Quality assessment of Land ECV data products

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Executive Summary

The QA4ECV Global broadband and the QA4ECV Regional spectral albedo, BHR-TIP fAPAR/LAI and global DHR-fAPAR all include uncertainty information on a per pixel basis which is a consequence of the application of optimal estimation techniques used in their retrieval, as described in the land ECVs’ ATBD (D4.3). In this work, we report on the analysis of these land ECVs with respect to (wrt) independent datasets, both for investigating their temporal consistency and their relative and absolute accuracy as well as determining the relationship of uncertainties estimated within the products and their absolute accuracy.

We first assess these new QA4ECV products against EO-derived global satellite products, which usually do NOT contain any uncertainty data and are considered here as relative accuracy assessments. The assessment of the 35 year record against contemporaneous EO albedos shows that we only have one record, CLARA-SAL to compare with for these early years on a global basis. However, CLARA-SAL is based on AVHRR only and the quality of this product judging by the scatter in the CLARA-SAL time series data appears dubious. The next longest record is the 18 years of comparison with VEGETATION and the shortest with MODIS for 16 years. Time series analysis shows consistency in the QA4ECV product apart from three time periods where the data quality is very poor or completely missing (e.g. last quarter of 1994) and the results depend solely on the use of the MODIS prior.

These intercomparisons with other global products suggest that the QA4ECV broadband albedos are brighter than the other datasets with a bias of around +0.085 for the shortwave BHR (SW: 0.4-3µm). Attempts were made to try to find which spectral region the bias comes from and this is reported on here. This bright bias is hypothesized as originating from (a) cloud contamination in GEO or AVHRR even after application of the improved cloud and snow masks or (b) from poor atmospheric aerosol correction in the VIS. Both of these hypotheses are explored.

For SW albedo, in situ measurements from tower-derived albedometer instruments are shown for 13 representative sites worldwide (7 SURFRAD and 6 FLUXNET). Further tower sites are also investigated but the results are not shown here. In D5.2, the full set of tower sites is listed and described. One of the critical areas which is explored is the impact of resolution (scale) as the albedometer subtends a footprint of between 100-500m depending on the height of the tower and the height of the vegetation canopy.

In D5.1, the scaling-up of albedometer measurements from two sites, a CEOS-RADCALNET site known as Railroad Valley, NV, USA (known throughout as RRV) and a savannah site known as Skukuza, South Africa (referred to hereafter as ZA-KRU within the Kruger national park) were employed to provide absolute albedometer validation and how this relates to scale/resolution. Unfortunately, the RADCALNET sites are still not up and running as of the date of this report-writing so this could not be tested on a systematic time series.

For the SURFRAD sites, albedometer measurements were acquired at a height of 10m above ground level (ABGL). These have a projected footprint for these sites of some 126m over the short vegetation (grassland or crops) or desert canopy below. An analysis of the homogeneity
of these sites shows that often the EO-derived values are representative of neighbouring pixels and not the pixel associated with the location of the tower. This is usually because the canopy changes within the pixel size (0.05°) of the retrievals. One possible way to upscale is to select sites which show homogeneity using the spatial semi-variance method developed by Roman et al. (2009). However, this only examines homogeneity in a circular area with a diameter up to 3km which is too small for pixels of around 5 x 5km (~0.05°). An alternative is to look at downscaling using nadir images from other EO satellites, but this is only likely to work for VIS broadband as none of these higher resolution systems, except for LANDSAT-5,7 & 8 or Sentinel-2 MSI have any SWIR channels. This is also a very significant amount of processing.

For Arctic sea-ice albedo, tower values from the SURFRAD Barrow site close to the Arctic ocean are employed as a surrogate for sea-ice because there is no permanent tower site albedometer located on the sea-ice which can be employed instead. A comparison with NASA CAR data is also shown for spectral BRF values. Unfortunately, the ASD spectro-radiometer data collected during the SHEBA campaign has no georeferencing information so it is unusable for this purpose.

For albedo, in all cases we have had to perform the assessment using the SW component as there is no global network of downwelling PAR (0.4-0.7µm) sensors (for calculating the VIS component) or spectral albedo and EO-based measurements as discussed in D5.2 are not appropriate. Unfortunately, although the CEOS-WGCV sponsored RADCALNET data was promised for the last 2 years it has yet to appear even for the RRV site. That is most unfortunate as it would be helpful for looking at BRF scaling.

A new method was developed at UCL for assessing the accuracy of the albedo product and particularly relating this to the uncertainty of the product, by use of the diffuse-to-total ratio for selection of albedometer BHR (“white-sky” days) and DHR (“black sky” days). This method was applied to the 13 tower sites. Very little correlation is evident between this and the corresponding QA4ECV, MODIS Collection 6 and VEGETATION products.

The time coverage varies from tower station to tower station but generally it starts in the mid 1990s for SURFRAD and BSRN, and early 2000s for FLUXNET and OBOP.

Spectral BRF data has rarely been collected at field-scale with most measurements being conducted in the laboratory at grass to individual plant levels. A significant exception and the only working instrument left in the world is the NASA PARABOLA III instrument developed by Don Deering and colleagues originally at the NASA Goddard Space Flight Centre in the US in the 1990s. This was used to collect PARABOLA III data in various large-scale field campaigns and is now being systematically collected over the CEOS-WGCV-IVOS RADCALNET site, RoadRoad Valley, NV, USA since 2009.

The validation of two further products derived from the BHR albedos is included in the second section from FastOpt. These two products consist of the TIP-LAI (Two-stream Inversion Package Leaf Area Index) and TIP-FAPAR (Two-stream Inversion Package Fraction of Absorbed Photosynthetically Active Radiation) datasets using the Two-stream Inversion Package (TIP). The accuracy and reliability of uncertainty are to a large degree determined by the accuracy of the Bi-Hemispheric Reflectances (BHR). These appear to have a bright bias in the VIS BHR of about 0.068 and in the NIR BHR of about 0.103 against
comparable products (GlobAlbedo, MODIS MCD43C3, VEGETATION) as described below. The consequences for QA4ECV-TIP-LAI/FAPAR are shown to be non-negligible.

In the third set of product validations, the Joint Research Centre (JRC) retrieval algorithm is used to derive the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) from daily spectral measurements acquired by the Advanced Very High Resolution Radiometer (AVHRR) onboard a series of National Oceanic and Atmospheric Administration (NOAA) platforms from 1982 to 2006. The input data are the surface Bidirectional Reflectance Factors (BRFs), derived from the normalised surface reflectances provided by the Land Long Term Data Record (LTDR) project (http://ltdr.nascom.nasa.gov).

The methodology itself is based on previous JRC-FAPAR algorithms such as the ones developed for the Medium Resolution Instrument Sensor (MERIS) and the Ocean Land Colour Instrument (OLCI), except surface reflectances instead of top of atmosphere ones are used as inputs. The uncertainty computations follow the main principles described in the Quality Assurance Framework For Earth Observation (QA4EO) guidelines (QA4EO 2012), e.g. using the uncertainties propagation theory.

The DHR-FAPAR report concerns the validation of the QA4ECV-FAPAR-AVHRR products through quality control at global scale from daily to 10-days and monthly period at 0.05° × 0.05° and 0.5° × 0.5° spatial scale, with comparisons at local scale against other space products, i.e. LTDR AVHRR AVH15 and Two-stream Inversion Package (TIP) products, using as inputs the MODIS Collection 6 surface albedo and ‘green’ a priori, and ground-based measurements.
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<td>Algorithm Theoretical Basis Document</td>
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<td>AVHRR</td>
<td>Advanced Very High Resolution Radiometer, a long-term met. system</td>
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<td>BHR</td>
<td>Bi-Hemispherical Reflectance, referred to as “White Sky Albedo”</td>
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<td>BRF</td>
<td>Bi-directional Reflectance, sometimes referred to as reflectance</td>
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<td>CCI</td>
<td>ESA Climate Change Initiative</td>
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<tr>
<td>DHR</td>
<td>Direct Hemispherical reflectance, referred to as “Black sky albedo”</td>
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<td>ECV</td>
<td>Essential Climate Variable</td>
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<td>FAPAR</td>
<td>Fraction of Absorbed Photosynthetically Active Radiation</td>
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<td>Global AVHRR Coverage, a simple subsetting scheme used by NOAA to collect global AVHRR data and reduce the native resolution at nadir form 1.1km to 4.4km (take every 4th pixel in column and 4th pixel in row)</td>
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1. Introduction

The QA4ECV Global broadband and the QA4ECV Regional spectral albedo, BHR-TIP fAPAR/LAI and global DHR-fAPAR all include uncertainty information on a per pixel basis which is a consequence of the application of optimal estimation techniques used in their retrieval, as described in the ATBD (D4.3) for the land ECVs. For albedos this was first demonstrated through the ESA Globalbedo project.

In this work, we report on the analysis of these land ECVs with respect to (wrt) independent datasets, both for investigating their temporal consistency and their relative and absolute accuracy as well as determining the relationship of uncertainties estimated within the products and their absolute accuracy.

The validations of the BHR-TIP and DHR-fAPAR products are described in the respective sections later in this report, so they will not be discussed further here.

Here we focus on an evaluation of the 3 albedo products produced within QA4ECV: the global broadband and regional MISR sea-ice and regional MODIS-like spectral albedo products.

We begin first with an assessment of the input data quality from the AVHRR product which was generated by NASA and NOAA and is referred to as AVH09C1 (Claverie et al., 2016; Franch et al., 2017). This product includes surface reflectance (SR) measured in two wavelengths (red, 580–680 nm, and near-infrared, 725–1000 nm) and resampled at the CMG spatial resolution (0.05º). The SR is normalized for BRDF effects (nadir view and 45° solar zenith angle). This SR was then processed by JRC to retrieve the BRF at the correct time and associated solar and view angles in the original product for subsequent processing into the BRFs employed within the BRDF retrieval. The first version of this product was delivered to UCL in September 2016, six months later than originally expected and planned.

Time series analysis of this product at a global scale showed some serious issues with the underlying dataset containing numerous artefacts. An assessment of the surface reflectance was carried out by Yves Govaerts using a simulation framework described in Govaerts (2015). A step-function in BRF was found between NOAA-16 and NOAA-18 towards the end of 2000. This was previously reported by Heidinger et al (2010) but unfortunately the methods employed in this paper could not be applied to the AVH09C1 time series dataset. A complete re-processing by NASA of the entire time series resulted in a further ten months of delays. The final version began to be processed in the late Autumn of 2017. Examples of these issues are given in the next section.

The cloud and cloud shadow mask was found to be “unfit for purpose” in this product and there was no snow/ice mask product included or available from elsewhere. A machine learning based algorithm was developed and the results from the latter are assessed against the corresponding ones from the MODIS product for coincident time periods.

The EUMETSAT daily surface BRF and associated RPV BRDF parameters and DHR (all computed over a ten day window) were provided from a variety of different years depending on the satellite. These are described further below. A separate assessment of the BRF was made by EUMETSAT which is described in the same section. Subsequently, a better cloud mask was developed but unfortunately too late to be used within the project.
The first assessment made, a “reality check” looking at a time series of the product and comparing the product against other land surface albedo sources on a per pixel basis (referred to here as a relative accuracy assessment) showed an apparent bright bias which is shown and discussed in the relevant section. For the MISR sea-ice product, a comparison is made with coincident NASA-CAR spectral BRF data at the same view and solar angles. For the spectral product over Europe at the same wavelengths as the MODIS product, an intercomparisons is performed against the MODIS spectral BRF products for one overlapping time period in 2005.

To evaluate the absolute accuracy of the output EO-derived broadband and MISR sea-ice albedo product, ground-truth (in-situ) data are needed in order to compare against. Thus, data from several well-established networks such as FLUXNET\(^1\), SURFRAD\(^2\), BSRN\(^3\) and OBOP\(^4\) have been collected. It is well known that instruments from these networks, especially for our selected sites, are regularly calibrated and the data are publicly available.

The selected sites are generally homogenous in land cover, and thus the footprint of site albedometer (10s of metres of diameter projected onto the ground) should be representative of the EO footprint (100s to 100s of metres). This selection criteria is crucial because the spatial resolution of our albedo product is much wider (1km to 0.05º).

Unfortunately, most sites deploy albedometers operating across broadbands , mainly shortwave (~[300nm, 3000nm]) with some exceptions when towers also measure upwelling Near-Infra-Red radiation. However, the accuracy at shortwave should be a very reliable indicator for all the spectral albedos products of QA4ECV because the shortwave product is an aggregation of all spectral albedos. Nevertheless, to verify the later assumption, measurements of Spectral Albedo from a ground-based scanning radiometer called “PARABOLA” are used. However, this is limited to some desert, forest and savannah sites, and for specific dates most of which are pre-2001.

Report D5.2 described the location and characteristics of the in-situ data that is used in the validation of albedo products. So, here we just list the sites with their key characteristics, show their geographic distribution, and present a list of variables that will be deployed. Also, we describe how the comparison was performed. Next, we will talk about PARABOLA instrument and QA4ECV albedo products. Finally, a conclusion summarising the main observations will be discussed.

We complete this introduction with a presentation of the timelines of all the input datasets which were employed by the QA4ECV land ECV products. These are shown in Figures 1-3 below for the input platforms and instruments for polar-orbiters and geostationary systems.

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1 https://fluxnet.ornl.gov/
2 https://www.esrl.noaa.gov/gmd/grad/surfrad/
3 https://www.esrl.noaa.gov/gmd/grad/bsrn.html
4 https://www.esrl.noaa.gov/gmd/obop/
Figure 1. Polar orbiting sun synchronous satellites and instruments used either as inputs (NOAA, SPOT VEGETATION, MISR, MODIS, MERIS + AATSR) or contemporaneous systems not employed in the later years.

