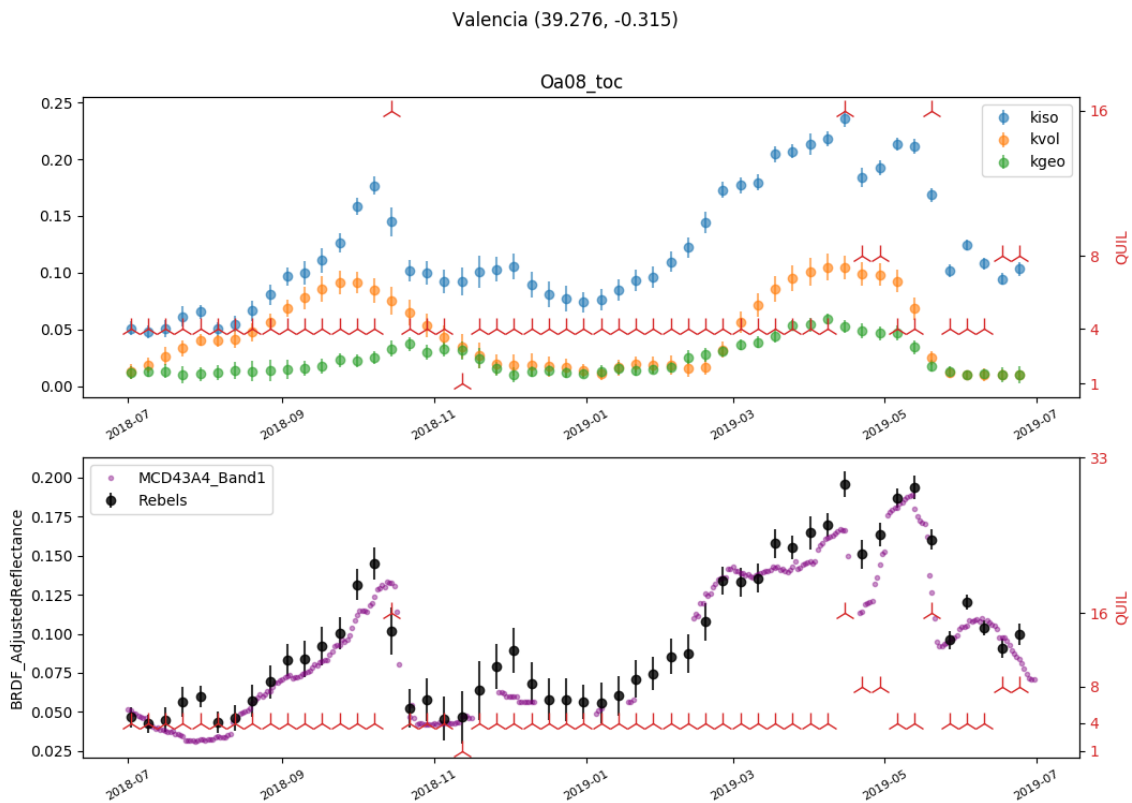
Number of layer	ReBeLS TOCR	Description
1	TOCR	BRDF adjusted reflectance
2	$\sigma$ TOCR	BRDF adjusted reflectance uncertainty
3	QUIL	Quality information layer -- see Table 6 for details on encoding
4	$N_{obs}$	Number of clear observations in a predefined time window.

### 3.4 EVALUATION OF THE ALGORITHM PERFORMANCE

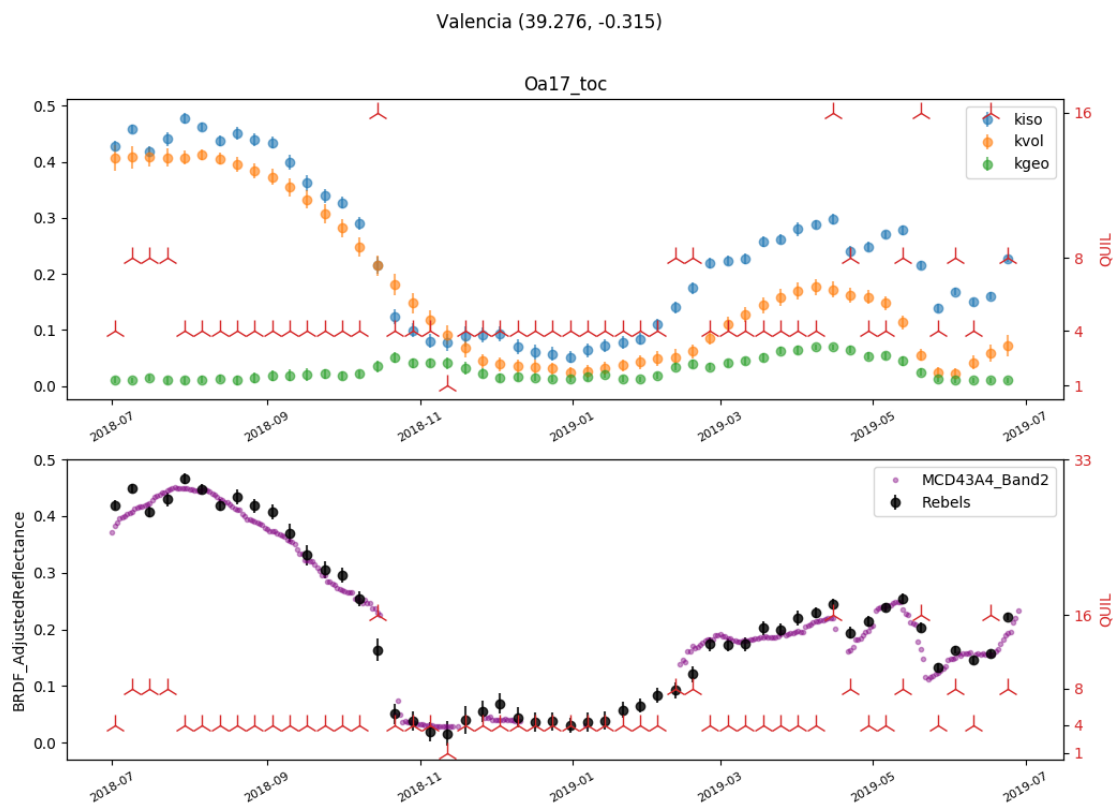
The analyses presented in this section focus on pixels of Sentinel-3 and PROBA-V 333m datasets encompassing the period from July 2018 to June 2019 from the above-mentioned dataset.

Figure 6 and Figure 7 show the temporal evolution of the weekly retrieved BRDF descriptors (top panel) and BRDF adjusted reflectance (bottom panel) for the pixel of Albufera site, near Valencia, Spain, in Sentinel-3 OLCI Oa08 and Oa17 spectral bands, respectively. At first glance, the temporal trajectories of the BRDF descriptors retrieved (top panels in Figure 6 and Figure 7) follow a phenological cycle expected in a cultivated area in consistency with the land cover for this site. The variations in the BRDF descriptors retrieved show a smooth evolution which seems physically reasonable for this site in the absence of sharp changes in the reflectance signal (e.g. fire, flash flooding, etc.).

As described in section 3.3, the wavelength dependent BRDF descriptors retrieved are used to adjust surface reflectances to a common Sun-sensor configuration. The OLCI Oa08 and Oa17 BRDF adjusted reflectances (computed as described in section 3.3.1) for the above mentioned site are shown in the bottom panels of Figure 6 and Figure 7, respectively.



