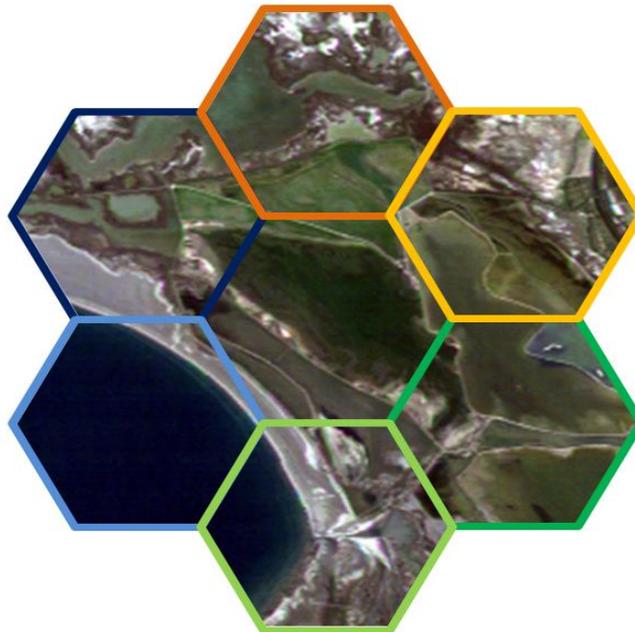


**ARGANS and ARESYS proposal in response to ESA ITT  
“Earth Observation Multi-Mission Phase-E2 Operational Calibration: assessment of enhanced and new methodologies, technical procedures and systems scenarios”:**

**MOSAEC – Methodologies for Operational Systems:  
Assessment of Enhanced and new Calibration approaches.**

***EXECUTIVE SUMMARY***



	<p>“Earth Observation Multi-Mission Phase-E2 Operational Calibration: assessment of enhanced and new methodologies, technical procedures and systems scenarios”.</p> <p><b>FINAL REPORT</b></p>	<p><b>Reference:</b> MO-MAN-ARG-FR+ES  <b>Revision:</b> 1.0  <b>Date:</b> 28/05/2014  <b>Page:</b> 2</p>
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## Signatures

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## Change log

Version	Date	Author	Changes
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	<p style="text-align: center;">“Earth Observation Multi-Mission Phase-E2 Operational Calibration: assessment of enhanced and new methodologies, technical procedures and systems scenarios”.</p> <p style="text-align: center;"><b>FINAL REPORT</b></p>	<p><b>Reference:</b> MO-MAN-ARG-FR+ES <b>Revision:</b> 1.0 <b>Date:</b> 28/05/2014 <b>Page:</b> 3</p>
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## 1 Executive Summary

### 1.1 Scope of the document

This document overviews and reviews the work and achievements of ESA contract (4000101605/10/NL/CBi) “Earth Observation Multi-Mission Phase-E2 Operational Calibration: assessment of enhanced and new methodologies, technical procedures and systems scenarios”; hereafter named MOSAEC (“Methodologies for Operational Systems: Assessment of Enhanced and new Calibration approaches”). The project is reviewed in terms of the work initially proposed, eventual deviations and explanations for those deviations, and the eventual outcomes. The consortium was led by ARGANS Ltd (United Kingdom). ARGANS Ltd led the Optical Carious Calibration component and ARESYS (Italy) Led the SAR calibration component.

### 1.2 Applicable Documents

Id	Document	Reference
AD-1	Invitation to Tender and Statement of Work – Earth Observation Multi-Mission Phase-E2 Operational Calibration: assessment of enhanced and new methodologies, technical procedures and systems scenarios	1-7043/11/F/MOS
AD-2	ARGANS Proposal in response to ESA ITT AO7043	003-013

### 1.3 Major project objectives

ESA has a leading role in establishing and maintaining quality control (QC) and quality assurance (QA) strategies in all phases of its Earth Observation (EO) missions. Expressed in the Mission Requirement Documents (MRDs) and in the Phase E Management Plan, these strategies ensure that instrument performance and generated products are monitored and that the scientific and operational mission requirements are met or even exceeded.

This study, named MOSAEC (**M**ethodologies for **O**perational **S**ystems: **A**ssessment of **E**nhanced and new **C**alibration approaches), directly addressed the overall objective: to assess appropriate Phase E operational calibration methodologies for technical procedures and systems scenarios for two different EO systems. MOSAEC was split into two separate studies led by ARGANS and ARESYS:

- Synthetic Aperture Radar (SAR) external calibration (ARESYS); and
- High- and medium-resolution optical sensor vicarious calibration (ARGANS).

Each system has similar requirements upon them, to deliver new and improved calibration methodologies for consideration in the future Sentinel EO missions; MOSAEC outcomes aimed at benefiting both current and future EO missions; and making efforts towards harmonising

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Calibration/Validation (Cal/Val) efforts, towards optimisation of data applicability and instrument interoperability.