Figure 2. Broadband BRF processed from all 5 geostationary satellites. Corresponding date: 2000-02-28T

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<td>MFG</td>
<td>MSG</td>
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Figure 3. Time span of geostationary satellites employed in the combined AVHRR+GEO albedo data product
2. Input AVH09C1 assessment for “fitness for purpose”

In order to assess the input AVH09C1 BRF dataset, daily animations were produced by UCL and the JRC of BRFs of channels 1 and 2. The first author then went through these annual daily animations of tens of thousands of daily BRFs marking up the dates which contained artefacts when they affected a significant amount of the data including the identification of relevant geographical regions affected. An example of a couple of these artefacts are shown in Figure 4 and Figure 5 below.

Thousands of corrupted BRF files were corrected by E. Vermote and co-workers at NASA/NOAA. The new machine learning based snow masks also showed a solar zenith angle dependence when $SZA>70^\circ$. These were partially fixed but for a few years and for a few days each year are still visible as a line artefact in northern Siberia which moves with DoY when the prior data replaces the actual BRF inversions as we go into and out of Arctic polar night.

Figure 4. Examples of artefacts discovered in the first release of AVH09C1. Upper: bad orbits; Lower: issue fixed after new version delivered.
In addition, two “features” of the MODIS priors were found which had to be taken into account within the optimal estimation inversion. Several of the permanent ice areas, particularly Antarctica and Greenland had BRF values > 1. These were rejected resulting in “holes” in the prior which can be observed in Figure 5 below. After changing the thresholds, these were all fixed.

Finally, another problem with the land-water mask became apparent due to the use in the MODIS BRDF product of inversions in shallow seas (depth ≤ 50m) which resulted in artefacts in the Arctic ocean. These were fixed by generating a new land-water mask from the MODIS Prior which eliminated these areas.

![Figure 5](image)

Figure 5. Left: example of missing data caused by BRFs > 1 in the MODIS Prior; Right: after fix was applied.

The CEOS-PICS sites were used to assess the changes in reflectance from AVHRR/2 to AVHRR/3 in 11/2000 which were previously referred to in the paper by Heidinger et al (2010). An example is shown in Figure 6 below and the final processed datasets for two other PICS sites shown in Figure 7 after re-processing by NASA-NOAA.

![Figure 6](image)

Figure 6. Libya-4 CEOS-PICS site showing the “cliff” between AVHRR/2 and AVHRR/3 only visible on bright reflectance sites as the optimisation of the time series of AVHRR was optimised for dark (vegetated targets).
Figure 7. Algeria-1 CEOS-PICS site showing the reduction in the artefact. It should also be noted that there are some breaks in coverage of the input dataset between NOAA-9 and NOAA-11, the large 3 month gap in Q4 of 1994 from NOAA-11 to NOAA-14 and the much better quality of the post-2000 input data.

As there was no snow mask in the AVH09C1 product and the quality of the cloud masks left a great deal to be desired, a new snow/cloud mask was generated from the 5 spectral channels available in the AVHRR product using machine (deep) learning techniques based on 20 features which will be described elsewhere. The resulting land/cloud/snow/water masks for the AVHRR product were then compared for each day from 2000-2016 when AVHRR and MODIS surface reflectance products were available. This showed 95% relative accuracy when compared against the MOD09 masks. A summary of this is shown in Figure 8 below.

Finally, 13.5 million reflectance sample matchups of AVHRR and MODIS with very similar solar and view angles from 2000..2016 were compared to derive the spectral mapping of coefficients between AVHRR BRF1 & 2 and the corresponding MODIS-derived VIS, NIR and SW. These samples are shown in Figure 10 alongside the distributions and spectra mapping coefficients found.
3. Visual assessment of the final QA4ECV albedo products

The final stage in the quality assessment of the final QA4ECV broadband albedo products was performed by generating browse animations for all 35 years and stepping through each and every daily product for all 35 years. No obvious artefacts were detected beyond the ones referred to previously. A similar process of looking through annual animations of daily products was also performed for the spectral sea-ice product at 1km and for the daily European spectral product at 0.05° looking at each spectral band in turn. All of these animations are available on the QA4ECV website.
Figure 9. Sample Quicklook browse products for BHR-SW (upper panel), European spectral albedo at 0.05° for NIR channel 2 (865nm) and 1km MISR BHR-NIR at band 4 (870nm).

Figure 10. Assessment of spectral mapping between MODIS broadband and AVHRR for 13.5 million samples.

For each Global Broadband and every European spectral products, there are 3 quantitative quality measures: namely Weighted number of samples, Relative entropy and Coefficient of Variation (standard error divided by expectation value). Examples of all three are shown in Figure 11 for summer solstice (June 21, 1992). These show the lack of samples in austral night (top), the impact of these on the relative entropy and the areas with low uncertainties due to sufficient cloud-free coverage.
4. Inter-comparison with comparable global and regional products

The initial assessment of QA4ECV albedos is against comparable EO products in order to assess the relative accuracy of the QA4ECV products. Although some rudimentary attempts have been made to validate these comparable products, there is no definitive assessment of their accuracy. In particular, the tower data shown for their assessment is suspiciously free of any outliers.

4.1 QA4ECV Global product inter-comparisons

Intercomparisons were carried out for the QA4ECV broadband product against each of the following comparable products:

- **GlobAlbedo.** This BRDF/albedo product is produced at 8-daily and monthly time-steps at 1km, 0.05° and 0.5° using input data from ESA-ENVISAT MERIS, SPOT-4/5 VEGETATION using optimal estimation with a prior derived from MODIS collection 5 BRDF. An extensive validation report is provided and the product has been independently verified by several other groups.

- **MCD43C1.** Collection 6 of MODIS DHR & BHR products upscaled from 500m to 0.05° (2000-2016) using a temporal window of 16 days moved forward by one day to generate the next daily product. Validation reports in references detailed in.

- **Copernicus Global Land Service.** VEGETATION BHR_only product created at 1/112° (1998-2016) using a 30-day sliding window reported every 10 days. Older product validation reported in.

- **CLARA-A1.** AVHRR-based DHR_only product created at 0.25° globally and over the poles at 25km (1982-2009) using a 7 day window. Product validation in.

As GEO products were ingested into the processing stream for the combined AVHRR+GEO shortwave albedo, the official BHR albedo product was not employed in the subsequent validation. Readers are requested to examine the AlbedoVal-1,2 reports and other support documents which are available here. Although EUMETSAT established a global set of 2186 Surface Albedo Validation Sites (SAVS), only 652 were recommended. Of these only 149 meet the GCOS requirement, of which only 2 have independent tower measurements (ZA-KRU & DE-GEB). These SAVS sites were subsequently ignored in this analysis.

Two different analyses were performed of the QA4ECV product compared against these other 4 comparable products:

- For each coincident day of year, global inter-comparisons were performed for each and every day at the 0.05° resolution with either BHR and/or DHR depending on the product.

- A least-squares linear regression of the SW, NIR and VIS albedos for all 8.5 million pixels was performed which yielded a time series of RMSE, $R^2$, Slope, Intercept, Number. This time series of regression coefficients was then processed to yield mean and standard deviation values for the billions of pixels which were matched up.

For each of these comparisons, a 2D scatterplot was generated for each and every date as well as a side-by-side comparison of albedo values for either BHR and/or DHR.
An example is now given of these side-by-side comparisons of global albedos for all four products for a day of year as close as possible to the start of the 3 seasons (Spring, Summer, Autumn). Three of these are for BHR and the fourth for DHR (as CLARA only has DHR).

In the first intercomparison, QA4ECV vs GlobAlbedo, Figure 12 shows that there are no missing data as these are both gap-free products.

In the second part of the first intercomparison, QA4ECV vs GlobAlbedo, 2D scatterplots are shown in Figure 13 for the same 3 dates in SW (0.4-3µm), NIR (0.7-3µm) and Visible (0.4-0.7µm). In all 3 rows, the bright pixels in the 2D scatterplot are those associated with ephemeral snow and/or permanent ice and the differences between the Northern Hemisphere (NH) summer solstice and the other browse products where there is little ephemeral snow is clear. There appears to be a bright bias for the summer QA4ECV which is reduced at the other two dates for the SW and VIS but there is a bright bias throughout for the NIR.

The second intercomparison, QA4ECV vs MCD43C1, Figure 14 shows that the MCD43C1 product has lots of gaps during each season due to polar nights which are missing in the QA4ECV product whilst Figure 15 shows that the 2D correlations are quite different in the NIR cf VIS with the statistical behaviour of SW being somewhat between the two. There is only a clear bright bias in the NIR Spring equinox inter-comparison.

Figure 12. Inter-comparison of QA4ECV vs GlobAlbedo BHR-SW at dates closest to Spring equinox (DoY=81; 22.3.05), Summer Solstice (DoY=169; 18.6.05) and Autumn Equinox (DoY=265; 22.9.05).
Figure 13. Inter-comparison of 2D scatterplots alongside least squares regression of QA4ECV vs GlobAlbedo BHR-at dates closest to left column, Spring Equinox (DoY=81; 22.3.05), centre column Summer Solstice (DoY=177; 26.6.05) and right column Autumn Equinox (DoY=265; 22.9.05). From the top row, we see SW, NIR and VIS.

Figure 14. Inter-comparison of QA4ECV vs MCD43C1 BHR-NIR at dates closest to Spring equinox (DoY=81; 22.3.05), Summer Solstice (DoY=177; 26.6.05) and Autumn Equinox (DoY=265; 22.9.05). Notice the gaps in the MCD43C1 product due to polar night.
Figure 15. Inter-comparison of 2D scatterplots alongside least squares regression of QA4ECV vs MCD43C1 BHR-SW (top row), BHR-NIR (middle), BHR-VIS (bottom row) at dates closest to left column, Spring Equinox (DoY=81; 22.3.05), centre column Summer Solstice (DoY=177; 18.6.05) and right column Autumn Equinox (DoY=265; 22.9.05).

The third and final intercomparison is with the official Copernicus Global Land Service product based on SPOT-VEGETATION. For this, a comparison with the VIS channel is first shown which demonstrates the latitude cutoff which VEGETATION imposes with no observations acquired over the polar regions.

Figure 16. Inter-comparison of QA4ECV vs VEGETATION BHR-VIS at dates closest to Spring equinox (DoY=83; 24.3.05), Summer Solstice (DoY=174; 23.6.05) and Autumn Equinox (DoY=266; 23.9.05). Notice the gaps in the VEGETATION product due to latitude cutoff.
Figure 17. Inter-comparison of 2D scatterplots alongside least squares regression of QA4ECV vs VEGETATION BHR-SW (top row), BHR-NIR (middle), BHR-VIS (bottom row) at dates closest to Spring Equinox (DoY=83, 24.3.05), left column; Summer Solstice (DoY=174; 23.6.05), centre column and Autumn Equinox (DoY=266; 23.9.05), right column.

The results for VEGETATION in Figure 17 do not show any consistent bright bias for QA4ECV and demonstrate poorer agreement between the two datasets, especially when compared against the other two.

Finally, a comparison was performed of CLARA-A2 against QA4ECV in a similar manner but this time only for DHR-SW as no other channels exist for CLARA-A2. The CLAAR-A2 product also includes DHR for the ocean and the cloud gaps are very obvious, see Figure 18.
The 2D scatterplots along with the least-squares regression results are shown in Figure 19 below which show closer agreement than the other datasets but this is only to be expected as both QA4ECV and CLARA-A2 come from AVHRR sources whereas the other two do not.

Taking the least-squares regression for each and every date when there are match-ups, the variation with time for each parameter of the Least Squares Regression (RMSE, $R^2$, correlation, slope and intercept) of the independent global datasets compared to QA4ECV was calculated. GlobAlbedo is plotted in Figure 20. Next is MCD43C1 in Figure 21, VEGETATION in Figure 22 and finally CLARA-A2 in Figure 23. In all the plots the correlation coefficient $R^2$ is always lower in the winter compared with the summer. The closest agreement shown is between QA4ECV cf. MCD43C1. A suspicion was that this might be due to the use of MODIS prior climatology. However, two factors mitigate against this hypothesis, firstly the GlobAlbedo has a similar (albeit Collection 5) prior climatology and secondly the relative Entropy (see example in Figure 11) does not exhibit any high influence for most of the year except during the polar nights of a strong influence of the MODIS prior. The CLARA-A2 shows reasonable agreement.
Figure 20. Time series of least-squares regression coefficients for every single match-up date for BHR (left column) and DHR (right column) for SW (top panel), NIR (middle panel), VIS (bottom panel) for QA4ECV vs GlobAlbedo.

Figure 21. Time series of least-squares regression coefficients for every single match-up date for BHR (left column) and DHR (right column) for SW (top panel), NIR (middle panel), VIS (bottom panel) for QA4ECV vs MCD43C1.
Taking all the least-squares regression values for all the billions of pixels in the analysis, a table was produced summarising the mean and standard deviation of bias (intercept), correlation coefficient ($R^2$), number of match-ups and number of global inter-comparisons (which is related to the temporal sampling and the time range of each product). The intercept is taken as an approximation of the bright bias. The poorest correlation in all cases is with the NIR. This probably reflects the lack of SWIR sampling (>1µm) by the AVHRR and GEO sensors.
Summary of statistics of billions of matchup pixels for 4 comparable products to the global QA4ECV broadband product. N.B. By far the highest correlation is with the MCD43C1 product. Mean refers to the single value for each entry of all the inputs shown in the following columns.