**Figure 6: Temporal evolution of retrieved BRDF descriptors (top panel) and BRDF adjusted reflectance (bottom panel) for a pixel near Valencia (this site is also known as Albufera and is a cultivated area), Spain – see geographical coordinates at the top of the figure. The temporal trajectories of both BRDF descriptors and adjusted reflectances are obtained for OLCI spectral band Oa08 (RED spectral range). The bottom panel shows as a reference the MODIS band1 (RED) MCD43A4 (Nadir BRDF adjusted reflectances -- NBAR) time series for the same site. The type of BRDF descriptors retrieved is colour coded as shown in the legend of top panel. The time series of BRDF adjusted reflectances are colour and symbol coded as shown in the legend of the bottom panel. The quality information layer (QUIL – for details see section 3.2.4) for the BRDF retrievals is overlaid on the top panel where corresponding QUIL values can be found in the left y-axis. The latter also applies for the bottom panel, albeit for the TOCR QUIL (see section 3.3.2 for details). The error bars shown in both panels correspond to the uncertainties estimated as described in section 3.2.3 and 3.3.1.**



**Figure 7: Same as in Figure 6 but for Sentinel-3 OLCI Oa17 spectral band ( NIR). The bottom panel shows as a reference the MODIS band2 (NIR) MCD43A4 NBAR time series for the same location.**

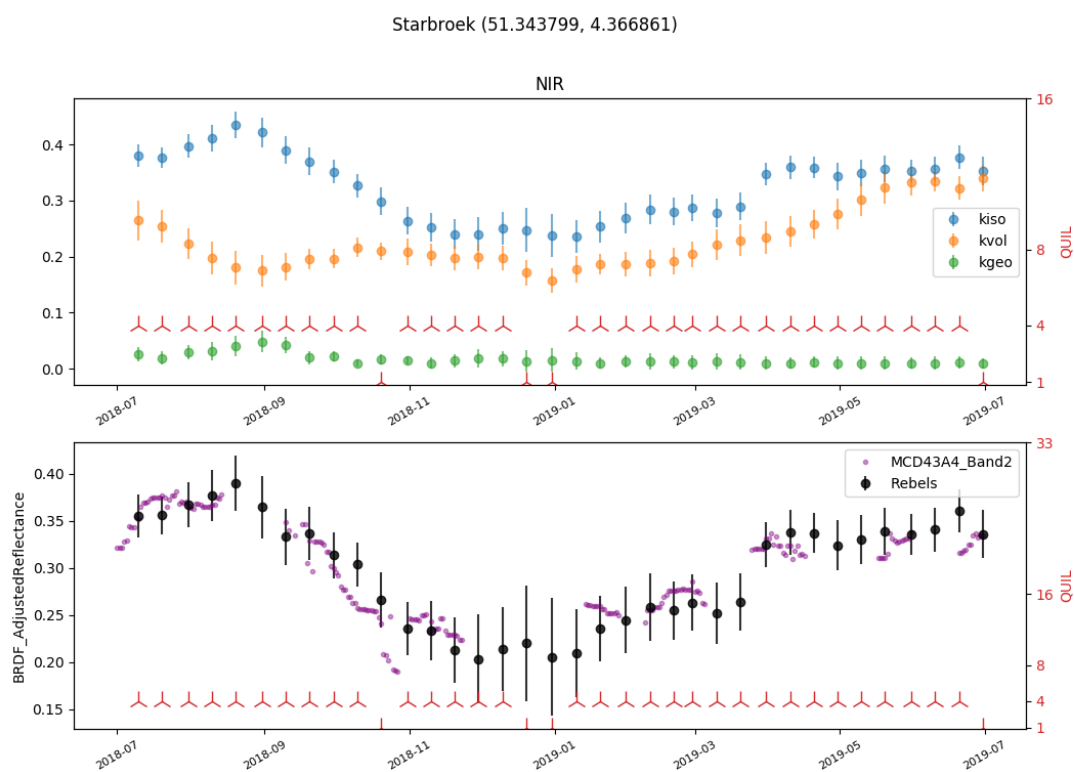
The impact of directional effects on TOC surface reflectance time series can be identified by the presence of a high frequency noise component which, in turn, results in spurious deviations with time scales shorter than the characteristic vegetation activity timescales. From Figure 6 and Figure 7, it can be seen that, no step changes in the BRDF adjusted reflectance signal can be identified. Moreover, the temporal trajectories of the BRDF adjusted reflectances are consistent with those shown in the MODIS MCD43A4 NBAR time series extracted for the Valencia pixel.

Before performing any comparison with the MODIS MCD43A4 product, there are a couple of issues to bear in mind: (i) Although there is an overlap between spectral bands from MODIS and Sentinel-3 OLCI (and PROBA-V), these are not identical which can, in turn, introduce differences that are not intrinsic to the observed targets but associated to the instruments themselves; (ii) Although ReBeLS uses the same BRDF kernels as MODIS MCD43A4, the optimal BRDF descriptors estimation is significantly different (e.g. accumulation period, BRDF descriptors optimal estimation framework, usage of regularisation, frequency of BRDF descriptors retrievals –daily for MCD43A4 while 7-days frequency for ReBeLS in these examples).

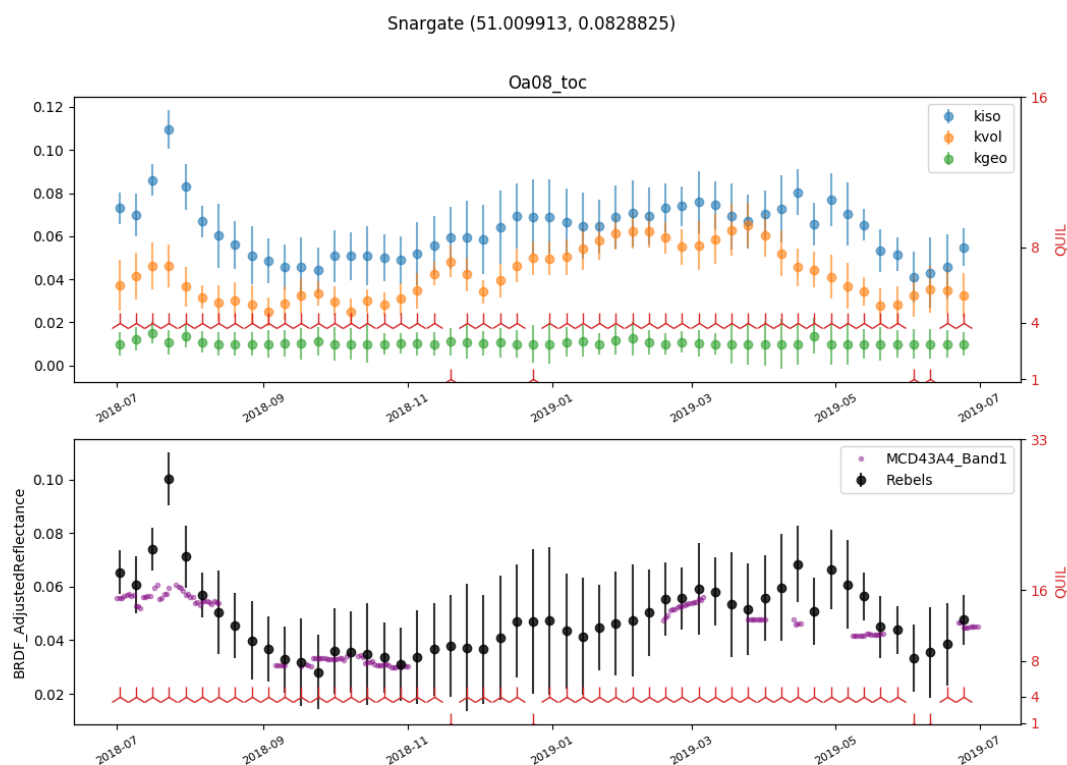
Figure 6 and Figure 7 show an overall agreement between MODIS MCD43A4 NBAR time series and BRDF adjusted reflectances obtained with ReBeLS for a pixel near Valencia. The consistency between time series is not only at the levels of BRDF adjusted reflectance signal but also in terms of phenology. More specifically, the onset of the vegetation growing season denoted by an increase of NIR reflectance signal (see bottom panel of Figure 7 around 2019-06) is consistent between both BRDF adjusted reflectance time series.

Since the MCD43A4 product is obtained with a daily cadence, the consistency seen in the bottom panels of Figure 6 and Figure 7 adds confidence in the near real timeliness of the BRDF adjusted reflectances obtained with ReBeLS which, in turn, suggests that the BRDF descriptors retrievals adequately fit the Sentinel-3 TOC observations and the BRDF adjusted reflectance obtained with ReBeLS show a phenological cycle consistent with MODIS MCD43A4.

Within the Sentinel-3 TOC reflectance dataset (see section 1.3.2), the pixel near Valencia is not characterised by a high frequency of cloud occurrence. Figure 8 and Figure 9 show the PROBA-V based temporal trajectories of BRDF descriptors retrievals (top panels) and BRDF adjusted reflectances (bottom panels) for PROBA-V and Sentinel-3 pixels near Starbroek (Belgium) and Snargate (England), respectively. These pixels correspond to geographical regions with high cloud occurrence.