## 1.4 SAR External Calibration

### 1.4.1 Overview

SAR images, as output by typical SAR software that performs range and azimuth compressions (i.e. SLC images), are expressed as digital numbers and not directly exploitable by any application. The process that converts the digital numbers to scientific measurements of the targets’ radar cross section (RCS) is the SAR calibration.

External calibration is related to measurements of external **known** signals by the instrument, to cope with unknown residual gains in the end-to-end acquisition chain and to correct the biases of the internal calibration itself, the external calibration is a fundamental step to ensure the radiometric quality of the SAR images

The **known** targets used for external calibration are typically represented by corner reflectors (triangular), active instruments (transponders) and homogeneous targets (rain forest). Persistent Scatterers (PS) are natural targets with a stable RCS (although unknown), available in almost any acquired SAR image and especially in the cities. Since several factors requires external calibration to be repeated many times throughout the life of the instrument, the possibility to exploit these targets to obtain reliable information about the *evolution* of the radiometry of the instrument is particularly attractive. In fact, these targets can be used as a complementary source of information with respect to traditional external calibration approaches, without cost for the mission planning, since interferometric stacks acquired over cities can be exploited.

The aim of the work is the assessment of the technique accuracy, compared to traditional external calibration methods, and the investigation of key points to be taken into account, in view of its application for the Sentinel-1 external calibration plan.

### 1.4.2 Activities summary

The first task of the work has been a careful investigation of existing calibration strategies, with a focus on ERS and ASAR missions, but looking also into methods exploited by the other known SAR missions. The aim is to identify main benefits and issues of such techniques, and to produce a publication with the results obtained.

Then, application of PS Calibration (PSCal) technique to SAR data has been performed. The first step has been the identification of suitable data stacks to carry out the analysis, by taking into account a number of factors such as the availability of other reference measures, the suitability of the area for PSCal and the representativeness of the acquisitions compared to those that will be obtained by Sentinel-1. A number of indicators (i.e., number of images of the stacks, temporal span covered) has been defined to select the stacks which better fit the desired characteristics.

Once the stacks has been selected, the processing chain needed to obtain calibration values has to be performed. For each selected stacks, fine co-registration is firstly performed in

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order to have the possibility to correctly locate the PS all over the stacks; PSCal processor is then run to identify PS and obtain calibration image for each image of the stack. After PSCal run, the possibility to discard unreliable estimate has been investigated, based on abnormal values of a previously defined set of parameters (Doppler Centroid, Baseline, Coregistration accuracy). Detection is made necessary by a variety of factors (mis-registration, abnormal values of Doppler Centroid or Baseline if compared to the master image), as shown in Figure 1.

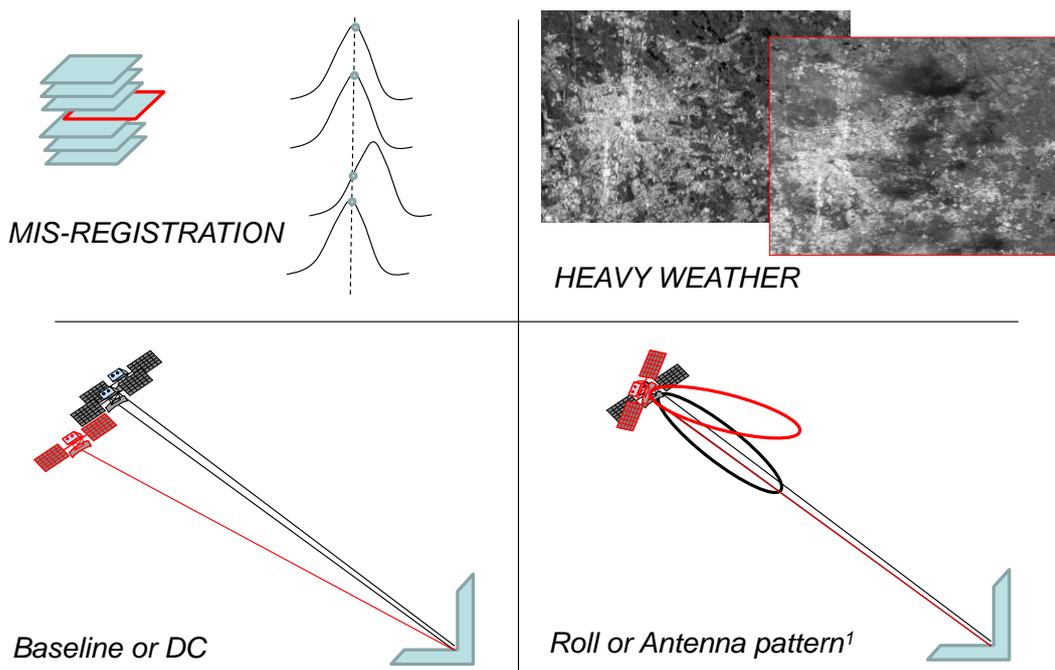


Figure 1: Possible reasons for PSCal estimate outliers

Since PS RCS is unknown, relative calibration series will be obtained; however, the knowledge of one absolute calibration value is sufficient to obtain the absolute calibration series.