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<th></th>
<th>intercept</th>
<th>( R^2 )</th>
<th>K correlations</th>
<th>Eastimated total</th>
<th>Npixels</th>
<th>Mean</th>
<th>stdev</th>
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4.2 QA4ECV European Spectral Albedo assessment

The daily spectral albedo reported at the MODIS spectral bands after applying the spectral transformation coefficients are difficult to validate as there are no spectral albedo products at the same wavelengths (VEGETATION is not the same) so the only assessment made is for coincident MCD43C1 for the same dates. An example intercomparison is shown for MODIS band 1 (645nm) BHR spectral vs QA4ECV spectral in Figure 24. For an intercomparison date of 30-April 2000, the results for MODIS band 5 at 1.24\( \mu \)m are rather poor (see Figure 25) but for 1-May-2005 the results look more reasonable (see Figure 25). The dataset in 2000 does not have the benefit of MERIS (as this did not commence until 6/2002) whereas the one in 2005 did. However, this initial look does suggest that we are able to extend the MODIS record back to 6/1998.

A lack of time did not allow a more extensive assessment to be made of the QA4ECV spectral product. Individual users can do this themselves using the time series extraction tool on the main QA4ECV website along with any of the other processed albedo products.
Figure 24. Intercomparison of MODIS spectral BHR albedo at band 1 (645nm) with the corresponding QA4ECV European spectral albedo product at the same band. Over land there are few, if any differences.
4.3 Assessment of MISR Spectral albedo over sea-ice

The only other sea-ice product before the QA4ECV MISR albedo which has been produced is the CLARA-SAL (25km) referred to at the beginning of this chapter. This is derived from AVHRR-GAC data, as is the QA4ECV broadband land product but an earlier version of the GAC data. Very little is discussed in the aforementioned paper about correction of artefacts and the validation is rudimentary. Nevertheless, an analysis was performed for a small sample of the QA4ECV MISR albedo product averaged over the same 5 day time period as CLARA-SAL. An example of the two products in the DHR-SW is shown in Figure 26 below. The sea-ice edges do not agree well and the MISR sea-ice contains so much more detail. A least squares regression was then performed of the DHR-SW which shows differences in slope (see Figure 27), albeit the correlation coefficient is statistically significant given the number of samples.

Figure 25. Intercomparison of spectral albedo between MODIS and QA4ECV for 30-April-2000 (upper panel) and 1-May-2005 (lower panel) showing the high degree of correlation between the two.

Figure 26. Intercomparison of MISR sea-ice (left) vs AVHRR-based CLARA-SAL DHR-SW for the same 5 day time period from 20-25 June 2006, mislabelled as 2007). White=missing data.
A more in depth analysis was performed with MISR and NASA CAR\textsuperscript{13} data acquired during the ARCTAS campaign in 2001\textsuperscript{14}. The flight-paths of the NASA-CAR instrument are shown in Figure 28 along with a MISR An (nadir) image showing the location of the Elson lagoon (purple area) where the intercomparisons took place between MISR spectral BRFs and corresponding CAR spectral BRF at the closest spectral band and closest time in 2001 during the NASA ACRTAS field campaign.

A sample panorama taken from the NASA CAR instrument (see Figure 29) as the aircraft circles at a particular altitude (3 were employed here) focused on one site on the ground so having a fixed view zenith for all view azimuth regions (takes around 2 minutes per circular flightpath). Note the saturated regions on the left & right which correspond to the Sun, and the sky-ground horizon across the centre of the image.
Figure 29. Example of false-colour composite of the NASA-CAR data showing the Sun and its aureole (left and right saturated areas), the blue sky and the ground which is acquired continuously as the aircraft circles around the measurement test site.

Taking all the spatially co-registered matched-up zenith and azimuths corresponding to the MISR spectral BRFs in the 9 MISR views at blue (472nm) and NIR (870nm), a least-squares regression was performed between the matched-up BRFs. The representation in BRDF space for the CAR (background field) and MISR (spots superimposed) is shown in Figure 30 as well as the least-squares regression which shows a strong correlation in the NIR and less so in the blue.
Figure 30. Upper panels show spectral BRDF over Elson lagoon sea-ice from MISR at blue (472nm) and NIR (870nm) whilst lower panels show the least-squares regression of CAR vs MISR data. Note the worse agreement for the blue, probably due to the fact that the CAR data had not been atmospherically corrected.

Taking 3 flight altitudes (200m, 640 and 1700m) we can see from Figure 31 that at NIR, the best agreement between CAR and MISR is at the highest altitude. The shadow of the aircraft at the so-called “hot-spot” can be clearly seen at the lower two altitudes. The weakness of least-squares regression is shown in the central panel of the aforementioned figures as one outlier distorts the results even though the vast majority of the data points are on the 1:1 line.

Figure 31. Intercomparison of NASA-CAR derived BRDF (upper panel) showing range of BRFs from 0.6-1.8 and corresponding least-squares regression between at-aircraft CAR spectral BRF at 870nm and MISR “at ground” 275m spectral BRF (867nm). Three different altitudes for the aircraft are shown (200m, 640m and 1700m) corresponding to pixel sizes of ≈3m, 9m and 25m at nadir and up to 9 times larger at VZA≥70°
Absolute accuracy can only be assessed using independent measurements of albedo. Currently the only mechanism for performing such an independent accuracy assessment is against measurements of shortwave albedo taken from tower sites from different networks.

Data from 166 sites from 4 different networks (FLUXNET, SURFRAD, BSRN) were downloaded and examined. It was decided to focus on all 7 SURFRAD sites in the USA and 4 FLUXNET sites in Europe and 1 BSRN site in Alaska. Table 2 shows the sites recorded together with their location, time period and land cover class.

<table>
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<tr>
<th>Site</th>
<th>Acronym</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Network</th>
<th>Period</th>
<th>Land cover</th>
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<td>Croplands</td>
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<td>2002-2015</td>
<td>Snow and Ice, Tundra</td>
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Table 2. In-situ data from 12 sites used to validate satellite-derived broadband albedo.

Figure 32 shows the spatial distribution of these sites (and a few others) over the globe taken form D5.2. These tower sites represent various land cover types such as cropland, forest, snow, bare soil and savannah. All sites are in US or Europe. The FLUXNET towers are at different heights whereas the SURFRAD towers are all set at 10m which projects an albedometer FoV to around 125m. Figure 33 shows an overhead view of each site taken from Google Earth with a fixed scale-bar of 1500m. Superimposed are 3x3 pixels of 1 x 1km grid either in equal area sinusoidal projection such as for MODIS or equal angle projection (e.g. VEGETATION). Around each tower is the FoV of a tower albedometer set at 40m. In fact this is likely to be one-quarter of this size for the 7 SURFRAD sites. The large distortion of the SIN grid as one nears the pole is obvious as are the skew direction being different on either side of the Greenwich meridian.
Figure 32. Geographical distribution of our selected sites; red: FLUXNET, green: SURFRAD, blue: BSRN, Yellow: OBOP.
Figure 33. Google Earth extracts over the 12 tower sites showing the high degree of variability over each site. Superimposed are 500m footprint of the tower albedometer, 1km MODIS pixels (red skewed grid) and 1/112° VEGETATION equal angle grid (cyan square grid). All images shown with the same scale bar of ≈1500m altitude. N.B. The QA4ECV global broadband and European spectral are both at 0.5° x 0.5°. Tower sites shown in alphabetical order in raster fashion (left-to-right row-by-row) DE-GE, DE-HAI, FR-GRI, IT-REN, SURFRAD–BND, BRW, DRA, FPK, GCM, PSU, SXF, TBL.

There were insufficient resources available to study the impact of comparing tower-based shortwave from the tiny albedometer footprint of 125-500m when compared against the QA4ECV shortwave albedo products of 0.05° x 0.05°. An assessment of these upscaling issues for 2 sites (RailRoad Valley, NV, USA a vicarious calibration site of a fairly uniform salt-pan and Skukuza, a woody savannah site in Kruger National Park, South Africa) taking a variety of different empirical and numerical radiative transfer simulations were performed. These are described in QA4ECV Report no. D5.1 to which the reader is referred.

6. In-Situ data

In previous validation exercises when comparing tower and satellite-based albedo measurements, with in-situ albedo, a Blue-Sky-Albedo (Albedo_{sat}) is generated using both satellite-derived albedo White-Sky-Albedo (WSA) and Black-Sky-Albedo (BSA), and a portion of diffuse irradiance (d) over a fixed time interval (usually an hour around satellite overpass time) using

\[ \text{Albedo}_{sat} = d \times \text{WSA} + (1-d) \times \text{BSA} \]

The value of d (portion of diffuse irradiance) can be extracted from in-situ data in such a way that the time of d coincides with the time of the satellite-derived albedo.

This Albedo_{sat} is then compared to in-situ derived albedo (Albedo_{site}) that represents the portion of incoming total radiation (IN_Total) to the outgoing total radiation (OUT_Total) at certain time.

\[ \text{Albedo}_{site} = \frac{\text{IN}_\text{Total}}{\text{OUT}_\text{Total}} \]

In addition to timestamp and geographic coordinates three variables from in situ data is used in the calculation of albedo:

- Incoming total radiation
- Outgoing total radiation
- Incoming diffuse radiation
The following table gives the names of the variables employed for the 3 networks. Some FLUXNET sites do not provide “Incoming diffuse radiation” (SW_DIF). Thus, another variable captured called Potential Incoming (Top of Atmosphere) is employed. This is WS_IN_POT to estimate the proportion of diffuse component as follows:

\[(SW_{IN\_POT} - SW_{IN\_F})/IN\_POT\]

The above formula was tested and validated using data from sites having SW_DIF.

Table 3. Names of variables for the in-situ data by Network. These variables can be used to calculate the in-situ Blue Sky Albedo and to convert the satellite’s BSA and WSA to blue sky albedo.

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<td>BSRN/OBO</td>
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Although such an approach has a well-established history, it is only an indirect method for assessing the BHR and DHR.

As a result of a separate study funded by the JRC, a different approach was developed and applied here\(^{15}\). This new approach selects dates within a temporal window used for acquiring the EO-based albedo (e.g. 16 days for MODIS every day, 30 days for VEGETATION every 10 days, daily for the QA4ECV product). For each of these windows, it searches for those days when \(d>0.99\) which are referred to as BHRs and when \(d<0.01\) which are referred to as DHR. The tower data are therefore sampled specifically for BHR and DHR and subsequently the validation of the EO data uses the most appropriate tower-based BHR and DHR. An example is shown of the process to extract BHR and DHR (see Figure 34).
7. Time series

To get an idea about the consistency and the continuity of the in situ data the following figures show time series data from the FLUXNET, SURFRAD, and BSRN/OBOP networks respectively and their inter-comparison with data from the EO sources of interest (MODIS, GlobAlbedo and QA4ECV) firstly for BHR from FLUXNET (see Figure 35). For all 4 FLUXNET tower sites, the QA4ECV BHR-SW is higher than the corresponding MODIS and GlobAlbedo BHRs which themselves are also higher than the tower BHR measurements. The thickness of each line in the plot is proportional to the uncertainty for QA4ECV and GlobAlbedo. MODIS does not measure uncertainty. This may be related to the use of GAC sampling in the original AVHRR data or the radiometric adjustments which were made with the AVH09 product. It may also be related to the use of the BHR sampling scheme as numerical radiative transfer simulations (Y. Govaerts, RAYference, private communication) indicate a bright bias due to these fully cloudy conditions. Several of the tower sites indicate unreasonable values (BHR>>1) as well as a great deal of scatter.
Figure 35. FLUXNET site intercomparison of BHR from QA4ECV, MODIS and VEGETATION with corresponding BHR from tower sites.

The next set of plots show the DHR calculated for the FLUXNET sites in Figure 36. In this case the MODIS and GlobAlbedo (with the notable exception of the peculiar behaviour of IT-
REN) are much more closely aligned with the tower DHR and the QA4ECV again shows a significant bright bias.
All of these sites were in Europe with only one site being defined as near homogeneous (DE-HAI) although there is no obvious way of telling this apart from the other 3 FLUXNET sites. Moving to the USA, Figure 35 and Figure 36 show results for all 7 of the SURFRAD sites for BHR & DHR. In the case of BHR, VEGETATION sites are also included in addition to the 3 EO before and in the case of DHR, CLARA-A2 is included. The most obvious point is that the CLARA-A2 is extremely noisy when compared against the other EO data products. This time it is not at all obvious that QA4ECV has a bright bias consistently for all time periods and in one case the tower results are consistently higher (SURFRAD_BND) than the EO results.
Figure 37. Comparison of time series of BHR (left column) and DHR (right column) for all 7 SURFRAD sites investigated. The same EO data products are extracted for the pixel closest to the site of the tower, namely QA4ECV, GlobAlbedo, MCD43C1 and for BHR, VEGETATION is added whilst for DHR, CLARA-A2 is employed. N.B. The thickness of the lines is proportional to the uncertainty for each pixel, where measured (e.g. QA4ECV and GlobAlbedo).

For each tower site, the bias (mean difference) of the BHR or DHR is calculated and plotted for all the EO data products taking the tower data as “ground truth”. These are plotted for all FLUXNET and SURFRAD sites in Figure 38. It is not all clear that QA4ECV has a particular bright bias when compared against the other sites and the fact that often QA4ECV has as many points above as below the zero line suggests that this is not the reason for the bright bias observed in some of the FLUXNET sites.
Figure 38. Comparison of time series of BIAS = BHR - Tower (left column) and DHR - tower (right column) for all 4 FLXUNET and 7 SURFRAD sites investigated. The same EO data products are extracted for the pixel closest to the site of the tower, namely QA4ECV, GlobAlbedo, MCD43C1 and for BHR, VEGETATION is added whilst for DHR, CLARA-A2 is employed. N.B. The thickness of the lines is proportional to the uncertainty for each pixel, where measured (e.g. QA4ECV and GlobAlbedo).
Lastly, an attempt is made to try to assess quantitatively the correlation between the tower measurements and different EO products. Both the BHR and DHR results are shown here for completeness in 4 figures, one pair of BHR for FLUXNET and SURFRAD separately as Figure 39 and Figure 40 respectively as SURFRAD also has a comparison with VEGETATION. A 2D scatterplot table is also shown in Figure 41 for DHR SURFRAD including CLARA-A2. There is no obvious “winner” in this comparison and the lack of time does not allow us to try to establish whether the off-axis points are snow or points in error. Suffice it to say, the spread across the range for tower which is not reflected in the EO datasets suggests that some other factor other than snow may be to blame.