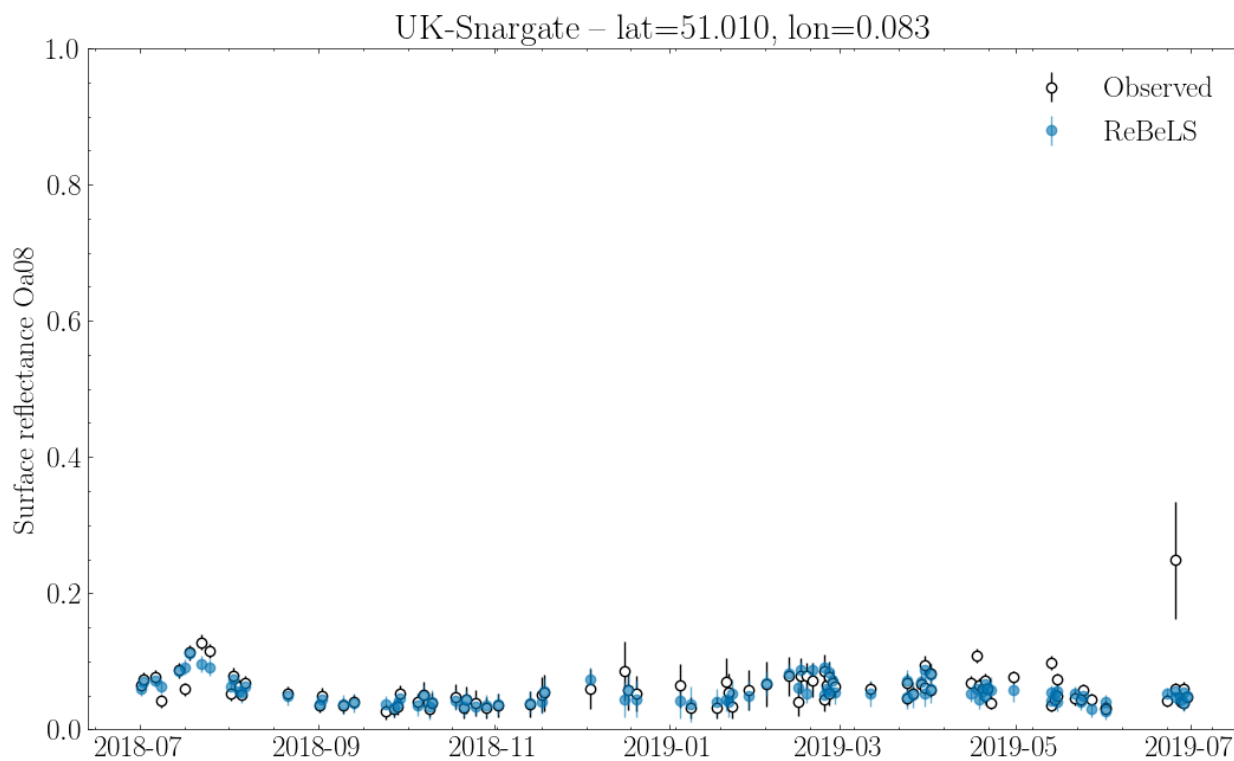
**Figure 8: Same layout as Figure 7 but for a PROBA-V 333m pixel near Starbroek, Belgium – see geographical coordinates at the top of the figure.**



**Figure 9: Same layout as in Figure 6 but for a Sentinel-3 pixel near Snargate, England – see geographical coordinates at the top of the figure.**

The above discussion -- on the temporal evolution of the ReBeLS BRDF retrievals and consistency between ReBeLS BRDF adjusted reflectance and MCD43A4 -- for the pixel near Valencia (see Figure 6 and Figure 7) also applies for pixels where the cloud coverage can be a major concern for the retrieval of BRDF descriptors (Figure 8 and Figure 9).

However, as shown in Figure 9, the Sentinel-3 BRDF adjusted reflectances show a clear deviation from the MCD43A4 time series at the beginning of the time series (i.e. around 201808). At first glance, this could be attributed to the processing of an undetected cloud. Nevertheless, when looking at the observed Sentinel-3 TOC temporal trajectories – see Figure 10, it becomes evident that the peak seen in the Sentinel-3 BRDF adjusted reflectances is associated to the TOC reflectance signal rather than a single occurrence undetected cloud as seen by the end of the time series (around 201907 in Figure 10).

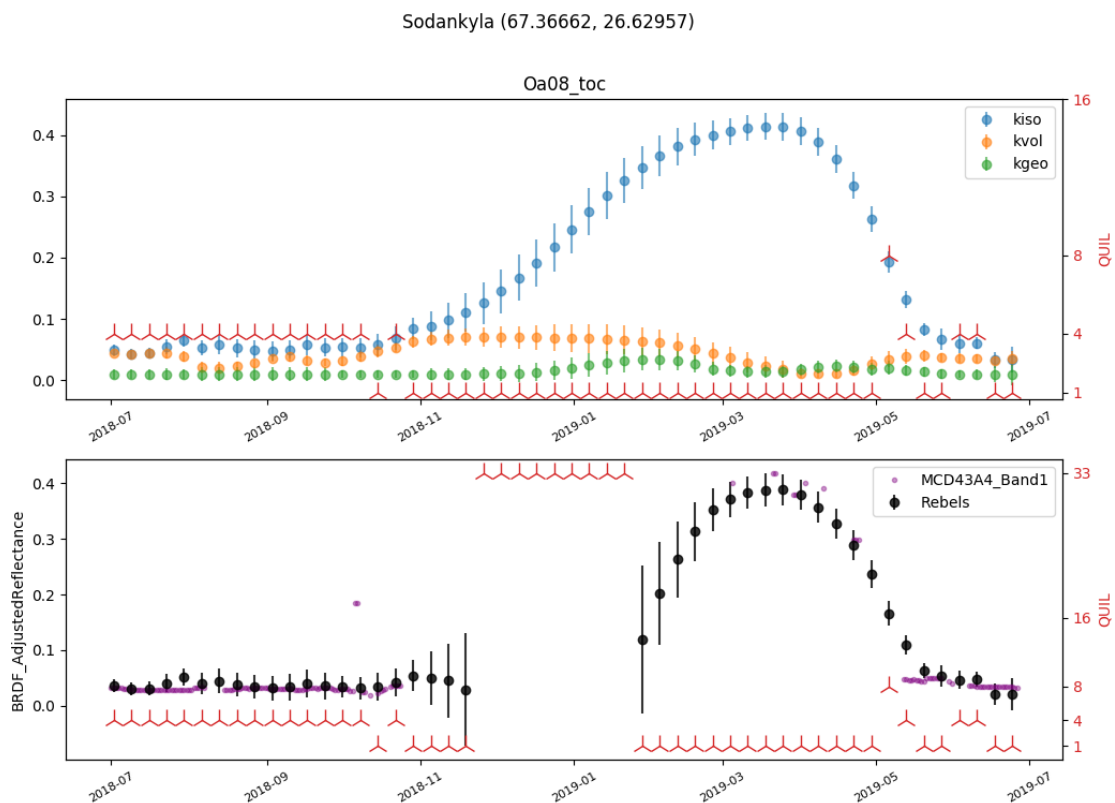


**Figure 10 Temporal evolution of OLCI Oa08 TOC reflectance observed and BRDF adjusted for a pixel near Snargate (England – see Figure 9). The type of reflectance datasets is colour and symbol coded as shown in the legend.**

Figure 11 shows the results of the presented algorithm for a Sentinel-3 pixel near Sodankyla (northern Finland) for which its TOC reflectance time series is significantly hampered by a high frequency of cloud occurrence and long periods of natural darkness. BRDF descriptors retrieved and BRDF adjusted reflectances for this pixel ) are shown in the top and bottom panels of Figure 11, respectively. By looking at the QUIL states over the time series, the lack of observations denoted by QUIL state equal to 1, (see Table 4 and Table 6 for the definitions of the QUIL layer) spans a period from late October to late April which is a significant gap in the time series.