Analysis of the results obtained and comparison with calibration series of transponders has been performed in order to obtain guidelines for an operational use of the technique. The analysis is focused on the Sentinel-1 mission, with general considerations for extensions to other SAR missions.

Within this task, the possibility to use PSCal for polarimetric product has been also reviewed.

### 1.4.3 Results

Investigation of calibration strategies highlighted many common aspects in the case studies, like the use trihedrals and transponders for absolute calibration, or of rain forest for both absolute calibration and relative calibration (particularly for antenna patterns). Most of the effort in SAR design was to build systems that are intrinsically stable: in these cases preflight modeling and analysis are exhaustively carried out to characterize all the element affecting relative calibration, particularly the antenna patterns. For such systems, the use external

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calibration is limited to verification, usually for a subset of all the combinations of beams and modes.

A total of 12 data stacks (7 ASAR stacks, 5 ERS2, for a total number of about 500 images) has been selected for the analysis. Flevoland and Ottawa sites have been selected because they have reference Ground Truth measurements available due to the presence of a transponder. For the other stacks, Milan, Paris and London have been identified as best candidates (Figure 2).

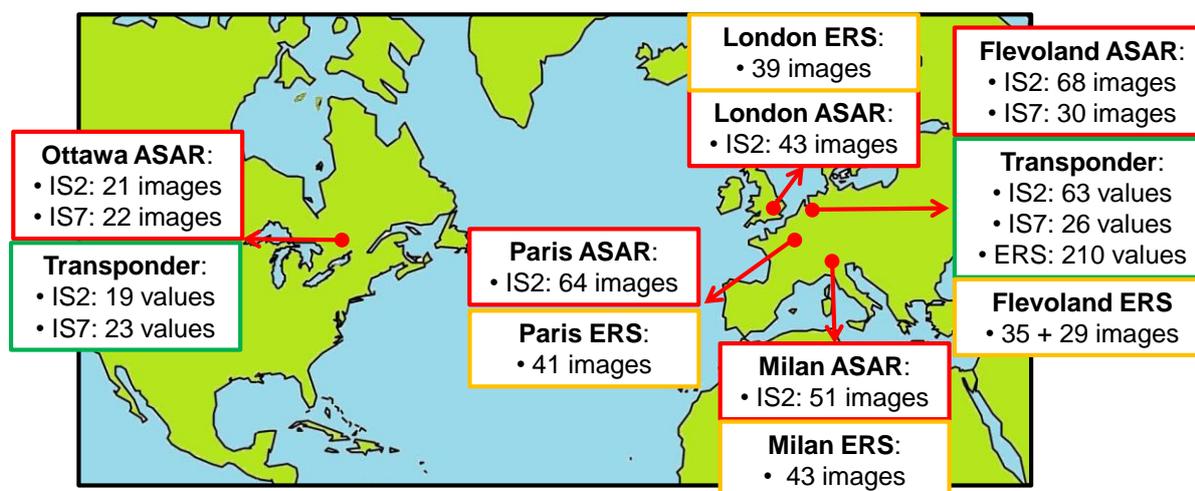


Figure 2: Data sets selected for the PSCal analysis

After creating a calibration series for each stack of the image, all the results obtained have been merged together in order to obtain a single calibration series for each sensor. The results are shown in Figure 3, where the calibration series obtained for the ERS2 and ASAR sensors are displayed. The comparison with the transponder has shown a noteworthy agreement, with a standard deviation of the differences equal to 0.24 dB if no detection is performed, and 0.16 dB in case of elimination of bad PSCal estimates after applying the proposed detection technique. It should be noted that this value can be considered as a worst case accuracy expected for the technique, since it assumes that transponders estimates are always correct (which may not be the case). The analysis shows also an unexpected seasonal trend of the estimates, never mentioned in the works related to calibration. Comparison with the WaveCal calibration techniques (based on the analysis of Wave ocean data) shows an agreement between the two calibration techniques, with a positive calibration peak found in the winter season and a negative one in the summer season (shown in Figure 4).

The importance of the detection step is highlighted by Table 1, where the differences between transponder estimates and PSCal technique is shown: detection allows an improvement of the results in the order of 0.06 dB for the ASAR case, where a larger number of images has been analyzed.

Table 1: PSCal agreement with transponders reference values.