Figure 39. 2D scatterplots of BHR-SW for tower vs GlobAlbedo (left), MCD43C1 (centre) and QA4ECV (right) for the 4 FLUXNET sites.
Figure 40. Intercomparison of tower BHR-SW with GlobAlbedo (leftmost column), MCD43C1 (2nd column), QA4ECV (3rd column), VEGETATION (4th column)
Figure 41. Intercomparison of tower DHR-SW with GlobAlbedo (leftmost column), MCD43C1 (2nd column), QA4ECV (3rd column), CLARA-A2 (4th column)

A final assessment is performed for the sea-ice BHR-SW using the screening criteria for BHR as defined above. This final figure is shown in Figure 42 below. This shows very close results for the BHR with bias ≤±5%. 
An assessment has been carried out of albedo measurements both at the global level for billions of per pixel match-ups against comparable EO products. This indicates that QA4ECV albedos are closest to MODIS. It is not possible to say whether this might be due to the use of the MODIS prior in the optimal estimation or because of the fact that the AVH09C1 product was developed to be as consistent as possible with MODIS to provide long-term continuity. Suffice it to say the product does appear to be very highly correlated with other EO global products, albeit that the correlation for all of these EO products drops substantially in the
NIR. Intercomparisons of QA34ECV spectral albedos over Europe indicate that when MERIS data is available the agreement is very close for all 6 of the MODIS spectral bands. For QA4ECV SW albedo over sea-ice shows some correlation with the pre-existing CLARA-A2 product but significant differences in the value of the correlation. Over the limited number of tower sites, all the tower data (BHR & DHR) have a very high significant amount of scatter when compared with EO, being far from any one-to-one correlation. The lack of resources and time meant that it was not possible to examine this in more depth, especially to employ snow vs nosnow and uncertainty estimates available for GlobAlbedo and QA4ECV. For SW albedo of sea-ice the bias is less than 10%.


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Terms and Acronyms:

ATBD  Algorithm Theoretical Basis Document
BHR  Bi-Hemispheric Reflectance
CCI  Climate Change Initiative
ECV  Essential Climate Variable
FAPAR  Fraction of Absorbed Photosynthetically Active Radiation
LAI  Leaf Area Index, see Introduction for Definition
LUT  Look-Up Table
PUG  Product User Guide
QA4ECV  Quality Assurance for Essential Climate Variables
RT  Radiative Transfer
TIP  Two-stream Inversion Package
TOC  Top Of Canopy
Executive Summary

This document aims to give an overview about the validation studies carried out for version 1.0.1 of the TIP-LAI (Two-stream Inversion Package Leaf Area Index) and TIP-FAPAR (Two-stream Inversion Package Fraction of Absorbed Photosynthetically Active Radiation) datasets as produced in the QA4ECV project. This version is based on version 1.0 of QA4ECV Global Broadband albedo, the broadband visible and near infrared Bi-Hemispheric Reflectances from the same project. It aims to help the user in making a decision on the fitness-for-purpose of the products for their application. Both, value of the variable and reliability of its uncertainty estimate are targeted. Owing to the 1-D approach, TIP-LAI is an effective quantity. Both retrievals, along with their uncertainties are retrieved in a highly efficient manner from look-up-tables (LUTs) of inversions of the Two-stream Model (Clerici et al. 2010; Pinty et al. 2006), which relates Bi-Hemispheric Reflectances (BHRs) to various canopy parameters and fluxes. This is called the Two-stream Inversion Package (TIP). The approach is designed to deliver datasets, which are consistent with the type of near surface radiative transfer models typically used in climate models and the LAI specifications from remote sensing. When comparing with in-situ measurements or 3D-RT simulations, the domain averaging and the homogeneity assumptions of TIP must be taken into account. Also, accuracy and reliability of uncertainty are to a large degree determined by the accuracy of the Bi-Hemispheric Reflectances (BHR), which were reported to have a bright bias in the VIS BHR of about 0.068 and in the NIR BHR of about 0.103 against comparable products (GlobAlbedo, MODIS MCD43C3, VEGETATION; see table 1 of part 1 of this report). However, scatter plots indicate that the structure of the deviation is more complicated than a general bias. This information was not available at the time of the TIP processing. The consequences for QA4ECV-TIP-LAI/FAPAR are shown to be non-negligible.
1 Introduction

1.1 Product name

TIP-LAI and TIP-FAPAR are effective Leaf Area Index and Fraction of Absorbed Photosynthetically Active Radiation. They are retrieved by applying the TIP to visible (VIS) and near infrared (NIR) broadband albedos. TIP is based on the Two-stream Model developed by Pinty et al. 2006, which implements the two-stream approximation of radiative transfer for a homogeneous canopy (“1D-canopy”). This report is based on the input BHRs version 1.0 from QA4ECV. For details on their accuracy and reliability refer to the corresponding project report for QA4ECV Global Broadband albedo validation. TIP uses look-up tables tiptable_version = “V1.3” and product_id = “TIP-QA4ECV”. For validation of the TIP algorithm itself, please refer to the sources listed in the ATBD and the PUG (http://qa4ecv-land.eu/document.php), and to the QA4ECV D5.3 report on the validation against virtual validation sites.

1.2 Purpose and Scope of Document

This document aims to establish an estimate of the accuracy and reliability of TIP-LAI and TIP-FAPAR and their uncertainties in order to help the user in making a decision on the fitness-for-purpose of the product for their application. Firstly, animations were generated and time series at selected locations are shown, and their features discussed. Comparisons to existing products and in-situ measurements follow.

1.3 Definitions

1.3.1 LAI

Here, LAI is defined as half the total canopy area per unit ground area (m²/m²) for a homogeneous canopy of infinitesimally small lambertian surfaces, akin to a turbid medium, consistent with the assumptions of the Two-stream Model of Pinty et al. 2006. It is related to the LAI of a real-world canopy through a canopy-dependent structure factor.

1.3.2 \( \sigma_{\text{LAI}} \)

This is the uncertainty of LAI given as one standard deviation of a Gaussian distribution. Tails outside the physically meaningful range reflect the possibility that the value cannot be consistently retrieved under the assumptions made.

1.3.3 FAPAR

The simulated absorption of the photosynthetically active radiation (estimated for the visible band, VIS) by a homogeneous canopy of infinitesimally small lambertian surfaces, akin to a turbid medium, consistent with the assumptions of the Two-stream Model of Pinty et al. 2006.

1.3.4 \( \sigma_{\text{FAPAR}} \)

This is the uncertainty of FAPAR given as one standard deviation of a Gaussian distribution. Tails outside the physically meaningful range reflect the possibility that the value cannot be consistently retrieved under the assumptions made.
1.3.5 **VIS and NIR bands of input albedos**

Bi-Hemispheric Reflectances (BHR) are used in two spectral broadbands, called visible (VIS) and near infra-red (NIR). For QA4ECV Global Broadband albedo, VIS covers 400–700 nm and NIR covers 700–3000 nm. Here, the spectral range of the VIS band implicitly determines the spectral range of the photosynthetically active radiation (PAR) for the FAPAR computation.
2 Validation of QA4ECV-TIP-LAI/FAPAR

2.1 Introduction

As a first sanity check, global animations were generated from the data set, which allow for a quick check of general plausibility and data coverage (section 2.2). This is followed by a short study on the impacts of an albedo bias on TIP in section 2.3. Time-series at selected locations are compared with in-situ data in section 2.4. Comparisons to existing products are demonstrated in section 2.5. A general caveat has to be issued, for the QA-albedo v1.0 based v1.0.1 product, which is that after processing a general bright bias was found in the QA4ECV Global Broadband albedo. This leads, together with the non-linear nature of the TIP, to errors in the QA4ECV-TIP-LAI/FAPAR which are hard to quantify in a systematic way (cf. Sec 2.3).

2.2 TIP-FAPAR animations

Animations for FAPAR are available through http://qa4ecv-land.eu/movies.php. These animations allow for a quick overview on the data and their quality by presenting various aspects of the retrieval in multiple panels. Currently, for QA4ECV-TIP-LAI/FAPAR, only FAPAR animations are available (select “Broadband”, “daily”, “0.5°” or “0.05°”, a year, and “BHR-TIP fAPAR”).

2.2.1 Method

As shown in Fig. 1 four panels are presented in the animations:

- At the top, TIP-FAPAR itself with the date showing all available inversions, flagged and non-flagged,
- at the bottom left the surface mode used in the TIP-processing,
- at the bottom centre a traffic-light-like data quality panel for missing (red), dubious (yellow) – in the sense that you should hesitate to use it without a clear understanding of its deficiencies), and regular data coverage (green),
- and at the bottom right selected levels of relative uncertainty, limited to data for which, based on the retrieval_flag, the uncertainty is expected to be reliable.

At the bottom margin, the unique tracking ID required by CCI standards (ESA Climate Change Initiative, http://cci.esa.int/sites/default/files/CCI_Data_Requirements_Iss1.2_Mar2015.pdf) is shown for the file from which the information for all four panels is extracted. The two leftmost bottom panels and anything said on the retrieval_flag below concerns LAI and FAPAR alike.

2.2.2 Analysis

Missing data: In the data quality panel at the bottom centre of figure 1, sometimes (on average 1 % of the grid cells or 0.4 % of the area) red areas are visible at high latitudes and some other areas. These mark inputs which were not usable by TIP, because they in turn were either missing, incomplete or physically inconsistent (out of range). For details on the criteria, please refer to the PUG.
Figure 1: Single frame from TIP-FAPAR animation.
**Dubious data:** This panel makes use of the `retrieval_flag` included in the data to mark data which should be treated with special caution or for which no uncertainty estimate can be given. Shown in yellow are all flag vectors matching the bit pattern 0x740, which evaluates to: all high uncertainty in input-flags (high meaning > 20%), untrusted inversion, and inconsistent (but somehow usable) input (cf. PUG at http://qa4ecv-land.eu/document.php for details). The inconsistent-flag typically includes the fairly frequent case of albedo input which is not based on observations, marked by Weighted_Number_of_Samples of the albedo input being zero, for which the albedo algorithm falls back on prior values in the absence of better data. Naturally, this happens frequently over polar night areas, but other areas are also affected, most notably during a gap in the availability of AVHRR data in late 1994. In the final QA4ECV-TIPLAI/FAPAR, the untrusted inversion flag is typically raised for less than 5 % of the pixels, and does only rarely coincide with one of the other flags from this category. Otherwise sane data is flagged high uncertainty in input for about 10 – 20 % of the pixels and for 30 – 40 % of the inconsistent (but somehow usable) pixels, typically totalling about 50 %.

**Good data** This data is good in the sense that no obvious inconsistencies and problems were detected in the processing chain. Exclusively for such grid cells, the 1-sigma rel. unc. panel at the bottom right of the animations shows the relative uncertainty of TIP-FAPAR based on 1 sigma. For very low FAPAR values, as prevalent in deserts, the uncertainty estimate meets the GCOS target requirements (Global Climate Observing System, GCOS Steering Committee 2016), interpreted as a single coverage interval in the way it was defined in the antecedent document of GCOS Steering Committee 2016. However, visual inspection of the animations reveals occasional cloud contamination of otherwise good data, which is not covered by the flags, and would have to be dealt with at the level-1 screening stage. The same applies to biases in the albedo. The remainder of this document will focus on the good data in the sense of this section.

The population of these three data categories of the QA4ECV-TIPLAI/FAPAR are visualised in Figs. 2 and 3. Note that the fallback on prior in the Fall of 1994 leads to a high proportion of flagged data in QA4ECV-TIPLAI/FAPAR. This is due to missing satellite data. The differences between the grid cell based and the area-weighted version is in line with the visual impression from Fig. 1, namely that data with any of the “yellow” flags tends to appear at high latitudes (polar night effect, small area per grid cell), while “good” data tends to be located at lower latitudes (large area per grid cell). Note that the user does not have to follow the choices made for the “yellow” category here, since the retrieval_flag flag vector allows for a very fine grained selection.

Figs. 4 to 6 show in detail the conditions which are summarised in the flags obs_unusable (red), or obs_inconsistent and tip_untrusted (both yellow). Over snow and ice surfaces QA4ECV Global Broadband albedo sometimes shows BHR values larger than 1. Therefore the range ]1..2[ is only flagged...
as obs_inconsistent, cut back to 1 and used in the TIP anyway. Even larger values, as for instance those visible about South-West Ethiopia in the top left panel of Fig. 4 or near Belém, Brazil visible in Fig. 5, are excluded from further processing.

When the Weighted_Number_of_Samples in the albedo data goes to zero, e.g. over areas in polar night, the albedo data has been filled up with the 2005-centred MODIS prior, in order to provide a gap-free product. This condition is grouped with a few others and derogatorily flagged as obs_inconsistent (part of “yellow” flagging, bottom left of the small panels of Figs. 4 to 6).

Some of the “yellow” flagging is caused by TIP itself, namely the tip_untrusted flag, which is raised, whenever the inversion finds a minimum which is in substantial disagreement with prior assumptions or data. Visual inspection of the spatial distribution of incidences of this conditions reveals that the majority is located over bright, non-vegetated surfaces. Another, smaller fraction appears to be caused by cloud contamination or misclassified snowy surfaces (bottom right of the small panels of Figs. 4 to 6).