Nevertheless, for this example, the ReBeLS BRDF processor provides an estimate of the evolution of the BRDF descriptors for each week in the time series. These estimates should be interpreted bearing in mind that in the event of a persistent absence of observations yielding to significantly long gaps in the TOC reflectance time series, the estimation of BRDF descriptors is dominated by the prior BRDF descriptors climatology used in the optimal estimation framework. However, as clear observations are available (see Figure 11 around May 2019), these are assimilated to provide temporal trajectories of BRDF descriptors which can reflect the current conditions of the surface. The correspondence between MCD43A4 NBAR and ReBeLS BRDF adjusted reflectances seen after May

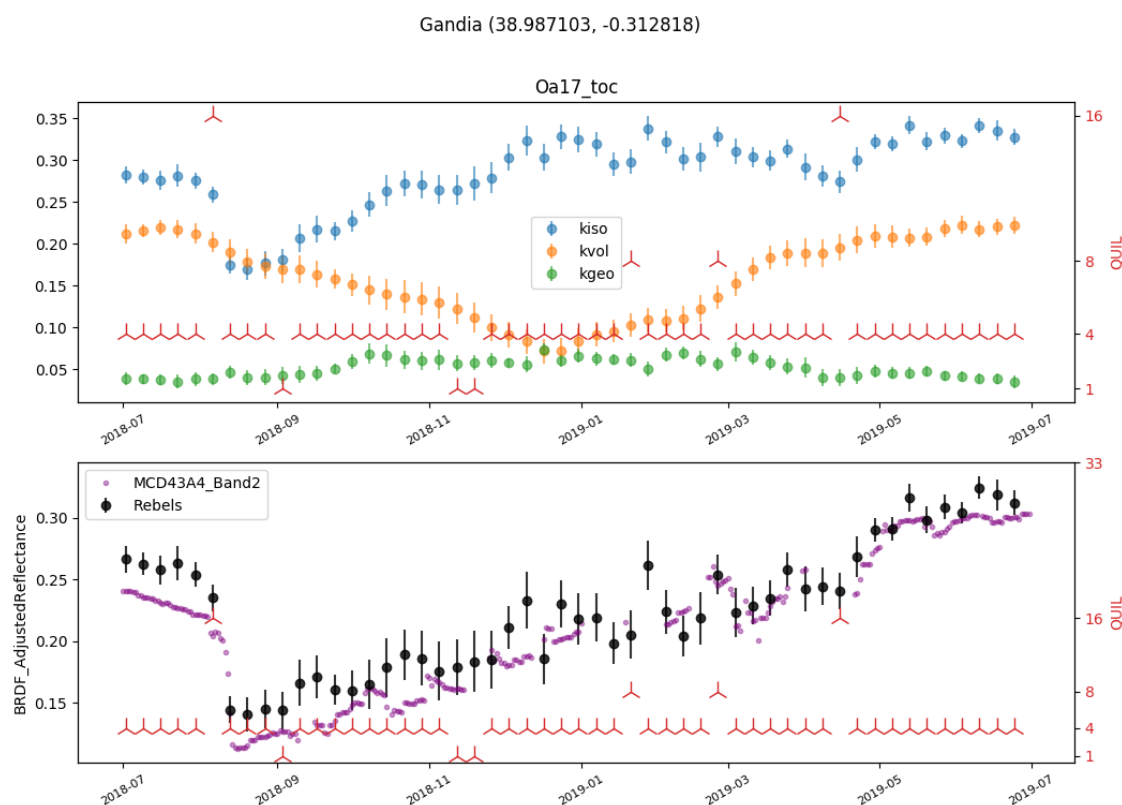
2019 (bottom panel of Figure 11) adds supporting evidence to the later statement. Furthermore, it is important to observe that the BRDF descriptors and BRDF-adjusted reflectance yielded by ReBeLS during periods lacking clear observations align well with the MCD43A4 datasets. This alignment is clearly visible from March to May 2019 in the lower panel Figure 11.



**Figure 11: Same layout as in Figure 6 but for a pixel near Sodankyla, Finland – see geographical coordinates at the top of the figure.**

The prior of BRDF descriptors (based on MODIS MCD43A1 and MCD43A2 products – see section 2.2 for details) used by ReBeLS to optimally estimate BRDF descriptors plays a key role in constraining the BRDF inversion solution. As shown in Figure 11 and discussed in the above paragraph, the prior will dominate the solution in the absence (or scarce availability) of TOC reflectance observations. However, the prior does not significantly influence the BRDF inversion solution when TOC reflectance observations are available and the information to noise ratio (e.g. an ensemble significantly populated with surface reflectance observations for which atmospheric effects were not properly removed will have a low information to noise ratio) in the ensemble of TOC reflectance observations accumulated is high. From Figure 11, it is noteworthy that around April 2019 the surface was snow-covered as seen by MODIS; however, ReBeLS displays a QUIP=1

indicating no data. The later apparent contradiction reflects the severe limitations of the snow-cloud mask in the Sentinel-3 TOC dataset, which misclassifies the snow pixels as clouds [CGLOPS1\_QAR\_S3-CloudMask].



**Figure 12:** Layout is the same as in Figure 6 but for a pixel near Gandia, Spain (see geographical coordinates at the top of the figure). On 8<sup>th</sup> of August 2018 a massive burning of vegetation was reported in a region surrounding this pixel. A sharp drop in Oa17 BRDF adjusted reflectance around this date is evident.

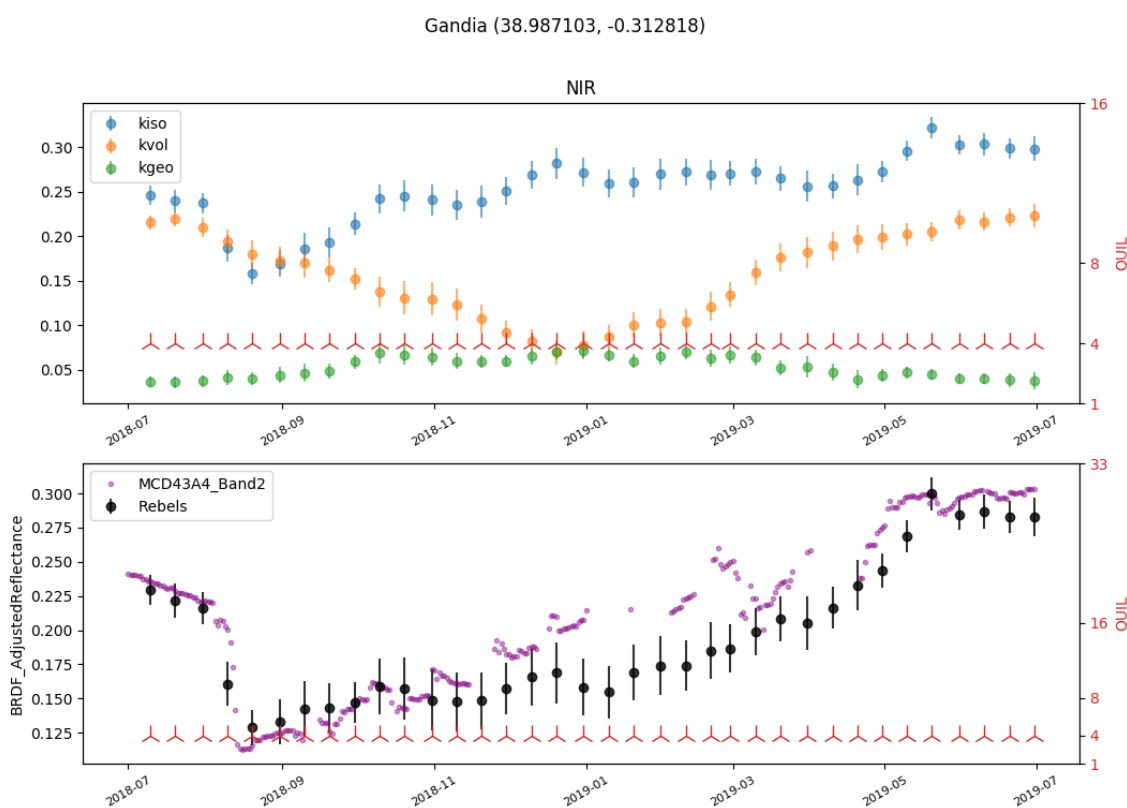
As an example of the later, Figure 12 shows the temporal evolution of BRDF descriptors (top panel) and BRDF adjusted reflectance (bottom panel) for a Sentinel-3 pixel near Gandia, Spain. According to the CCI Land Cover <sup>23</sup> maps (accessed on 15<sup>th</sup> June 2020), the land cover associated to this pixel is tree or shrub cover. Thus, sharp (and rapid variations) as those seen in August 2018 (see Figure 12) cannot be associated to the natural phenological cycle of this site but rather to a reflectance signal characteristic of a sudden and devastating event. Indeed, on 8<sup>th</sup> August 2018 a fire was reported<sup>24</sup> on

<sup>23</sup> <http://maps.elie.ucl.ac.be/CCI/viewer/index.php>

<sup>24</sup> [https://elpais.com/politica/2018/08/08/actualidad/1533709205\\_292531.html](https://elpais.com/politica/2018/08/08/actualidad/1533709205_292531.html)