Stack	# imgs	Coincident Dates (# images)		
		No detection	Simple detection	Complete detection
Ottawa IS2	21	0.26 (16)	0.19 (8)	0.13 (14)
Ottawa IS7	22	0.18 (13)	0.10 (6)	0.10 (10)
Flevoland IS2	72	0.25 (31)	0.20 (17)	0.21 (28)
Flevoland IS7	30	0.22 (12)	0.14 (9)	0.12 (7)
Err. avg. ASAR	145	0.24 (72)	0.18 (40)	0.16 (59)
Flevoland ERS	35	0.27 (27)	0.26 (14)	0.22 (25)

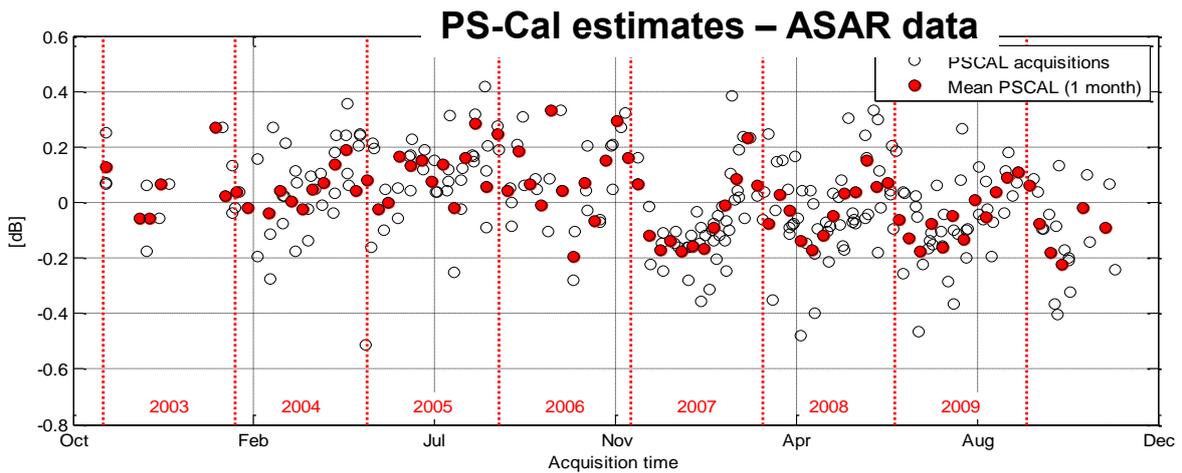
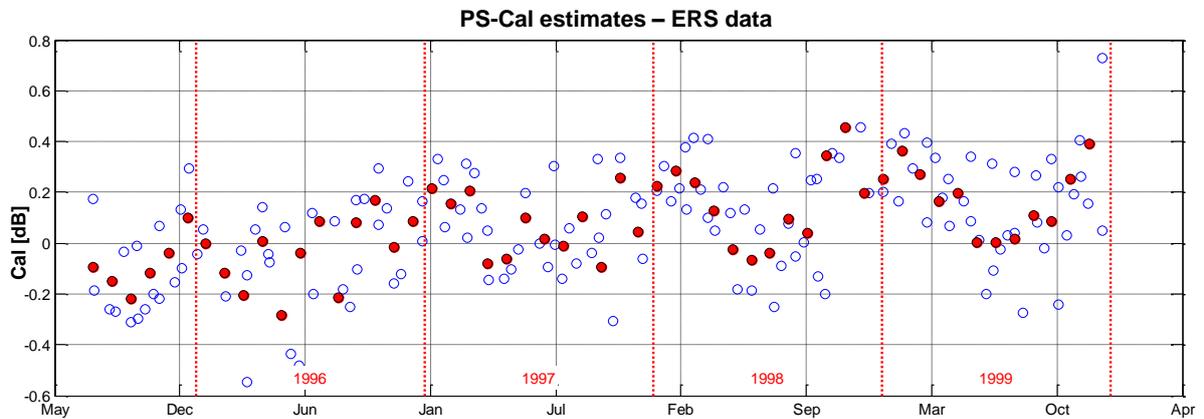