The bottom Figure of Figs. 4 to 6 summarises the quality flags and corresponds to the red and yellow part of the quality panel of the animations.

2.2.3 Study Summary
The animations of FAPAR along with a visualisation of some key processing information and uncertainty shows some missing and a relatively high amount of dubious data. The remainder of this report will focus on the data which is unaffected by this. Also, for FAPAR, uncertainty estimates locally meet GCOS requirements where FAPAR is very low, but are relatively high in general, especially over certain areas.

2.3 Consequences of the albedo bias
QA4ECV-albedos were reported to have a mean bright bias in the VIS BHR of about 0.068 and in the NIR BHR of about 0.103 against comparable products (GlobAlbedo, MODIS MCD43C3, VEGETATION; see part 1 of this document, QA4ECV Global Broadband albedo verification report, table 1). However, scatter plots of FAPAR between QA4ECV Global Broadband albedo and the individual references indicate that the structure of the deviation is more complicated than a general bias, and especially the correlation of the NIR BHR with reference datasets is significantly lower than the ones of the other bands (SW, VIS; see abovementioned table 1). This information was not available at the time of the TIP processing. In this section, it is shown that the consequences for QA4ECV-TIP-LAI/FAPAR are not negligible.

2.3.1 Method
To demonstrate the potential consequences of a bias in the inputs of TIP, the analysis is built around a dataset which is not known to be biased to such a high degree. Global 0.5 degree albedos from four individual days, evenly distributed over the year from the GlobAlbedo product are taken as a reference
Figure 4: Quality checks of 0.05 degree QA4ECV Global Broadband albedo done prior to TIP-processing, adding to retrieval_flag the conditions obs_unusable (red), obs_inconsistent (yellow) and inversion flag tip_untrusted (yellow), shown for 2010-06-04. The conditions are (top to bottom, left to right): BHR_RANGE_RED – any required BHR >=2, ALPHA_RANGE – inter-band correlation outside [0..1], BHR_RANGE_YELLOW – any required BHR in range [1..2], BHR_HIUNC – any required relative BHR uncertainty > 20 %, WNS_ZERO – Weighted_Number_of_Samples is zero (albedo prior used), TIP_UNTRUSTED – TIP-inversion not trusted, and a combined plot of all the above.
Figure 5: as Fig. 4, but for 2005-01-30.
Figure 6: as Fig. 4, but for 1992-10-18.
point and then offset with the suggested bias. TIP is applied to both datasets. The results are presented as scatter plots. In a second step, white Gaussian noise, N(0,0.1), is added, in addition to the offset. This decreases the correlation with the original data to about 0.85. Again TIP is run on both datasets, original and distorted and the results are presented as scatter plots.

2.3.2 Analysis

Fig. 7 shows the results of the experiment with the offset data. It is obvious that the albedos with the artificial offset are seriously flawed to a degree, that even fitting statistical models cannot revert the effect. Many otherwise small FAPAR values are converted to zero, while higher values are about halved. The effects on LAI are similar, but even more pronounced (not shown). Fig. 8 shows the results of the combined

![Figure 7: Scatter plots of TIP applied to GlobAlbedo BHRs without and with artificial offset for the following dates (top to bottom, left to right): 2005-01-01, 2005-04-07, 2005-07-12, and 2005-10-16. The grey line marks 1:1 correspondence, the red line is the result of an orthogonal distance regression.](image-url)
effects of offsets in the VIS and NIR and noise in the NIR BHR. It appears that a lot of information about the canopy has been removed from the albedo data by the two distorting steps. These results will be referenced in the following sections.

![Graphs representing data from FAPAR res050 0.50deg 2005 001, 097, 193, 289](image)

*Figure 8: As Fig. 7, but with additional noise in the NIR BHR inputs.*

### 2.3.3 Study Summary

The presence of a bias in the inputs for QA4ECV-TIP-LAI/FAPAR has the potential to seriously degrade its quality. It is made worse by an additional error on the NIR BHR, the presence of which is indicated by albedo verification studies (cf. Figs. 20–23 of QA4ECV Global Broadband albedo verification report). This has to be kept in mind when interpreting the comparisons done in the following sections.
2.4 Comparison of QA4ECV-TIP-FAPAR with in-situ measurements

2.4.1 Method

Figure 9: Location of site (yellow pin), intermediate grid (grey lines) and nearest 0.05 degree product grid box (red) for the example of Bondville (US-Bo1, “AGRO” in Gobron et al. 2006). Image: Google Earth

Time series at selected locations are compared with FAPAR from in-situ measurements from the Big-Foot project, and from Gobron et al. 2006 and Gobron et al. 2007, as well as with their own year-to-year variability.

From these, the following sites are selected for presentation here: Bondville (US-Bo1, 40.006° N; -88.291° E, Turner et al. 2005), dominated by agricultural activities, Dahra North (SE-Dhr_North, 15.402° N; -15.432° E, Fensholt et al. 2004), a semiarid grass savanna, and Brasschaat/De Ins slag (BE-Bra, 51.309° N; 4.52° E, Gond et al. 1999), characterised by mixed forest (conifer, broadleaf, and shrub).

For simplicity, effects of the nearest neighbour regridding used in the albedo processing are disregarded. Fig. 9 illustrates this effect: In some cases, the nearest-neighbour regridding may give the red box the values of the grey box from the other side, rather than the one from where the yellow pin is.

2.4.2 Analysis

The time-series composite for Bondville in Fig. 10 show a strong intra-annual variability, with a growing season between May/June and October. For some years there are abrupt changes to FAPAR values above 0.8. These are related to the trajectory in the broadband-VIS/NIR space, which is passing through a region, in which the most probable inversion result changes without transition (also see a discussion of this in Voßbeck et al. 2010). While for these special cases the TIP-approach to uncertainty estimation may call for an extension, the estimated FAPAR value itself is the most probable under the assumptions of the Two-stream Inversion Package. As this behaviour is not as pronounced in TIP-GlobAlbedo results (not shown), it may be a consequence of a regime shift due to the biases present in the QA4ECV v1.0 albedos. Fig. 11
Figure 10: All available years of QA4ECV-TIP-FAPAR from 0.05 degree pixel extraction near Bondville. Values with “yellow” flags are plotted as small dots.

Figure 11: Comparison of observational and FAPAR for Bondville. Uncertainty is not plotted for values with “yellow” flags.
Figure 12: As Fig. 9, but for Dahra North (SE-Dhr_North). Image: Google Earth

Figure 13: As Fig. 10, but for Dahra North.
Figure 14: As Fig. 11, but for Dahra.

shows that the beginning and end of the vegetation period is well detected by QA4ECV-TIP-FAPAR. The maximum and variability, however, are not well matched.

The example of the Dahra North site (Fig. 12) shows a similar picture: noisy year to year variability with a pronounced growing season (Fig. 13). The phase match with the in-situ measurements (Fig. 14) is worse than in the previous example, missing the onset of greening by 2–3 weeks.

The mixed forest site Brasschaat/De Inslag (Fig. 15) has a marked growing season over a FAPAR background of about 0.2, supposedly stemming from non-deciduous vegetation. A faint echo of this behaviour is visible in the superposition of the years in Fig. 16. When comparing the actual year from QA4ECV-TIP-FAPAR with the in-situ measurements (Fig. 17), even less of this signal is visible. It has to be noted, however, that the in-situ data is within the uncertainty bounds of QA4ECV-TIP-FAPAR.

2.4.3 Study Summary

The quality of QA4ECV-TIP-FAPAR and consequently of QA4ECV-TIP-LAI appears to be seriously hampered. While for the differences of the FAPAR definitions used in TIP and the ground measurements along with the grid sampling errors may account for some difference in magnitude, the absence and the missing of signals (green season onset and variability) seen in the comparisons, points at some weaknesses of QA4ECV-TIP-FAPAR. However, these are in line with the potential effects shown for the biases and the low correlation of the BHR NIR in QA4ECV Global Broadband albedo shown in section 2.3. The uncertainty estimates coming with the product were calculated for the assumption of no systematic errors in the albedo input, and have to be considered unreliable for that reason.
Figure 15: As Fig. 9, but for Brasschaat (BE-Bra, “De Inslag” in Gobron et al. 2006). Image: Google Earth

Figure 16: As Fig. 10, but for Brasschaat/De Inslag.
2.5 Comparison of QA4ECV-TIP-FAPAR with existing products

2.5.1 Method

TIP has been used, by JRC (Joint Research Centre of the EC) and FastOpt to process data from various sensors. Existing datasets include:

- 1km global, 16-daily, 2000-2012, TIP based on MODIS BHRs as described in Pinty et al. 2011a,b,
- 1km global, 8-daily, 2002-2011, TIP based on GlobAlbedo BHRs described in Disney et al. 2013; Disney et al. 2016, combining ATSR, AATSR, MERIS, and SPOT VEGETATION, and
- 0.5 degree TIP based on GlobAlbedo, processed as reference within the project.

Almost all of these products have a finer resolution than the 0.05 degree of the QA4ECV-TIP-LAI/FAPAR. For a comparison, this requires a re-gridding to the regular 0.05 degree grid of QA4ECV-TIP-LAI/FAPAR, which is non-trivial due to the non-linear nature of the TIP processing step. Basically TIP-LAI and TIP-FAPAR re-gridded from a finer resolution are more accurate in the sense that they reflect the effect of the anisotropy of the canopy on the scale of the (finer) retrieval resolution, which is not present in the TIP processing of the coarser resolution. On the other hand, re-gridded TIP-LAI and TIP-FAPAR are not consistent with the Two-stream Inversion Package and the re-gridded BHRs any more. The exception from this is nearest-neighbour regridding, which in turn has the downside of taking a single fine resolution pixel to be representative of a potentially much larger coarse resolution pixel. Still, discrepancies in the comparison of TIP-products based on different albedo sources mostly reflect the differences of the albedos. However, by comparing them by their TIP results, this adds another perspective to the albedo quality monitoring. In this section, however, only comparison with TIP applied to GlobAlbedo at the same resolution are shown,

Figure 17: As Fig. 11, but for Brasschaat/De Inslag.
as the GlobAlbedo are taken to be sufficiently representative for other albedo sources, given the large deviations of the present dataset.

### 2.5.2 Analysis

We start with comparing 0.5 degree QA4ECV-TIP-FAPAR with 0.5 degree TIP based on GlobAlbedo. The results in Fig. 18 show little correspondence. The low value of the reduced chi-squared value, \( \chi^2 / (N - 2) \)-value, of the uncertainty-weighted orthogonal distance regression (ODR, with \( \chi^2 \) being the sum of the squared normalised residuals, and \( N - 2 \) being the degrees of freedom; expected value for reliable uncertainties is 1) indicates that the uncertainty estimates provided by TIP capture the problem. However, the cluster of zero-FAPAR may distort this statistics. Fig. 19 shows the corresponding comparison for

![Figure 18: Comparison of global 0.5 degree QA4ECV-TIP-FAPAR with GlobAlbedo (GA) for the following dates (top to bottom, left to right): 2005-01-01, 2005-04-07, 2005-07-12, and 2005-10-16. The grey line marks 1:1 correspondence, the red line is the result of an orthogonal distance regression.](image-url)
QA4ECV-TIP-LAI. In order to check whether reversal of the reported offsets in the VIS and NIR BHRs of

QA4ECV-TIP-LAI Global Broadband albedo can improve the correspondence of QA4ECV-TIP-FAPAR with the TIP-GlobAlbedo reference, TIP was applied to QA4ECV Global Broadband albedo with the offsets removed. However, the results in Fig. 20 indicate, that this is not sufficient to restore the canopy information in QA4ECV Global Broadband albedo. Figure 21 shows the same analysis for QA4ECV-TIP-LAI.