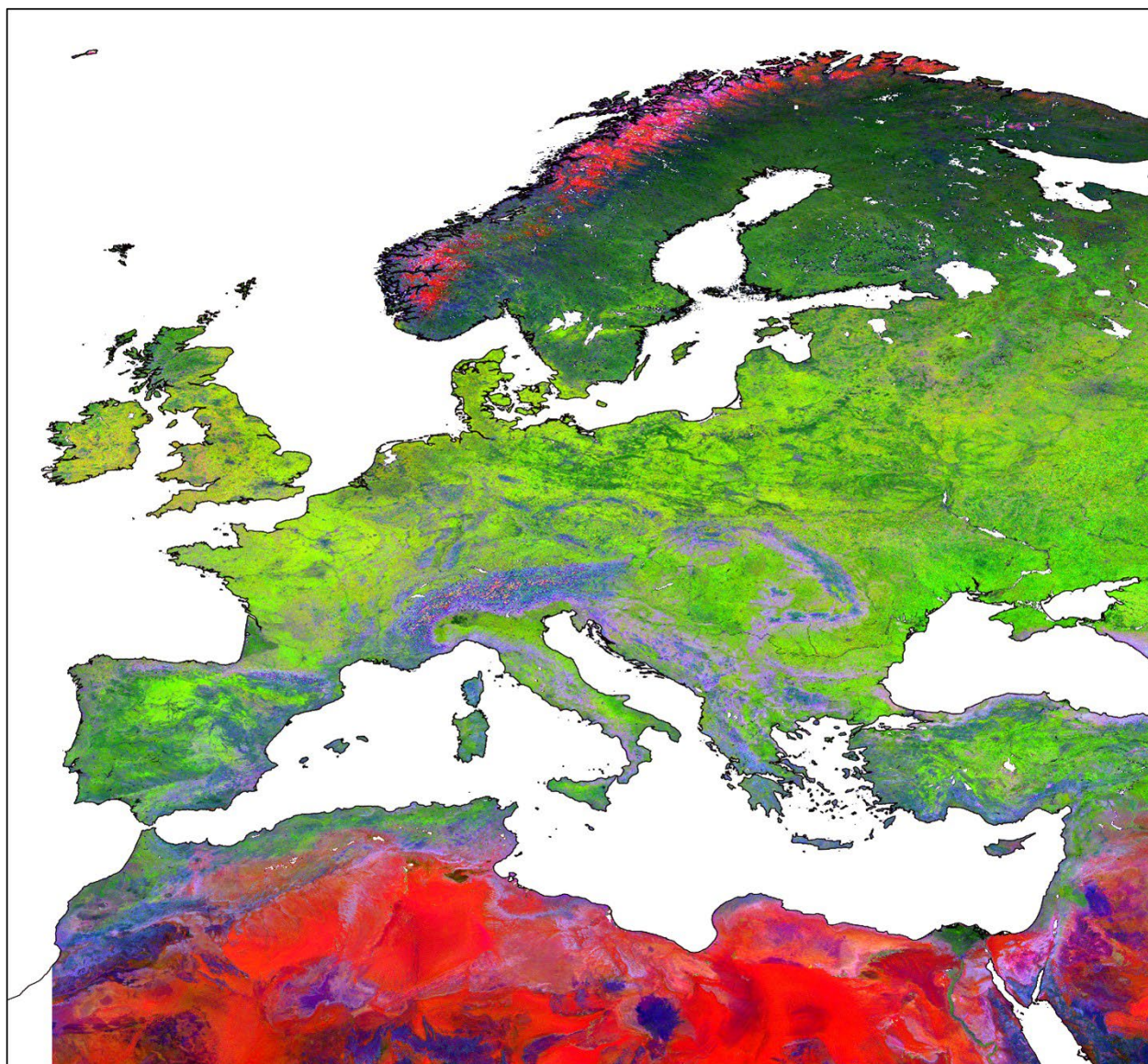
this region. Figure 13 displays the same temporal profiles but for the corresponding PROBA-V dataset.

Despite the usage of a prior of BRDF descriptors, step events (such as fires) can be well described by the methodology presented in this ATBD. The consistency between MCD43A4 NBAR and ReBeLS BRDF adjusted reflectance time series shown in the bottom panels of Figure 12 and Figure 13 adds confidence on the implementation of a BRDF model estimation based on Sentinel-3 and PROBA-V TOC reflectance data.



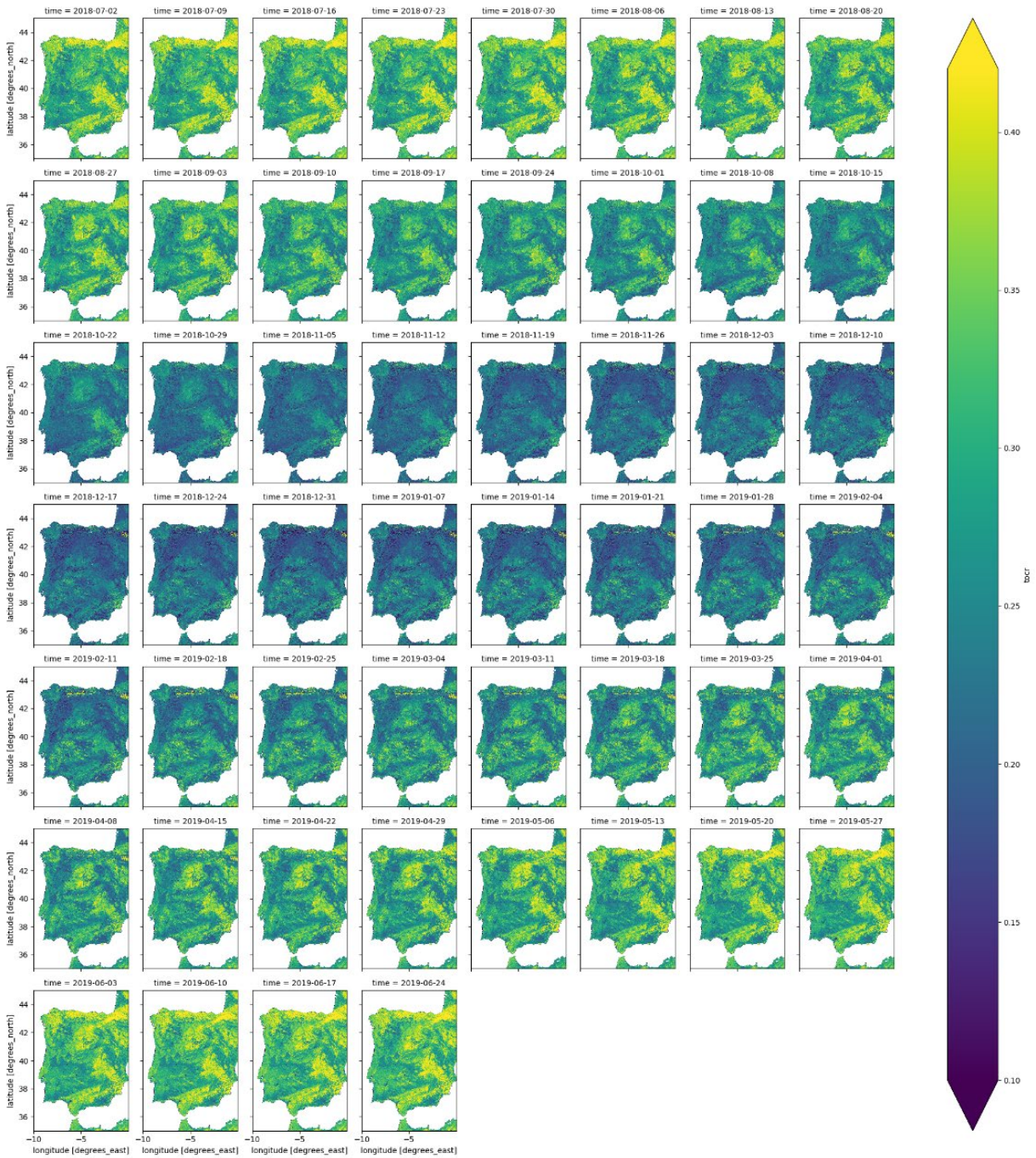
**Figure 13. Same as Figure 12 but for a PROBA-V pixel.**

The spatial consistency of the BRDF descriptors retrievals (for 3<sup>rd</sup> June 2019) at tile scale can be seen in the RGB image (R:  $k_{iso}$ , G:  $k_{vol}$ , B:  $k_{geo}$ ) displayed on Figure 14. At first glance, an agreement between structures in RGB BRDF images and land cover type can be noticed.