Figure 3: PS Cal time series for ERS2 and ASAR data

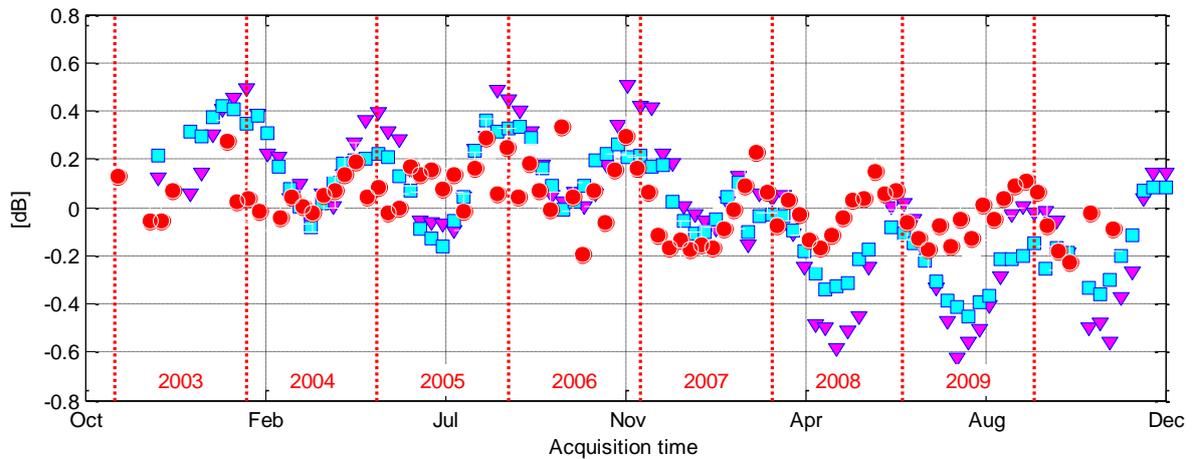
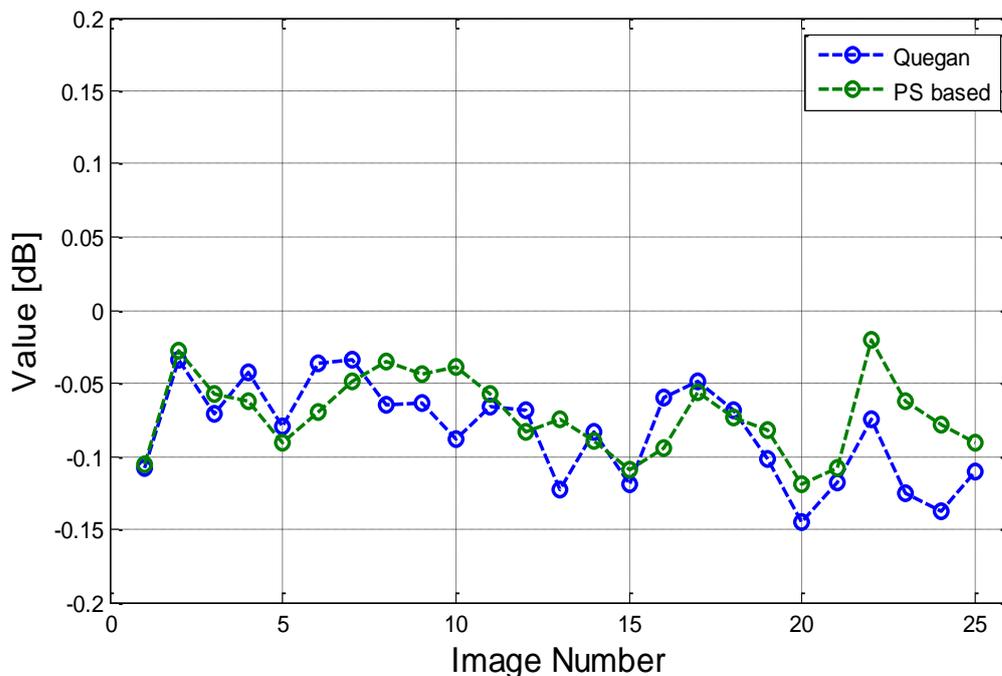


Figure 4: ASAR PS Cal time series and Wave Cal data comparison. The markers are the monthly averages (red circles for PS Cal, magenta triangles for Wave Cal - wind, light blue squares for WaveCal - width).

PSCal polarimetric technique showed very interesting results when applied to quad-pol data, as for example the C-band Radarsat data stack. Results obtained in terms of channel imbalance ratio are compared with those obtained by Quegan (1994) and shown in Figure 5. The application to dual pol data resulted very challenging because of the impossibility to estimate all the parameters from dual-pol acquisition and the difficulty in creating quad-pol acquisition by joining complementary dual-pol data (i.e., HH+HV at pass1 joined with a VV+VH at pass 2 over the same area) caused by target decorrelation.