2.5.3 Study Summary

Verification against TIP applied to GlobAlbedo albedos shows the de-correlated behaviour simulated in Fig. 8 of Section 2.3.
Figure 20: As Fig. 18, but with offset input albedos, as described in Section 2.3.
Figure 21: As Fig. 20, but for QA4ECV-TIP-LAI.
2.6 Time series of QA4ECV-TIP-FAPAR at further locations

For overview purposes, time series at a number of locations are included here. Fig. 22 shows the location and grid layouts for further sites used in Gobron et al. 2006, not already covered in section 2.4. Figures 23 to 55 show time series of pixels near the designated locations (for most of the site acronyms refer to FLUXNET; http://fluxnet.fluxdata.org/sites/site-list-and-pages/). Their year-composite time series are shown in alphabetical order. Note that the small dots in the figures are for values with one or more “yellow” flags. The time series mostly show features already discussed in Section 2.4. Additionally, we note the following peculiarities: Fig. 45, “US-Barrow-AK” is a victim of the nearest-neighbour-regridding of QA4ECV Global Broadband albedo and shows all missing values, because a water dominated albedo pixel is referenced at the site coordinates. Also, “IT-SRo” of Fig. 36 shows all missing data, because it is close to the coast and covered by a water-dominated grid box. Fig. 47, “US-Desert Rock, NV” shows a small amount of greening in late 1984, which we could not relate to an irregular precipitation event.
Figure 22: Further sites from Gobron et al. 2006; location of site (yellow pin), intermediate grid (grey lines) and nearest 0.05 degree product grid box (red) for SE-Dhr, SN-Tes, SN-Tes South, US-Ha1, US-Kon, US-Me5, US-Seg, and ZM-Mkt.
Figure 23: As Fig. 10, but for AU-Da2, AU-How, and AU-Tum.
Figure 24: As Fig. 10, but for AU-Wac, BE-Bra, and BR-Cax.
Figure 25: As Fig. 10, but for BR-Ma2, BR-Sa3, and BW-Ghg.
Figure 26: As Fig. 10, but for BW-Ghm, BW-Ma1, and CA-Ca1.
Figure 27: As Fig. 10, but for CA-Ca3, CA-NS1, and CA-NS2.
Figure 28: As Fig. 10, but for CA-NS3, CA-NS5, and CA-NS6.
Figure 29: As Fig. 10, but for CA-SF2, CA-SF3, and CA-WP1.
Figure 30: As Fig. 10, but for CZ-BK1, DE-Geb, and DE-Hai.
Figure 31: As Fig. 10, but for DE-Kli, DE-Tha, and DE-Wet.
Figure 32: As Fig. 10, but for DK-Sor, DOME-C, and ES-ES2.
Figure 33: As Fig. 10, but for ES-LMa, FI-Hyy, and FR-Fon.
Figure 34: As Fig. 10, but for FR-Hes, FR-Pue, and GF-Guy.
Figure 35: As Fig. 10, but for HU-Bug, IE-Dri, and IT-Bon.
Figure 36: As Fig. 10, but for IT-Col, IT-SRo, and Janina.
Figure 37: As Fig. 10, but for Jarvselja-Birch, Jarvselja-Pines, and JP-Mas.
Figure 38: As Fig. 10, but for KR-Kw1, Libya4, and Lope-Forest.
Figure 39: As Fig. 10, but for Nghotto, NL-Ca1, and NL-Lan.
Figure 40: As Fig. 10, but for NL-Loo, Ofenpass, and PT-Esp.
Figure 41: As Fig. 10, but for PT-Mi1, RU-Che, and SE-Dhr.
Figure 42: As Fig. 10, but for SE-Dhr-North, SE-Nor, and Skukuza.
Figure 43: As Fig. 10, but for SN-Tes, SN-Tes-South, and Thiverval-Grignon.
Figure 44: As Fig. 10, but for UK-Gri, US-Aud, and US-Bar.
Figure 45: As Fig. 10, but for US-Barrow-AK, US-Bn1, and US-Bo1.
Figure 46: As Fig. 10, but for US-Bo2, US-Bondville-IL, and US-Boulder-CO.
Figure 47: As Fig. 10, but for US-Desert-Rock-NV, US-Fmf, and US-Fort-Peck-MT.
Figure 48: As Fig. 10, but for US-FPe, US-Fuf, and US-Goodwin-Creek-MS.
Figure 49: As Fig. 10, but for US-Ha1, US-Ho1, and US-IB1.
Figure 50: As Fig. 10, but for US-Ivo, US-Kfs, and US-Kon.
Figure 51: As Fig. 10, but for US-Me5, US-MMS, and US-MOz.
Figure 52: As Fig. 10, but for US-Penn-State-PA, US-Seg, and US-Sioux-Falls-SD.
Figure 53: As Fig. 10, but for US-SRM, US-UMB, and US-WBW.
Figure 54: As Fig. 10, but for US-WCr, US-Wkg, and Wellington.
Figure 55: As Fig. 10, but for ZA-Kru, Zerbolo, and ZM-Mkt.
2.7 Validation of the Uncertainties

As much as possible, uncertainty has been treated along with the validation of the value it describes (see previous sections). In general the uncertainty estimates provided in QA4ECV-TIP-LAI/FAPAR appear to have a realistic magnitude, but also suffer from the offset and noise in QA4ECV Global Broadband albedo for which it is not trivial to account in a systematic way.
3 Validation Summary

QA4ECV-TIP-LAI/FAPAR shows to some degree realistic spatial and temporal patterns. Comparison with in-situ data, comparison with other products, and inspection of the year-to-year variability of the time series, however, reveals that the accuracy is limited. It is shown that a bias in QA4ECV Global Broadband albedo and an apparently high noise level in the BHR NIR band are likely the dominant reasons for the limited quality of QA4ECV-TIP-LAI/FAPAR.
References


QA4ECV

Quality Assurance for Essential Climate Variables

Project Number 607405

Deliverable 5.4: Validation Report for BS-FAPAR AVHRR
Responsible Partner: Joint Research Centre
Delivery date: January 2018
Validation Report for the black sky FAPAR from AVHRR

(Version 1.1)

Nadine Gobron, Jennifer Adams, Christian Lanconelli, Mirko Marioni, Monica Robustelli and Eric Vermote

European Commission
Joint Research Centre
Directorate for Sustainable Resources
a: NASA Goddard Space Flight Center
# Table 1: Change Record

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Terms & Acronyms

AVHRR Advanced Very High Resolution Radiometer
BBL Beer-Bouguer-Lambert
BRF Bidirectional Reflectance Factor
ECV Essential Climate Variable
EO Earth Observation
FAPAR Fraction of Absorbed Photosynthetically Active Radiation
FIPAR Fraction of Intercepted Photosynthetically Active Radiation
GCOS Global Climate Observing System
GLI GLobal Imager
GTOS Global Terrestrial Observing System
JRC Joint Research Centre
LAD Leaf Angle Distribution
LAI Leaf Area Index
LTDR Land Long Term Data Record
MERIS Medium Resolution Instrument Sensor
MODIS Moderate Resolution Imaging Spectroradiometer
NOAA National Oceanic and Atmospheric Administration
NN Neural Network
OLCI Ocean Land Colour Instrument
PAR Photosynthetically Active Radiation
PCA LICOR Plant Canopy Analyzer LICOR
QA4EO Quality Assurance Framework For Earth Observation
QA4ECV Quality Assurance For Essential Climate Variable
RMSD Root Mean Square Deviation
SeaWiFS Sea-viewing Wide Field of View Sensor
TIP Two-stream Inversion Package
TOA Top Of Atmosphere
TRAC Tracing Radiation and Architecture of Canopies
WP Work Package
Executive summary

The Joint Research Centre (JRC) retrieval algorithm is used to derive the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) from daily spectral measurements acquired by Advanced Very High Resolution Radiometer (AVHRR) onboard a series of National Oceanic and Atmospheric Administration (NOAA) platforms (Gobron 2017). The inputs data are the surface Bidirectional Reflectance Factors (BRFs), derived from the normalised surface reflectances provided by the Land Long Term Data Record (LTDR) project (http://ltdr.nascom.nasa.gov, Franch et al. (2017)).

The methodology itself is based on previous JRC-FAPAR algorithms such as the ones developed for the Medium Resolution Instrument Sensor (MERIS) and the Ocean Land Colour Instrument (OLCI), except surface reflectances instead of top of atmosphere ones are used as inputs. The uncertainty computations follow the main principles described into the Quality Assurance Framework For Earth Observation (QA4EO) guidelines (QA4EO 2012), e.g. using the uncertainties propagation theory.

This report concerns the validation of the QA4ECV-FAPAR-AVHRR products through quality control at global scale from daily to 10-days and monthly period at 0.05° × 0.05° and 0.5° × 0.5° spatial scale, with comparisons at local scale against other space products, i.e. LTDR AVHRR AVH15 (Claverie et al. 2016) and Two-stream Inversion Package (TIP) products (Pinty et al. 2011), using as inputs the MODIS Collection 6 surface albedo and ‘green’ a priori, and ground-based measurements.

1 Introduction

The FAPAR is recognised as one of the fundamental Essential Climate Variable (ECV) by Global Terrestrial Observing System (GTOS) (Gobron and Verstraete 2009) and Global Climate Observing System (GCOS) (GCOS 2003; GCOS 2016).

A series of JRC-FAPAR algorithms have been optimised for various optical instruments such as Sea-viewing Wide Field of View Sensor (SeaWiFS) (Gobron et al. 2002), VEGETATION (Gobron et al. 2002b), GLocal Imager (GLI) (Gobron et al. 2002a), MERIS (Gobron et al. 2004; Gobron 2011a), Moderate Resolution Imaging Spectroradiometer (MODIS) (Gobron et al. 2006b; Gobron et al. 2006a) and OLCI (Gobron 2011b).

Validation exercises for the FAPAR values at medium spatial resolution scale have been performed for both SeaWiFS (Gobron et al. 2006) and MERIS (Gobron et al. 2008).

In the context of QA4ECV Work Package (WP) 4, JRC generates daily FAPAR products at 0.05° × 0.05°; including its uncertainties from June 1981 to December 2006. From these daily products, both 10-days and monthly products are derived using time-composite
algorithms. Furthermore regridding process provides dataset at $0.5^\circ \times 0.5^\circ$ for being used in global change studies.

The retrieval value aims to extract the ‘green’ FAPAR at the times of data acquisition in the plant canopy (and the angular rectified channels in the Band 1 and Band 2) from various NOAA platforms.

In this report, we first check the quality of the long time series over the QA4ECV validation sites, defined in Gobron et al. (2015), from 1982 to 2006 using monthly products. In addition 10-days products are plotted over 2003-2004 against the 16-days JRC TIP that are processed using MODIS surface albedo Collection 6 under ‘green’ foliage assumption (see Pinty et al. 2011). The 3D-RT model simulations over the virtual scenes provide information of the expected differences between diffuse and direct values.

Secondly, ‘validation’ is assessed through comparison against time-series of past in-situ data, together with LTDR AVHRR FAPAR products (Claverie et al. 2016) and Two-stream Inversion Package (TIP) (Pinty et al. 2011) using as inputs the MODIS Collection 6 surface albedo and ‘green’ a priori. The overall results are discussed versus the source of problem using results from D3.7 Lanconelli et al. (2017). The comparison between Earth Observation (EO) products and ground-based estimations of FAPAR is presented using the same categorisation of the ground-based FAPAR datasets according to their most probable radiative transfer regimes as already done in Gobron et al. (2006).

Thirdly, global 10-days products are compared against SeaWiFS ones for two years, i.e. 1999 and 2003 at $0.05^\circ \times 0.05^\circ$ as these two years correspond to AVHRR2 and AVHRR3 satellites, respectively. Both bias and Root Mean Square Deviation (RMSD) are reported together with AVHRR FAPAR uncertainties and the spatial standard deviation of SeaWiFS that are regridded from native spatial resolution, i.e. 1 km products. Note that such comparisons are done only over the ‘best’ grid-cells that are defined by minimising the cloud/cloud shadow occurrences in both products.

Finally, analysis of comparisons of monthly products at $0.5^\circ \times 0.5^\circ$ is then performed by assessing the averaged monthly bias to possibly create a long term bias corrected dataset.

## 2 Products overview

### 2.1 Definition

FAPAR results of multiple fluxes measurements balance within plant canopies.

‘Total’ FAPAR (absorbed component) comes from the energy balance between sources and sinks, with positive inputs corresponding to:
• Incoming PAR at the top of the canopy (direct and/or diffuse);
• Incoming PAR from propagating horizontally (mostly important at very high spatial resolution);
• Light reflected by the underlying ground (soil and/or understory)

and losses corresponding to:
• Outgoing PAR reflected by the canopy (top and bottom)
• Outgoing PAR propagating horizontally

Leaves-only FAPAR refers to the fraction of PAR radiation absorbed by live leaves only, i.e., contributing to the photosynthetic activity within leaf cells.

This quantity is lower than ‘total’ FAPAR because it does not include PAR absorption by the supporting woody material (in forest) or by dead leaves (in crops). This is illustrated in section 3.1 with the help of 3D-RT simulations over QA4ECV validation scenes.

2.2 Earth Observation

The space retrieval method used in QA4ECV project assumes that the leaves are alive and photosynthesising, hence the name ‘green’ FAPAR.

It also means that the single scattering albedo of leaves is ‘fixed’ to only one value representing such ‘green’ leaves. This assumption is also used as ‘a priori’ when performing the TIP retrieval processing.

While FAPAR is typically based on an instantaneous measurement, for climate change applications representative daily values are required. They may be obtained through direct measurements, or by assuming variation with the cosine of the solar zenith angle to obtain the daily green FAPAR.

FAPAR products defined as a balance of multiple fluxes depends on the atmospheric conditions prevailing at the time of the measurements. In particular, estimates can be generated using direct, diffuse, or global radiation inputs. Knowledge on the type of incoming solar radiation fluxes is essential to properly interpret the data.

Similarly FAPAR can also be angularly integrated or instantaneous (i.e., at the actual sun position of measurement). As is the case for the surface albedo, one can define FAPAR estimates for a variety of atmospheric conditions and integrated in angles, space and times as needed.

QA4ECV FAPAR refers here to the instantaneous, i.e. black-sky, and green definition.
The theoretical FAPAR, values used in optimisation procedure are computed using the closure of the energy balance inside the plant canopy in the spectral range 400 to 700 nm (see Gobron 2017.)

**TIP-FAPAR refers to the diffuse, i.e. white-sky, and green definition.**

The FAPAR of the LTDR products, noted AVH15, is based on artificial neural networks (NN) calibrated using the MODIS FAPAR dataset (Claverie et al. 2016). The main algorithm is based on lookup tables (LUT) simulated from a 3-D radiative transfer model (Knyazikhin et al. 1998). The output is the mean FAPAR values computed over the set of acceptable LUT elements for which simulated and MODIS surface reflectances agree within specified level of (model and measurement) uncertainties. This NN is optimised over 6 land cover classes and no FAPAR values retrieval over bare or very sparsely vegetated area.

**AVH15-FAPAR refers to the direct, i.e. black-sky, at local noon and polychrome definition.**

### 2.3 Ground-based products

Past significant efforts were devoted to the validation of surface products such as FAPAR generated from data acquired by MODIS (Huemmrich et al. 2005; Wang et al. 2004; Shabanov et al. 2003). Ground-based FAPAR products correspond to physical quantities that can be measured in the field with different but **significant levels of difficulty**.