**Figure 14: RGB image of the Oa17 BRDF descriptors retrieved for 3<sup>rd</sup> June 2019. The colour channels are as follows: R:  $k_{iso}$ , G:  $k_{vol}$ , B:  $k_{geo}$ .**

Moreover, the temporal evolution of the BRDF adjusted reflectance for Sentinel-3 Oa17 and PROBA-V NIR bands in a  $10^{\circ} \times 10^{\circ}$  tile comprising the Iberian peninsula and Italy can be found in Figure 15 and Figure 16, respectively. From these figures, it is evident that the BRDF adjusted reflectance time series at tile scale follows the expected phenological cycle for the corresponding geographical regions.



**Figure 15: Temporal evolution of Oa17 BRDF adjusted reflectance (TOCR) for tile X17Y03. The BRDF adjusted reflectance time series at tile scale follows the expected phenological cycle for this geographical region.**



Figure 16. Same layout as Figure 15 but for PROBA-V data on file X19Y03.

### 3.5 DIFFERENCE WITH PREVIOUS VERSION V1.3

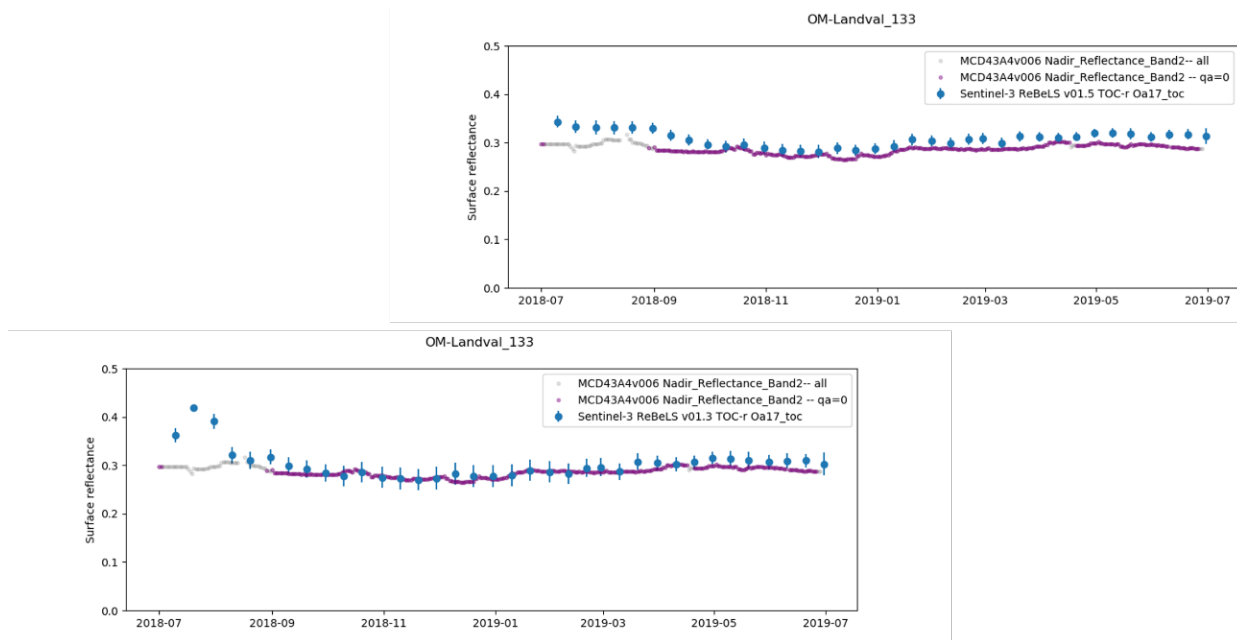
The main changes in ReBeLS v1.6 are listed as follows:

- ReBeLS can now process PROBA-V TOC reflectance datasets.
- Improved outlier detection: The uncertainties linked to the atmospherically corrected Sentinel-3 SLTR TOC data do not account for the radiometric uncertainty associated with the measurements, leading to underestimated TOC uncertainties. A module was incorporated into ReBeLS to address uncertainties limitations by generating additional synthetic uncertainties. Two factors determine these synthetic uncertainties:
  - A comparison with a reference dataset, which in current versions is the MCD43PGF dataset but could potentially be any other reference dataset.
  - An angular weighting factor that considers the geometry of the observation.

The procedure to compute the angular weights is detailed in section 3.2.1.4. However, in specific scenarios, the synthetic uncertainties assigned to outliers were smaller than those provided by the atmospheric correction process. This behaviour was not appropriate, especially in cases where the atmospheric uncertainties were already substantial, indicating the unusability of the measurement. This issue has been rectified in version v1.6, where a conditional check has been implemented to ensure that the synthetic uncertainties assigned to outliers are not smaller than those attached in the atmospheric correction procedure. It is essential to note that this modification impacts the covariance matrix of the observations. Therefore, when solving the matrix system in v1.6, one can anticipate obtaining a posterior covariance that differs from that obtained with version v1.3. This discrepancy manifests as a slight difference, which should not be regarded as significant, in the uncertainties associated with the retrieved BRDF descriptors and the BRDF-adjusted surface reflectance.

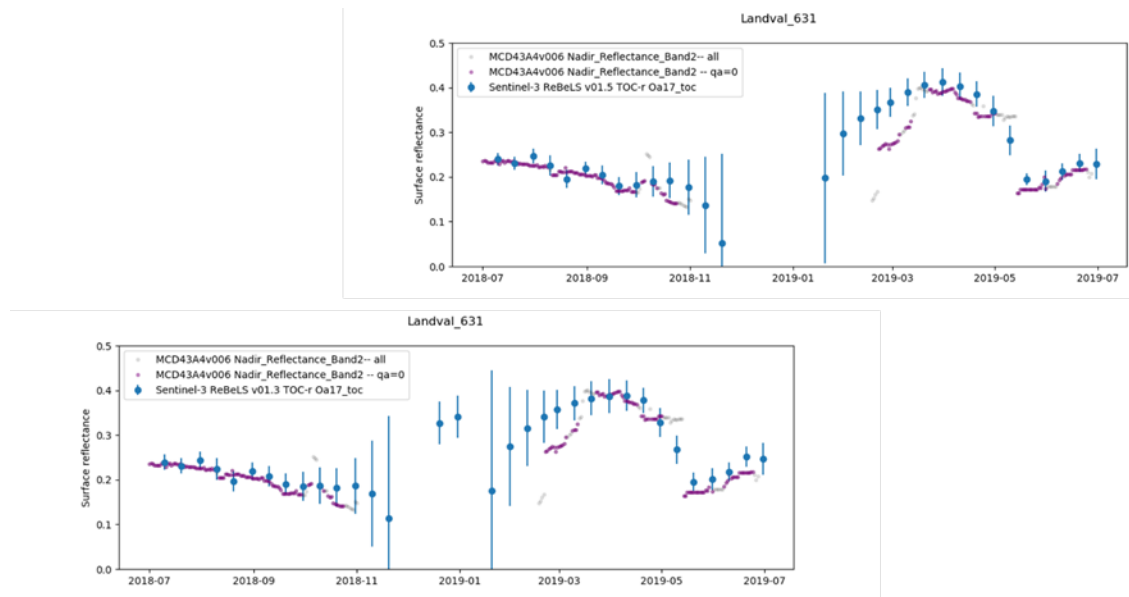
Figure 17 shows the temporal evolution of the NIR BRDF-adjusted surface reflectance for a pixel near the LANDVAL 133 station (lat=21.6045, lon=58.0374). The time series are derived from two versions of ReBeLS: v1.3 (bottom panel) and v1.6 (top panel). For reference, the MCD43A4 product for the same location is overlaid in purple. Notably, the bottom panel of Figure 15 reveals a distinctive elevation, or "bump," in the BRDF-adjusted surface reflectance profile, particularly around the summer of 2018. This bump is unexpected given that the station is characterised as a bare area, where such fluctuations are not anticipated and are likely attributed to outliers ingested during the BRDF inversion process. It is pertinent to observe that during the period when this bump is evident, no high-quality MCD43A4 product is available (denoted by grey dots). This absence of clear observations during this period is likely due to an unusual and persistent cloud cover.

In contrast, the top panel of Figure 15 showcases the BRDF-adjusted surface reflectance profile obtained with the updated version of ReBeLS, v1.6. Here, it is evident that the refined outlier detection strategy effectively identifies and suppresses the spurious deviations in surface reflectance, eliminating the bump observed at the beginning of the time series generated by ReBeLS v1.3. This example underscores the advantages of improved temporal consistency achieved through the updated outlier identification strategy in ReBeLS v1.6. Furthermore, one can observe a slight reduction in the uncertainty associated with the BRDF-adjusted surface reflectance profiles generated by ReBeLS v1.6. This reduction arises from the increased selectivity of the input covariance matrix. Although the difference in uncertainty between the two ReBeLS versions may be discernible, it does not appear to possess statistical significance.