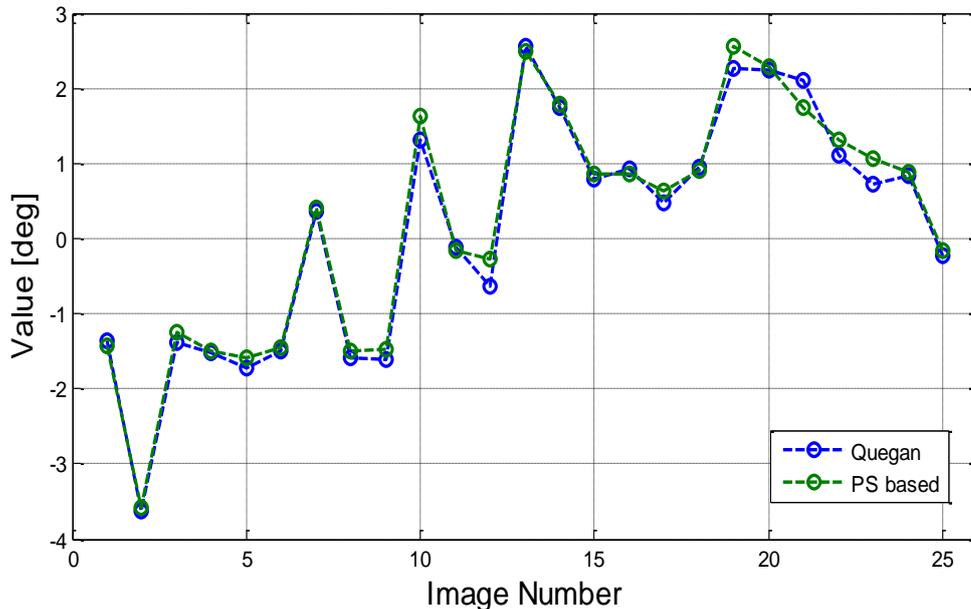


Figure 5: Channel imbalance ratio gain (top) and phases (bottom) computed with the PSCal and the Quegan technique

#### 1.4.4 Conclusions

In conclusion, the PS Calibration technique resulted to be a reliable tool for calibration, if compared to other calibration methods. In particular, it has shown a good agreement with the transponders traditionally used for calibration, with a standard deviation of the differences of about 0.15 dB in the case of ASAR data. Moreover, an outlier detection technique was proposed to discard the less reliable PS-Cal estimates: experimental results have shown an improvement of the accuracy of more than 0.05 dB when performing outlier detection. In optic of the Sentinel-1 PDGS processor, a simplified outlier detection method has also been proposed to discard unreliable PS-Cal estimates.

PS calibration constant obtained from different acquisition sites can be easily merged into a single time series, and a simple technique to obtain calibration series has been successfully tested in this work. Additionally, a technique to merge together the monthly average values obtained from transponders and PS Cal has been proposed: tests have shown that the technique is able to mitigate the negative effect of outliers in the calibration series, which affect in particular transponders measurements (being already eliminated from PS Cal series after detection).

An interesting outcome is the presence of a seasonal trend in the PS Cal and (less evident) in the transponder monthly averages. This trend is noticed also in the other techniques compared with the PS-Cal such as WSM and WaveCal techniques. This trend appears to be related to the latitude of the acquisitions, since the analysis of WaveCal calibration series obtained by the analysis of data acquired in different hemispheres shows a different trend: in both cases the positive peak is found in the winter season, which however corresponds to different months according to the considered hemisphere. This point may pose a challenge for the radiometric satellite calibration, since it would imply the dependence of the calibration

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constant on the latitude of the image to be calibrated, and on the period of the year. Further investigation is needed to fully understand the nature of the phenomenon.

In terms of polarimetric calibration, the PSCal showed very good results when applied to quad-pol data without Faraday Rotation, and promising accuracy in case of presence of Faraday Rotation. The application to dual-pol data posed bigger challenges related to the decorrelation of the targets required to perform polarimetric calibration.

#### 1.4.5 Outcomes of discussions with ESA after final meeting

The PSCalibration technique has provided very good results when tested in view of the use within Sentinel-1 calibration approach. The method has confirmed to be an important option as a complementary tool for calibration with respect to the use of transponders thanks to the very good results in terms of agreement with other techniques and the reduced cost of use.

One of the most relevant outcomes of the work has been the discovery of a seasonal trend affecting the calibration time series, with a positive peak during the cold months and a peak-to-peak value of about 0.4 dB. The trend pointed out by PSCal analysis is undoubtable since it is seen by several calibration techniques, and it has been seen cross-sensor by the PSCal experiments on ASAR and ERS. The reason of the trend is not clear, but it is for sure related to latitude and the season. It could be on the platform (impact of the space environment, variation of the position with respect to the sun) or geophysical (different behaviour of the targets): further investigation would be needed to fully understand the phenomenon. The recommendation from the analysis to change the original Sentinel-1 MPC calibration plan in order to derive different calibration series according to the latitude is taken into account by ESA.

Finally, PSCal has also shown very good results when considered for polarimetric calibration, despite the limited number of stacks available for testing. The quality of channel imbalances retrieved in case of quad-pol data has resulted to be very good if compared to the reference technique tested, even in presence of Faraday Rotation.

#### 1.4.6 Recommendations

Detailed recommendations regarding for the operational use of the PS-Cal tool are provided, based both on the literature and the detailed analysis performed in the project. The recommendations -outcomes of the work can be summarized as follows:

- **Need for outlier detection:** the use of an outlier detection technique as those tested in this work is suggested to discard unreliable PSCal estimates.
- **Number of acquisitions per site:** the minimum number of acquisition per site is 10; below this limit, the PS-Cal estimates cannot be considered as reliable. Because of this reason, the use of the PS Calibration is not expected to provide highly accurate results during the commissioning phase.
- Stable estimates are obtained by considering at least 20 images per stack, which can be easily obtained during the operational phase; above this limit, no further accuracy is obtained on the estimates.