Impacts of different types of internal variability of the extinction coefficient together with the resolution of the sampled domain on the radiation transfer regime for clouds was analyzed by Davis and Marshak (2004) and they established the conditions where 3-D effects are anticipated to play a major role in the establishment of the radiation transfer regime. Gobron et al. (2006) extrapolated their results to the case of land surfaces by associating the main radiative transfer regimes against statistical properties of the leaf extinction coefficient inside the spatial domain of investigation. Therefore, the ‘fast’ variability regime is associated in the case of statistically homogeneous, Poisson-like, distributions of the leaf density, the ‘slow’ variability regime where the leaf density distribution (LAD) is close enough to being homogeneous only locally such that local scale average flux values are meaningful and the ‘resonant’ regime in other cases where the spatial complexity is such that a typical photon beam samples various types of structures between entering and escaping the canopy. Table 2 summarises the approach to assess the FAPAR value over the different sites used in this report and Table 3 the geolocation of field site together with their categorisation and land cover type.
Table 2: Ground-based measurements types

<table>
<thead>
<tr>
<th>Field site Identification</th>
<th>Summary of the approach for domain-averaged FAPAR estimations</th>
</tr>
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<tbody>
<tr>
<td>SN-Dhr</td>
<td>based on BBL’s law with measurements of the LAD function</td>
</tr>
<tr>
<td>SN-Tes</td>
<td>FAPAR(µ₀) derived from the balance between the vertical fluxes</td>
</tr>
<tr>
<td></td>
<td>⟨LAI⟩ derived from PCA-LICOR</td>
</tr>
<tr>
<td>US-Seg</td>
<td>based on BBL’s law with an extinction coefficient equal to 0.5&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>⟨LAI⟩ derived from specific leaf area data and harvested above ground biomass</td>
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<tr>
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<td>advanced procedure to account for spatio-temporal changes of local LAI</td>
</tr>
<tr>
<td>US-Bo1</td>
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</tr>
<tr>
<td></td>
<td>⟨LAI⟩ from leaf area per plant area and plant density</td>
</tr>
<tr>
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<td>advanced procedure to account for spatio-temporal changes of local LAI</td>
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<tr>
<td>US-Ha1</td>
<td>based on BBL’s law with an extinction coefficient equal to 0.58&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>⟨LAI⟩ derived from optical PCA-LICOR data</td>
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<tr>
<td></td>
<td>advanced procedure to account for spatio-temporal changes of local LAI</td>
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<tr>
<td>BE-Bra</td>
<td>based on full 1-D radiation transfer models</td>
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<tr>
<td></td>
<td>⟨LAI⟩ derived from optical PCA-LICOR data</td>
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<tr>
<td></td>
<td>time-dependent linear mixing procedure weighted by species composition</td>
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<td>US-Me5</td>
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<td>advanced procedure to account for spatio-temporal changes of local LAI</td>
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<tr>
<td>ZM-Mkt</td>
<td>based on FIPAR estimated from TRAC data</td>
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<td>slight contamination by the woody canopy elements</td>
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<sup>a</sup> taken as constant, *i.e.*, independent of the Sun zenith angle.
Table 3: Anticipated radiation regime\(^{(a)}\) of field sites

<table>
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<tr>
<th>1 ‘Fast variability’</th>
<th>2 ‘Slow variability’</th>
<th>3 ‘Resonant variability’</th>
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<tr>
<td>Short and homogeneous over 1-2 km</td>
<td>Mixed vegetation with different land cover types</td>
<td>Intermediate height and low density</td>
</tr>
<tr>
<td>SN-Dhr (^{(b)})</td>
<td>US-Bo1(^{(c)})</td>
<td>US-Me5(^{(c)})</td>
</tr>
<tr>
<td>semi-arid grass savannah</td>
<td>corn and soybean</td>
<td>dry needle-leaf forest</td>
</tr>
<tr>
<td>SN-Tes(^{(b)})</td>
<td>US-Ha1(^{(c)})</td>
<td>ZM-Mkt(^{(e)})</td>
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<tr>
<td>semi-arid grass savannah</td>
<td>conifer/broad-leaf forest</td>
<td>shrub-land/woodland</td>
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<td>US-Seg(^{(c)})</td>
<td>BE-Bra(^{(d)})</td>
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<tr>
<td>desert grassland</td>
<td>conifer/broad-leaf/shrub forests</td>
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<tr>
<td>US-Kon(^{(c)})</td>
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<tr>
<td>grassland/shrub-land/cropland</td>
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</tr>
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</table>

\(a\) Based on Davis and Marshak 2004’s analysis.
\(b\) See Fensholt et al. 2004.
\(c\) See Turner et al. 2004.
\(d\) See Gond et al. 1999.
\(e\) See Huemmrich et al. 2005.
3 Quality control of FAPAR time series over the QA4ECV validation sites

QA4ECV FAPAR retrieval is designed separately for each NOAA platform from 07 to 16 taken into consideration their own spectral responses in both Band 1 and Band 2. We therefore expect to have no drift into the time series of FAPAR, except the inter-seasonal and inter-annual variations over vegetated canopies. Of course, inputs data impact the output products quality and uncertainty. The following sub-sections discuss the FAPAR results over the QA4ECV birch and pine forests, tropical forests, crops and shrub/savannah sites, respectively. The green (red) dotted symbol indicates the best composite value in the case of clear-sky (LTDR cloudy) pixel. Grey shaded bar is the daily uncertainty of representative day and the error bar represents the standard deviation during the temporal period.

3.1 Background: FAPAR over QA4ECV scenes

Table 4 summarises the geolocation and land cover type of the QA4ECV validation sites over which the results are presented. Figures 1 to 4 illustrate the range values depending on various FAPAR definitions. The left hand side panels show the ‘foliage’ absorption as function of AVHRR sun zenith angle (dotted symbols) in 2003 and under diffuse radiation condition (dashed line) for the scenes used over validation sites. The right hand side panels illustrate the same but for the total component. One must notice that the seasonality, in the figures 1 to 4, is not the actual one but the DHR-FAPAR variation as function of the local sun zenith angle at the acquisition time. Each colour correspond to a virtual scene used in the simulations. The black diamonds indicate the value of current sun zenith angle for the AVHRR acquisition. These results are mainly used to discuss results in the next sections.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude (°N+)</th>
<th>Longitude (°E+)</th>
<th>Land Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jarvselja-1</td>
<td>58.313</td>
<td>27.297</td>
<td>Birch Stand</td>
</tr>
<tr>
<td>Jarvselja-2</td>
<td>58.277</td>
<td>27.296</td>
<td>Pine Stand</td>
</tr>
<tr>
<td>Ofenpass</td>
<td>46.663</td>
<td>10.230</td>
<td>Pine Stand</td>
</tr>
<tr>
<td>Lope</td>
<td>-0.169</td>
<td>11.459</td>
<td>Tropical Forest</td>
</tr>
<tr>
<td>Nghotto</td>
<td>3.867</td>
<td>17.300</td>
<td>Tropical Forest</td>
</tr>
<tr>
<td>Zerbolo</td>
<td>45.295</td>
<td>8.877</td>
<td>Short Rotation Forest (Poplar)</td>
</tr>
<tr>
<td>Thiverval-Grignon</td>
<td>48.85</td>
<td>1.966</td>
<td>Wheat</td>
</tr>
<tr>
<td>Wellington</td>
<td>-33.600</td>
<td>18.933</td>
<td>Citrus Orchard</td>
</tr>
<tr>
<td>Skukuza</td>
<td>-25.0197</td>
<td>31.4969</td>
<td>Savannah</td>
</tr>
<tr>
<td>Libya4</td>
<td>28.55</td>
<td>23.39</td>
<td>Desert</td>
</tr>
<tr>
<td>Janina</td>
<td>-30.077</td>
<td>144.136</td>
<td>Shrub land</td>
</tr>
<tr>
<td>Dome-C</td>
<td>-75.100</td>
<td>123.300</td>
<td>Snow</td>
</tr>
</tbody>
</table>

Table 4: QA4ECV Validation Sites
Figure 1: Time series of diffuse and direct FAPAR over QA4ECV forest sites using actual sun zenith angles of AVHRR. Left and right hand side panels correspond to foliage and total component, respectively.
Figure 2: Same as Figure 1 but over QA4ECV tropical forest sites.
Figure 3: Same as Figure 1 but over QA4ECV crops sites.
3.2 Monthly time series over 1982-2006

The following section presents the time series of monthly AVHRR FAPAR products at 0.05° × 0.05° over the QA4ECV validation sites. The following subsections present results in accordance to each land cover type.

3.2.1 Birch stand and pine stand forest sites

The birch stand/pine stand forests sites results are plotted in Figure 5. Green (pink) circle symbols correspond to FAPAR best representative value that are not affected by cloud during each month over vegetation (soil). Red circle symbols indicate LTDR cloud flag meaning that no clear sky days were found during the time composite period.
Figure 5: Time series of monthly FAPAR products over QA4ECV forest sites

The shade bars indicate the uncertainties of this best day whereas the error bars represent the temporal standard deviations during a month. The inter-annual seasonalties over 1982 and 2006 are in general well represented expect over few months for which outliers are detected. The level over Ofenpass is very low comparing to Jarvselja-1 even so the same land cover, i.e. scene was assigned. The theoretical range of FAPAR that is expected over pine stand summer (winter) virtual scene over Ofenpass varies from 0.3 (0.2) to 0.6 (0.3) depending on the sun zenith angles. Over Jarvselja-1 we have slightly higher values. Using actual EO data, we found rather a bigger differences which may be explained by a wrong scene associated to Ofenpass. During northern
hemi \text{sphere winter seasons}, bright surfaces are detected over this site so null FAPAR values. Over Jarveljja-2 monthly products still provide a lot of data contaminated by clouds, especially during winter seasons.

3.2.2 Tropical forest sites

The two tropical forest sites long time series are plotted in Figure 6. The values over Lope present lower FAPAR values comparing to Nghotto and their respective maxima are 0.4 and 0.6, which is lower comparing to 3D-RT model simulations (see Figure 2). However, Lanconelli et al. (2017) show that when the retrieval algorithm is applied to simulated surface reflectance results are much higher than with real data: this means that atmospheric correction may suffer from clouds contamination at the $0.05^{\circ} \times 0.05^{\circ}$ as it is often the case over these tropical regions.

![Figure 6: Time series of monthly FAPAR products over QA4ECV tropical forest sites](image)

3.2.3 Crops sites

FAPAR time series over three different types of crops are plotted in Figure 7. The top panel shows short rotation poplar forest over Zerbolo site. The middle and bottom panels correspond to wheat and citrus orchard crops, respectively. Over this latter site, few outliers appear: one in 1998 and various in 1994 when inputs data suffer from three month of missing data and artefacts in south
hemisphere. One can notice that the products represent very well the expected seasonality over crops each year with high level during summer at about 0.7 over Zerbolo.

Figure 7: Time series of monthly FAPAR products over QA4ECV crops sites

3.2.4 Shrub and Savanna sites

FAPAR time series over shrub and savanna sites are displayed in Figure 8. The top panel reports the results over Skukuza site whereas the bottom one shows the shrub land FAPAR evolution.
over Janina site. Over both sites, few outliers appear in the three month of missing data and artefacts in 1994 for which only one day of results is available (indicating by the absence of error bar). The overall seasonality of both vegetation are well represented during the entire long period.

Figure 8: Time series of monthly FAPAR products over QA4ECV shrub and savanna sites

3.3 Two years of 10-days and TIP comparisons

This section shows the 10-days QAECV AVHRR FAPAR over 2003-2004 period together with the 16-days JRC TIP FAPAR at 1 km derived from MODIS albedo Collection 6. As already mentioned, QA4ECV AVHRR FAPAR values correspond to direct absorption of ‘green’ foliage, meaning that the FAPAR values depend on the actual sun zenith angle, whereas the TIP values provide the diffuse FAPAR values. The expected differences, from a theoretical point of view, are assessed using the 3D-RT model simulations as function of the day of the year over each site using respective 3D scene(s) from Figure 1 to Figure 4.
3.3.1 Birch stand and pine stand forest sites

Three panels in Figure 9 illustrate two years of 10-days AVHRR and 16-days JRC TIP FAPAR over Jarvselja-1, Jarvselja-2 and Ofenpass sites, respectively. Dotted green dots represent the QA4ECV results with error bar for the temporal standard deviation during the 10-days period and uncertainty with shade grey colour.

Figure 9: Time series of 10-days FAPAR products over QA4ECV forest sites with JRC TIP C6
When results are associated with a LTDR cloud mask, the formers are plotted in red colour. Bar soil flag are displayed in pink colour. JRC TIP are over-plotted in blue colour triangle symbols. During summer months the results between the two land algorithms agree well over the three forest canopies but are slightly different over Ofenpass site for which AVHRR FAPAR provide lower values: this can be due to the difference between diffuse and direct values as shown in bottom panel in Figure 1. During winter months, there is no result provided by AVHRR or un-trustable due to cloud/snow contamination contrary to TIP as this retrieval algorithm can assume a prior snow background.

3.3.2 Tropical forest sites

Two panels in Figure 10 illustrate the 10-days AVHRR and 16-days JRC TIP FAPAR over tropical forest sites over 2003-2004. Dotted green dots represent the QA4ECV results with error bar for the temporal standard deviation during the 10-days period and uncertainty with shade grey colour.

Figure 10: Time series of 10-days FAPAR products over QA4ECV tropical forest sites with JRC TIP C6

When results are associated with a LTDR cloud mask, the formers are plotted in red colour. Bar soil flag are displayed in pink colour. JRC TIP are over-plotted in blue colour triangle symbols.
symbols. Over Lope site, top panel, TIP retrieved less results than AVHRR ones that can be due to low level of quality in MODIS albedo due to recurrent cloud contamination over tropical zone. Its level is however high with value around 0.5 which is anyway lower than the expected theoretical values, \( i.e. \ 0.7 \), found in top panel of Figure 2. The values of direct FAPAR are low comparing to theoretical value which can be explained by the leaf single scattering albedo assumed in JRC algorithm. Over Nghotto site, bottom panel, the two products provide same amplitude variability except during summer months.