**Figure 17. BRDF-adjusted surface reflectance temporal evolution for a pixel near station Landval 133. Bottom and top panels show the BRDF-adjusted reflectance obtained from ReBeLS v01.3 and v1.6, respectively. Datasets are colour coded, as shown in the legend.**

- Filtering extreme geometries when computing TOCR: ReBeLS v1.3 computed TOCR for all illumination conditions. However, in the northernmost regions, large solar zenith angles at 12PM are reached during wintertime, and these angles can approach a singularity in the analytical expressions used to compute the BRDF kernels. When this singularity point is reached, the surface reflectance model becomes unreliable and cannot be applied. It is worth noticing that such extreme illumination geometries are not frequently encountered. ReBeLS v1.6 introduces a filter to prevent such unusual illumination scenarios. Figure 16 provides an example of the BRDF-adjusted reflectances that are excluded due to their extreme geometries. The figure displays the Oa17 BRDF-adjusted surface reflectance for the Landval site 631 (latitude: 67.031, longitude: 26.219) obtained using ReBeLS v1.3 and v1.6 in the bottom and top panels, respectively. In late December 2018, TOCR computation occurred under extreme illumination conditions, where the Sun was below the horizon. As expected for these high northern latitudes, the scene was in complete darkness during these periods. Consequently, the BRDF kernels computed to estimate the predicted surface reflectance would reach the singularity mentioned earlier, rendering the surface reflectance model unreliable. ReBeLS v1.6 addresses this issue, as depicted in Figure 16, by rejecting predicted surface reflectance values in December under such extreme illumination conditions. These rejected values are no longer included in the BRDF-adjusted dataset, ensuring the quality and reliability of the data.



**Figure 18. Same layout as Figure 17 but for Landval 631 station.**

### 3.6 LIMITATIONS

WIS TOC reflectances are the input of the methodology presented in this ATBD allowing us to retrieve BRDF descriptors and to adjust TOC reflectances to a common Sun-sensor configuration. Therefore, 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 (see section 3.2.1.3), its performance is significantly diminished in periods with a high frequency of cloud occurrence. The latter issue can be augmented when misclassified shadows -- as identified in the current version of the Sentinel-3 TOC reflectances [CGLOPS1\_QAR\_S3-CloudMask] -- are present in the dataset.

BRDF descriptors and BRDF adjusted reflectances (TOCR) estimates are provided each dekad (or any cadence defined by the user) even if no observations were available within that dekad (e.g. see Figure 11). These estimates are significantly dominated by the prior of BRDF descriptors (based on MODIS MCD43A1 and MCD43A2 products – see section 2.3 for details) used by ReBeLS. Since no Sentinel-3 observations are available to verify these estimates (which do follow the temporal evolution of the prior), caution should be exercised when using and interpreting these values.

The MCD43P dataset matches adequately the spatial variability displayed by the Sentinel-3 TOC data at a global scale. However, a caveat to bear in mind is that the MCD43P dataset has been assembled by reprojecting and resampling (these steps can alter the original data) MODIS MCD43A1 and MCD43A2 products from 500m to 333m spatial resolution.

When assembling this climatology of kernel weights MCD43P, the most recent version of the MCD43 suite of products was V006. However, since 2021, an updated version V006.1 is available, and a

potential update of the ReBeLS processor must consider updating the MCD43P climatology by using MCD43 V006.1 products. For other caveats related to the MCD43P dataset, we refer the reader to section 2.3

### **3.7 RISK OF FAILURE AND MITIGATION MEASURES**

In case of Sentinel-3A or Sentinel-3B fails, the amount of data provided by only one of the Sentinel-3 sensors can serve to deliver BRDF descriptors retrievals and BRDF adjusted reflectances. As a probe of the later, the Sentinel-3 TOC reflectance dataset used to develop this algorithm encompasses the period July2018 to Jun2019, though the first half of the Sentinel-3 time series is populated solely by observations acquired with the Sentinel-3A sensor. The latter adds supporting evidence for the ReBeLS BRDF processor being able to deliver adequate results with data from a single Sentinel-3 sensor.

Since the methodology presented in this ATBD is sensor independent, in the unfortunate event of losing both Sentinel-3A and Sentinel-3B satellites, thanks to the algorithm implementation structure of ReBeLS, the data stream of other satellites (e.g. MODIS, VIIRS) can be fed to ReBeLS without requiring a large amount of effort for implementation. Thus, minimizing a large interruption of the near-real time services.

## 4 COPERNICUS BRDF DATA (CBD) PRODUCTS

The output of the algorithm are the BRDF descriptors (CBD\_K) and the BRDF adjusted reflectances (CBD\_TOCR) . The BRDF adjusted reflectances in the NIR and RED spectral ranges are used to perform an arithmetic computation of NDVI and are the inputs for the LSP products within the Copernicus Global Land Service. Therefore, as an aid to users, the main characteristics of these intermediate products are in Table 8 and Table 9.

**Table 8: Information on the ReBeLS BRDF (CBD\_K) product files.**

<b>Data format</b>	GEOTIFF
<b>Cadence</b>	User defined
<b>Naming convention</b>	CBD_K_Tile_SpectralBand_Year_Doy.tif Tile: PROBA-V XY tile grid Doy: day of year Example: CBD_K_X17Y03_Oa17_toc_2019_161.tif
<b>Projection and Grid information</b>	Coordinate System is: GEOGCS["WGS 84", DATUM["WGS_1984", SPHEROID["WGS 84",6378137,298.257223563, AUTHORITY["EPSG","7030"]], AUTHORITY["EPSG","6326"]], PRIMEM["Greenwich",0], UNIT["degree",0.0174532925199433], AUTHORITY["EPSG","4326"]]
<b>Number of layers</b>	9 (see Table 5)

**Table 9. Information on the ReBeLS TOCR (CBD\_TOCR) product files**

<b>Data format</b>	netCDF
<b>Cadence</b>	User defined
<b>Naming convention</b>	<p>CBD_TOCR_Tile_SpectralBand_Year_Doy.nc</p> <p>Tile: PROBA-V XY tile grid</p> <p>Doy: day of year</p> <p>Example:                  CBD_TOCR_X17Y03_Oa17_toc_2019_161.nc</p>
<b>Projection and Grid information</b>	<p>Coordinate System is:</p> <p>GEOGCS["WGS 84",                  DATUM["WGS_1984",                  SPHEROID["WGS                  84",6378137,298.257223563,                  AUTHORITY["EPSG","7030"]],                  AUTHORITY["EPSG","6326"]],                  PRIMEM["Greenwich",0],                  UNIT["degree",0.0174532925199433],                  AUTHORITY["EPSG","4326"]]</p>
<b>Number of layers</b>	4 (see Table 7)