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- **Calibration sites location:** the calibration sites should be selected between cities with similar latitudes. In particular, the analysis of three different calibration zones is proposed, according to the latitude (Northern Hemisphere, Equatorial region, Southern Hemisphere).
- **Calibration sites number:** the number of the calibration sites should enable to obtain at least 5 acquisitions per months (10 suggested). Therefore, the minimum number of calibration sites depends on how many acquisitions are performed per site. If we consider European cities (2 acquisitions expected per month), 3 sites is the minimum number of locations to be considered, 5 is the suggested one.
- **Calibration sites temporal coverage:** all the sites selected should contain acquisition of the whole mission period, in order to guarantee consistency when merging different time series.
- **Ps-Cal internal parameters:** the minimum number of PSs to be considered for calibration should be included between 1.000 and 3.000 (1.000 suggested). The  $\mu/\sigma$  value for PS selection should be increased with respect to the one originally foreseen for S1 mission, up to the value of 4.5. Not to include low quality targets, the maximum PS number should be set to 50.000.
- **Expected accuracy:** the expected accuracy is better than 0.15 dB for the operational phase. During the commissioning phase a much lower accuracy is expected due to the smaller number of possible acquisitions (accuracy worse than 0.25 dB).
- **Possible extension to other missions:** the PSCal is expected to provide similar results in the case of current and future C-band missions, which can be compared with the data sets considered in the experiments. Even better performances are expected for X-band sensors (both for the incoherent PSCal, and the coherent PSCal, which provides further advantages in terms of target detection and calibration quality). No experiments have ever been conducted on L- and P-band data; it is expected a reasonable good behaviour when the spatial resolution is similar to the one of ASAR sensor, even if further work is needed to validate the PS performances in case of different scattering behaviour.

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## 1.5 Optical vicarious calibration

### 1.5.1 Activities summary

DIMITRI has been substantially upgraded to version 3.0 (from version 2.0), with implementations of the following methodologies for the sites and sensors shown in Table 2:

1. **Absolute vicarious calibration over Rayleigh Scattering**, based on the methodology of Hagolle *et al* (1999) and Vermote *et al* (1992) and utilising open ocean observations, to simulate molecular scattering (Rayleigh) in the visible and comparing against *the observed*  $\rho_{toa}$  to derive a calibration gain coefficient;
2. **Vicarious calibration over sunglint**, based on the methodology of Hagolle *et al* (2004); similar to Rayleigh scattering approach but accounting for sunglint reflectance contribution;
3. **Improved automated cloud screening**, exploiting the spatial homogeneity (smoothness) of validation sites when cloud free and applying a statistical approach utilising  $\sigma(\rho_{toa})$  over a Region of Interest (ROI), and defining variability thresholds, such as dependence on wavelength and surface type.

There are three ATBDs available supporting these implementations and describing in detail:

- The principles of these methodology/approach;
- The implementation in DIMITRI\_v3.0;
- The results of implementation, sensitivity analyses and uncertainty estimations;
- Updates made to DIMITRI Human Machine Interface (HMI) and how the user can use it.

*Table 2: Sensors and sites included in the DIMITRI\_v2.0 database*

SENSOR	SUPPLIER	SITE	SITE TYPE
AATSR (Envisat)	ESA	Salar de Uyuni, Bolivia	Salt lake
MERIS, 2 <sup>nd</sup> and 3 <sup>rd</sup> reprocessing (Envisat)	ESA	Libya-4, Libyan Desert	Desert
ATSR-2 (ERS-2)	ESA	Dome-Concordia (Dome-C), Antarctica	Snow
MODIS-A (Aqua)	NASA	Tuz Golu, Turkey	Salt Lake
POLDER-3 (Parasol)	CNES	Amazon Forest	Vegetation
VEGETATION-2 (SPOT5)	VITO	BOUSSOLE, Mediterranean Sea	Marine
		South Pacific Gyre (SPG)	Marine
		Southern Indian Ocean (SIO)	Marine

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Figure 3 summarises the functionalities of DIMITRI\_v3.0 compared to those of DIMITRI\_v2.0.

One major update in DIMITRI\_v3.0 is the extraction and storage of per-pixel information, which is required by both the Rayleigh and sunglint methodologies over ocean. Although the necessary changes to the ingestion readers to enable this renders DIMITRI\_v2.0 and DIMITRI\_v3.0 non-compatible, both versions are available as stand-alone tools and users can choose the one which suits their requirements. The advantage of DIMITRI\_v2.0 is that the database is a smaller file, and L1b data ingestion is faster. Additionally in DIMITRI\_v3.0 a per-pixel binary cloud flag has been included stored in the TOA .dat binary file, indicating the presence or not of cloud in that pixel.