### 3.3.3 Crops sites

Figures 11 and 12 show the 10-days AVHRR and 16-days JRC TIP FAPAR over three crops sites over 2003-2004. Dotted green dots represent the QA4ECV results with error bar for the temporal standard deviation during the 10-days period and uncertainty with shade grey colour. When results are associated with a LTDR cloud mask, the formers are plotted in red colour. Bar soil flag are displayed in pink colour. JRC TIP are over-plotted in blue colour triangle symbols. Seasonality and amplitude of both products agree well with expected crop phenology over the three types of crop. Over Wellington site, covered by citrus orchard, TIP values are always higher. This maybe due to the spatial scale difference of products as TIP is at 1 km and AVHRR at 0.5°. One can notice higher seasonal variation with AVHRR products.

![Figure 11: Time series of 10-days FAPAR products over two QA4ECV crops sites with JRC TIP C6](image)
Figure 12: Time series of 10-days FAPAR products over QA4ECV Wellington site with JRC TIP C6

3.3.4 Savanna and shrub sites

Figure 13: Time series of 10-days FAPAR products over QA4ECV shrub and savanna sites with JRC TIP C6
Finally, both panels in Figure 13 show the 10-days AVHRR and 16-days JRC TIP FAPAR over Skukuza and Janina sites, respectively covered by savannah and shrub-land. Dotted green dots represent the QA4ECV results with error bar for the temporal standard deviation during the 10-days period and uncertainty with shade grey colour. The seasonalities of such canopies are well represented by both products with TIP values always higher than the AVHRR ones and in agreement with theoretical values. Here again spatial variability and assumption in the leaf single scattering albedo may be explain this difference.
3.4 Quality control of rectified channels in Band 1 and Band 2 over CEOS validation site

The rectified channels are surface reflectances decontaminated from angular effects. Time stability of the signal is expected in both channels. Top and bottom panels of Figure 14 display Band 1 and Band 2 results, respectively. In both channels, we can see various issues at the end of 1984, 1887 and 2006 and at the beginning of 1989. There are few outliers that are presented at the same times in both channels and provide lower values compared to averaged ones. These values come from daily inputs Top Of Atmosphere (TOA) artefacts that are propagated to the rectified channels.

Figure 14: Time series of monthly Rectified Band 1 and Band 2 products over QA4ECV CEOS site
4 Validation using ground-based measurements

The QA4ECV FAPAR products are now compared against ground-based measurements already used in Gobron et al. (2006). Table 2 summarizes the ground-based methodology information. In addition, daily products that used the same surface reflectance data (Claverie et al. 2016) and 16-days TIP FAPAR green products using as inputs the MODIS albedo Collection 6 are plotted in green diamonds and blue triangle colour symbols, respectively.

Figure 15: Time series associated with radiation transfer regime 1.
Figure 15 displays the time series of the space FAPAR products together with the ground-based estimations available from five sites, located in Senegal, i.e. SE-Dhr [15.366°N, -15.432°E]; SE-Dhr North [15.402°N, -15.432°E]; SN-Tes [15.883°N, -15.05°E] and SN-Tes South [15.816°N, -15.05°E], and in US over Sevilleta, US-Seg [34.35°N, -106.69°E], all associated with radiation transfer regime 1, corresponding to the so-called ‘fast variability’ category. The baseline FAPAR value over these sites is very low and signatures of the different vegetation phenological cycles (both for the growing and senescence periods) are remarkably well identified by both space and ground-based estimations.

Moreover, the amplitudes, both maxima and minima, are in very good agreement with all products although the space retrievals tend to slightly underestimate the ground-based values over the site of SN-Dhr during the peak season for 2001 (top left hand side panel). Indeed, at this latter site the landscape exhibits significant spatial heterogeneity at mesoscale which was not sampled by the ground-based measurements (and thus was not accounted for in the FAPAR ground-based estimations) but which was probably captured at the resolution available from the satellite FAPAR products. AVH15 is slightly larger than both AVHRR and TIP products, specially over the desert-grassland (bottom panel). Both TIP and AVHRR FAPAR products agree well within their respective uncertainties.

Figure 16: Time series associated with radiation transfer regime 2.

Results over vegetation conditions belonging to the ‘slow variability’ category, that is radiation transfer regime 2, are displayed in Figure 16. In the case of BE-Bra site [51.309°N, 4.52°E] (top
left hand side panel) the amplitudes in 1997 between the start and end of the growing season estimated from both remote sensing and ground measurements are in very good agreement. However QA4ECV results are suffering from cloud contaminations (blue dots) from June to August. The ground-based estimated FAPAR values over the agricultural field site identified as US-Bo1 [40.006°N, -88.291°E] follow a well-defined time trajectory that is correctly tracked by the QA4ECV FAPAR products (red dots) and JRC TIP (triangle) (top right panel of Figure 16). Daily AVH15 (green diamonds) reveal higher level than other measurements until June and after September. The third comparison performed with regime 2 canopy conditions, is conducted at the Harvard site (identified as US-Ha1) which is a mixture of conifer and hardwood forests. Results from TIP and QA4ECV data sets (bottom left hand side panel on Figure 16) compare very well with each other and ground-based measurements for the first 6 months of the year which includes the growing period. All space products then show systematically lower values than the ground-based estimations during the summer season where vegetation gets very dense over the site. The largest difference occur during the senescent period where a time delay of about 1 month is observed between the FAPAR signatures given by space and ground-based datasets. Both remote sensing and ground-based estimations of FAPAR over the US-Kon tallgrass prairie site [39.089°N, -96.571°E] indicate the occurrence of a well-marked vegetation seasonal cycle (bottom right hand side panel on Figure 16). JRC TIP and QA4ECV estimations are well correlated along the cycle over this site covered by mixed grassland/shrub land and cropland, although the JRC FAPAR products are slightly biased low. Such a bias occurring during the period of senescence is a consequence of using total (in ground-based estimations) instead of green (as assumed in the retrieval algorithm) values when assessing the FAPAR values as illustrated in Figure 3.

The comparison results of ground-based and space retrieved FAPAR over the US-Me5 site [44.437°N, -121.56°E], associated with regime 3 are shown in the top left hand side panel on Figure 17. The two main interesting findings are that 1) both sources of information indicate no strong seasonal cycle, as could be expected over this ponderosa pine conifer forest, and 2) the discrepancy in the FAPAR amplitudes between space and ground-based datasets is extremely high (about a factor of 2). Both TIP and QA4ECV products show same amplitude of values whereas AVH15 do not provide values, maybe because of no expected values are retrieved. Interestingly this is a typical class of vegetated canopies deviating significantly from the 1-D statistically homogeneous situation. In that instance, the classical Beer-Bouguer-Lambert law of exponential attenuation applies only if the 3-D radiative effects are adequately parameterised which is not the case in the ground-based measurements.
The additional ground-based dataset associated with regime 3, identified in Table 3 is over ZM-Mkt [-15.438°N; 23.253°E], derives from a collection and analysis of the canopy gap fraction using the TRAC instrument over two consecutive years in a mixed shrub-land/woodland environment. Figure 17 (top right hand side and bottom panels) shows the time series of the space FAPAR products for year 2000, 2001 and 2002 together with the measurements (in terms of FAPAR spatial averages and associated standard deviations) collected by the TRAC instrument over three transects of 750 m at a spatial resolution of about 1.7 cm. These data include a numerically small correction to account for the 3D contributions. During both wet seasons, that is, approximately from September to January, the agreement between space data and ground-based estimations is good. By contrast, AVHRR QA4ECV FAPAR products are systematically biased low, by about 0.2 on average, during the two dry seasons, although the uncertainty ranges of both estimations do overlap and the correlation between the two estimations always remains quite high. This is not the case with the JRC TIP and AVH15 products as their values agree well with ground-based measurements. One may keep in mind that the remaining contamination of the FIPAR measurements by the woody (non-green) elements of the canopy favours the occurrence of a bias greater than 0.1 with respect to the QA4ECV FAPAR values as shown in Figure 4. This feature is expected to be higher during dry seasons when the relative contribution to the extinction process by the leaves only is decreasing, especially with such a low density canopy (the $\langle LAI \rangle$ varies approximately in the range [1-1.5] during the dry seasons Privette et al. (2004)).
5 Global product comparisons against SeaWiFS data

This section presents the comparison between QA4ECV and JRC SeaWiFS products at two temporal and spatial scales. The first exercise focuses on the daily products at 0.05°×0.05° whereas the second analysis presents the comparisons of monthly products at 0.5°×0.5°. This latter analysis shows that, despite a bias, both long time series can be used together by applying a bias correction as done in Gobron and Robustelli (2013) for global change studies.

5.1 Daily products at 0.05°×0.05°

Daily QA4ECV AVHRR FAPAR products are benchmarked against SeaWiFS over two years, i.e. 1999 and 2003. SeaWiFS products are derived using the same type of land retrieval method (Gobron et al. 2002; Gobron et al. 2006) except that the inputs are from the top of atmosphere measurements.

Figure 18: Direct comparisons between daily AVHRR and SeaWiFS FAPAR products in 1999. Only valid grid-cells for which JRC flag in AVHRR products is set to vegetated area and where there is less than 50% of clouds in SeaWiFS ones are plotted.
In order to minimise the impact of remaining cloud effects in AVHRR dataset (such as the red dotted points in previous section) and in SeaWiFS aggregated products, data are filtered by keeping only the grid cells that contain less than 50% of cloudy pixels at 1km. Figures 18 and 19 show the scatter-plots for individual month in 1999 and 2003, respectively.

Figure 19: Direct comparisons between daily AVHRR and SeaWiFS FAPAR products in 2003. Only valid grid-cells for which JRC flag in AVHRR products is set to vegetated area and where there is less than 50% of clouds in SeaWiGS ones are plotted.

Daily statistics are reported in Figures 20 and 21. Bias and RMSD are plotted in red and pink colour, respectively. In addition the spatial standard deviation within SeaWiFS is displayed in green whereas the uncertainties of AVHRR FAPAR in blue. We can see that for 1999 and 2003, bias (RMSD) values are lower than 0.05 (0.10) during winter days but increase during summer days. These values are always smaller when comparing against the actual uncertainties of FAPAR, i.e. $\sigma$, except over various month for the RMSD. The spatial deviation within SeaWiFS values at the same order of the uncertainties of daily AVHRR FAPAR. In 1999, both values of bias and RMSD are higher comparing to 2003, this may be due to inter-calibration bias between platform NOAA14 and NOAA16.
Figure 20: Daily bias and RMSE in 1999

Figure 21: Daily bias and RMSE in 2003
5.2 Monthly products at 0.5°×0.5°

This subsection displays the mean average bias between SeaWiFS and AVHRR monthly products at 0.5°×0.5°over 1998-2003 period. Figure 22 illustrates the monthly mean bias over the globe for individual month. Reddish (blueish) colour shows negative (positive) values. In general SeaWiFS FAPAR values are lower over lower vegetated canopies, such as over Australia and south of Africa, mainly during north hemisphere winter season and higher over other land cover types.

Figure 22: Average monthly bias between SeaWiFS and AVHRR FAPAR over 1998-2003

A monthly pixel by pixel bias correction is applied for rectifying the AHRR monthly products to further use them together. Figure 23 shows the scatterplot of 12 months by 6 years with histogram of differences. We can see that the mean difference <δ> is at −0.09 with σ = 0.0974. When we apply the correction using values of maps displayed in Figure 22, the comparison show the reduced scatters in Figure 24 where < δ > drops to 0.0002 and σ = 0.0449.
Figure 23: Scatterplots between monthly SeaWiFS and AVHRR FAPAR over 1998-2003.

Figure 24: Scatterplots between monthly SeaWiFS and Corrected AVHRR FAPAR over 1998-2003.
6 Conclusion

In this report, we validate and check the quality of the QA4ECV black-sky FAPAR long time series products at $0.05^\circ \times 0.05^\circ$ and $0.5^\circ \times 0.5^\circ$ at either daily, 10-days and monthly period.

Over the QA4ECV validation sites, defined in Gobron et al. (2015), monthly products at $0.05^\circ \times 0.05^\circ$ from 1982 to 2006 are used to check inter-annual variations and to identify outliers. Moreover the 10-days products are compared over 2003-2004 against the 16-days JRC TIP (using MODIS surface albedo Collection 6 as inputs and under ‘green’ foliage assumption) and their comparison shows that both products seasonality is well retrieved except when snow and cloud contamination exists. Their level of divergence is within the expected one due to various assumptions in their retrieval algorithm, mainly from diffuse and direct definitions.

Validation, through comparison against time-series of past in-situ data together with LTDR AVHRR FAPAR products and TIP, is presented using the categorisation of the ground-based FAPAR datasets according to their most probable radiative transfer regimes. Due to the spatial scale change between these ground-based measurements and QA4ECV products, we find a relatively good agreement. Further additional analysis are however needed to take into account of the spatial scale deviation.

We compare the global 10-days products against SeaWiFS ones for two years, i.e. 1999 and 2003 at $0.05^\circ \times 0.05^\circ$. Both bias and Root Mean Square Deviation (RMSD) are reported together with AVHRR FAPAR uncertainties and the spatial standard deviation of SeaWiFS and we find larger differences in 1999 than in 2003. However both bias and RMSD values are at the same order that the QA4ECV uncertainties.

The last section shows that monthly bias at $0.5^\circ \times 0.5^\circ$ can be used to correct the QA4ECV AVHRR black-sky FAPAR products for future analysis of global change over terrestrial surfaces.

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References