## 5 REFERENCES

- Baret, F., Weiss, M., Lacaze, R., Camacho, F., Makhmara, H., Pacholczyk, P., Smets, B., 2013. GEOV1: LAI and FAPAR essential climate variables and FCOVER global time series capitalizing over existing products. Part 1: Principles of development and production, *Remote Sens. Environ.* 137, 299-309. <http://dx.doi.org/10.1016/j.rse.2012.12.027>
- Bréon, F., Vermote, E., 2012. Remote Sensing of Environment Correction of MODIS surface reflectance time series for BRDF effects. *Remote Sens. Environ.* 125, 1–9. <https://doi.org/10.1016/j.rse.2012.06.025>
- Breon, F.M., Maignan, F., 2017. A BRDF-BPDF database for the analysis of Earth target reflectances. *Earth Syst. Sci. Data* 9, 31–45. <https://doi.org/10.5194/essd-9-31-2017>
- Claverie, M., Vermote, E., Franch, B., He, T., Hagolle, O., Kadiri, M., Masek, J., 2015. Evaluation of medium spatial resolution BRDF-adjustment techniques using multi-angular SPOT4 (Take5) acquisitions. *Remote Sens.* 7, 12057–12075. <https://doi.org/10.3390/rs70912057>
- Franch, B., Vermote, E.F., Sobrino, J.A., Julien, Y., 2014. Retrieval of surface albedo on a daily basis: Application to MODIS data. *IEEE Trans. Geosci. Remote Sens.* 52, 7549–7558. <https://doi.org/10.1109/TGRS.2014.2313842>
- Gao, F., Jin, Y., Li, X., Schaaf, C.B., 2002. Bidirectional NDVI and Atmospherically Resistant BRDF Inversion for Vegetation Canopy 40, 1269–1278.
- Geiger, B., Carrer, D., Franchistéguy, L., Roujean, J.L., Meurey, C., 2008. Land surface albedo derived on a daily basis from meteorological second generation observations. *IEEE Trans. Geosci. Remote Sens.* 46, 3841–3856. <https://doi.org/10.1109/TGRS.2008.2001798>
- Hagolle, O., Lobo, A., Maisongrande, P., Cabot, F., Duchemin, B., Pereyra, A. De, 2004. Quality assessment and improvement of temporally composited products of remotely sensed imagery by combination of VEGETATION 1 and 2 images 94, 172–186. <https://doi.org/10.1016/j.rse.2004.09.008>
- Klisch, A., Atzberger, C., 2016. Operational Drought Monitoring in Kenya Using MODIS NDVI Time Series. *Remote Sens.* 2016, Vol. 8, Page 267 8, 267. <https://doi.org/10.3390/RS8040267>
- Léon-Tavares, J., Gómez-Dans, J., Roujean, J.-L., Bruniquel, V., 2024. Retrieving land surface reflectance anisotropy with Sentinel-3 observations and prior BRDF model constraints. *Remote Sens. Environ.* 302. <https://doi.org/10.1016/j.rse.2023.113967>
- Lewis, P., Gómez-Dans, J., Kaminski, T., Settle, J., Quaife, T., Gobron, N., Styles, J., Berger, M., 2012. An Earth Observation Land Data Assimilation System (EO-LDAS). *Remote Sens. Environ.* 120, 219–235. <https://doi.org/10.1016/j.rse.2011.12.027>
- Lewis, Philip, Guanter, L., Lopez Saldana, G., Muller, J.P., Watson, G., Shane, N., Kennedy, T., Fisher, J., Domenech, C., Preusker, R., North, P., Heckel, A., Danne, O., Kramer, U., Zuhlke, M., Fomferra, N., Brockmann, C., Schaaf, C., 2012. The ESA globAlbedo project: Algorithm, in: *International Geoscience and Remote Sensing Symposium (IGARSS)*. pp. 5745–5748. <https://doi.org/10.1109/IGARSS.2012.6352306>
- Los, S.O., North, P.R.J., Grey, W.M.F., Barnsley, M.J., 2005. A method to convert AVHRR

- Normalized Difference Vegetation Index time series to a standard viewing and illumination geometry. *Remote Sens. Environ.* 99, 400–411. <https://doi.org/10.1016/j.rse.2005.08.017>
- Lucht, W., Schaaf, C.B., Strahler, A.H., 2000. An algorithm for the retrieval of albedo from space using semiempirical BRDF models. *IEEE Trans. Geosci. Remote Sens.* 38, 977–998. <https://doi.org/10.1109/36.841980>
- Maignan, F., Breon, F.-M., Lacaze, R., 2004. Bidirectional reflectance of Earth targets : Evaluation of analytical models using a large set of spaceborne measurements with emphasis on the Hot Spot 90, 210–220. <https://doi.org/10.1016/j.rse.2003.12.006>
- Meroni, M., Fasbender, D., Rembold, F., Atzberger, C., Klisch, A., 2019. Near real-time vegetation anomaly detection with MODIS NDVI: Timeliness vs. accuracy and effect of anomaly computation options. *Remote Sens. Environ.* 221, 508–521. <https://doi.org/10.1016/J.RSE.2018.11.041>
- Muller, J., Lewis, P., Fischer, J., North, P., Framer, U., 2011. The ESA GlobAlbedo Project for mapping the Earth ' s land surface albedo for 15 years from European sensors. *Geophys. Res. Abstr.* 13, 4–5.
- Pokrovsky, I., Pokrovsky, O., Roujean, J., 2003. Development of an operational procedure to estimate surface albedo from the SEVIRI / MSG observing system by using POLDER BRDF measurements II . Comparison of several inversion techniques and uncertainty in albedo estimates 87, 215–242. [https://doi.org/10.1016/S0034-4257\(03\)00166-4](https://doi.org/10.1016/S0034-4257(03)00166-4)
- Quaife, T., Lewis, P., 2010. Temporal constraints on linear BRDF model parameters. *IEEE Trans. Geosci. Remote Sens.* 48, 2445–2450. <https://doi.org/10.1109/TGRS.2009.2038901>
- Roujean, J.-L., Leroy, M., Deschamps, P.-Y., 1992. A bidirectional reflectance model of the Earth's surface for the correction of remote sensing data. *J. Geophys. Res. Atmos.* 97, 20455–20468. <https://doi.org/10.1029/92JD01411>
- Roujean, J., Leon-Tavares, J., Smets, B., Claes, P., Camacho, F., Coca, D., Sanchez-zapero, J., 2018. Remote Sensing of Environment Surface albedo and toc-r 300 m products from PROBA-V instrument in the framework of Copernicus Global Land Service. *Remote Sens. Environ.* 215, 57–73. <https://doi.org/10.1016/j.rse.2018.05.015>
- Roujean, J.L., 2017. Inversion of lumped parameters using BRDF kernels, in: *Comprehensive Remote Sensing*. Elsevier, pp. 23–34. <https://doi.org/10.1016/B978-0-12-409548-9.10346-X>
- Roy, D.P., Zhang, H.K., Ju, J., Gomez-Dans, J.L., Lewis, P.E., Schaaf, C.B., Sun, Q., Li, J., Huang, H., Kovalskyy, V., 2016. A general method to normalize Landsat reflectance data to nadir BRDF adjusted reflectance. *Remote Sens. Environ.* 176, 255–271. <https://doi.org/10.1016/j.rse.2016.01.023>
- Sánchez-Zapero, Jorge, et al. "Global estimates of surface albedo from Sentinel-3 OLCI and SLSTR data for Copernicus Climate Change Service: Algorithm and preliminary validation." *Remote Sensing of Environment* 287 (2023): 113460. <https://doi.org/10.1016/j.rse.2023.113460>
- Samain, O., Roujean, J.L., Geiger, B., 2008. Use of a Kalman filter for the retrieval of surface BRDF coefficients with a time-evolving model based on the ECOCLIMAP land cover classification. *Remote Sens. Environ.* 112, 1337–1346. <https://doi.org/10.1016/j.rse.2007.07.007>
- Schaaf C.B., Liu J., Gao F., Strahler A.H. (2010) Aqua and Terra MODIS Albedo and Reflectance

- Anisotropy Products. In: Ramachandran B., Justice C., Abrams M. (eds) *Land Remote Sensing and Global Environmental Change. Remote Sensing and Digital Image Processing*, vol 11. Springer, New York, NY. [https://doi.org/10.1007/978-1-4419-6749-7\\_24](https://doi.org/10.1007/978-1-4419-6749-7_24)
- Schaaf, C.B., Strahler, A.H., Lucht, W., 2002. First operational BRDF , albedo nadir reflectance products from MODIS.
- Valentine, A.P., Sambridge, M., 2018. Optimal regularization for a class of linear inverse problem. *Geophys. J. Int.* 215, 1003–1021. <https://doi.org/10.1093/GJI/GGY303>
- Vermote, E., Justice, C.O., Bréon, F.M., 2009. Towards a generalized approach for correction of the BRDF effect in MODIS directional reflectances. *IEEE Trans. Geosci. Remote Sens.* 47, 898–908. <https://doi.org/10.1109/TGRS.2008.2005977>
- Wang, Y., Li, X., Nashed, Z., Zhao, F., Yang, H., Guan, Y., Zhang, H., 2007. Regularized kernel-based BRDF model inversion method for ill-posed land surface parameter retrieval. *Remote Sens. Environ.* 111, 36–50. <https://doi.org/10.1016/j.rse.2007.03.007>
- Wang, Z., Schaaf, C.B., Sun, Q., Shuai, Y., Román, M.O., 2018. Capturing rapid land surface dynamics with Collection V006 MODIS BRDF/NBAR/Albedo (MCD43) products. *Remote Sens. Environ.* 207, 50–64. <https://doi.org/10.1016/j.rse.2018.02.001>
- Wanner, W., Li, X., Strahler, A.H., 1995. On the derivation of kernels for kernel-driven models of bidirectional reflectance. *J. Geophys. Res. Atmos.* 100, 21077–21089. <https://doi.org/10.1029/95JD02371>