*Table 3: Functionality of DIMITRI\_v3.0 compared to the predecessor, DIMITRI\_v2.0*

	<b>DIMITRI_v2.0</b>	<b>DIMITRI_v3.0</b>
<b>Sensors</b>	AATSR (2 <sup>nd</sup> reprocessing, some 3 <sup>rd</sup> reprocessing), A-MODIS, MERIS (2 <sup>nd</sup> and 3 <sup>rd</sup> reprocessing), POLDER-3, ATSR2; SPOT VEGETATION and VIIRS	AATSR (2 <sup>nd</sup> reprocessing), A-MODIS, MERIS (2 <sup>nd</sup> and 3 <sup>rd</sup> reprocessing), POLDER-3, ATSR2 and SPOT VEGETATION
<b>Validation Sites</b>	Libyan desert (Libya), Salar Uyuni (Bolivia), Dome-C (Antarctica), Amazon, BOUSSOLE, SIO, SPG and TuzGolu	Libyan desert (Libya), Salar Uyuni (Bolivia), Dome-C (Antarctica), Amazon, BOUSSOLE, SIO, SPG and TuzGolu
<b>Date range</b>	2002 to 2014	2002 to 2012
<b>Functionality</b>	<ul style="list-style-type: none"> <li>• Extracted TOA reflectance time series and variability.</li> <li>• ROI averages stored.</li> <li>• Doublet intercomparison</li> <li>• Radiometric recalibration &amp; BRDF modelling</li> <li>• L1b auxiliary data extraction (e.g. ozone, water vapour)</li> <li>• Updated quicklook generation with ROI overlays (semi-transparent squares)</li> <li>• Automated &amp; manual cloud screening of all products;</li> <li>• CSV outputs and improved JPGs</li> <li>• Interactive HMI and Data visualisation tool</li> <li>• Absolute angular matching criteria</li> <li>• Instrument spectral response comparison tool</li> <li>• Updated BRDF computation;</li> <li>• VEGETATION simulation.</li> </ul>	<ul style="list-style-type: none"> <li>• Extracted TOA reflectance time series and variability.</li> <li>• Per-pixel ROI extractions stored.</li> <li>• Doublet intercomparison</li> <li>• Rayleigh scattering methodology option</li> <li>• Sunglint calibration option</li> <li>• Uncertainty estimates computed and provided to the user</li> <li>• Improved methodology 1</li> <li>• Radiometric recalibration &amp; BRDF modelling</li> <li>• L1b auxiliary data extraction (e.g. ozone, water vapour)</li> <li>• Updated quicklook generation with ROI overlays (transparent squares)</li> <li>• Automated &amp; manual cloud screening of all products;</li> <li>• CSV outputs and improved JPGs</li> <li>• Interactive HMI and Data visualisation tool; two new methodologies and a post-ingestion cloud screening tool</li> <li>• Absolute angular matching criteria</li> <li>• Instrument spectral response comparison tool</li> <li>• Updated BRDF computation;</li> <li>• VEGETATION-2 simulation.</li> </ul>

DIMITRI\_v2.0 and v3.0, are freely (without L1b data) available. DIMITRI\_v2.0 is available following registration at [www.argans.co.uk/dimitri](http://www.argans.co.uk/dimitri). DIMITRI\_v3.0 is a larger file (approx. 55GB) so is available upon request; ARGANS or ESA will make it available on an FTP server.

### 1.5.2 LibRadtran-generated LUTs

Look up tables of atmospheric path reflectance, total transmission and relative optical thickness over wavelength as required by both the Rayleigh calibration and the sunglint calibration in DIMITRI, were generated using the radiative transfer code, LibRadtran and the MYSTIC solver. Since many of the sensors in DIMITRI cover the same wavelength ranges the approach taken was to produce one overall hyperspectral look-up table that was convolved with each sensor band using the relative spectral response function (RSR) of each band.

### 1.5.3 Results

#### Rayleigh Scattering

The Rayleigh calibration method implemented in DIMITRI\_v3.0 follows essentially the initial work of Hagolle *et al.* (1999), with several adaptations taking into account more recent and well-tried ocean colour modelling in marine reflectance and aerosol contribution. DIMITRI\_v3.0 provides through the stored SAV files all necessary data for further exploiting the methodology. Coefficients for vicarious calibration were in excellent agreement with other published approaches (Lerebourg *et al.*, 2011; Fougnie *et al.*, 2012; Figure 6) and within the expected L1b calibration uncertainty (Bourg and Delwart, 2012). Analysis with sensor-specific radiative transfer look-up tables, generated in LibRadtran, gave very consistent coefficients; also in excellent agreement. These LUTs are available in the release of DIMITRI\_v3.0.

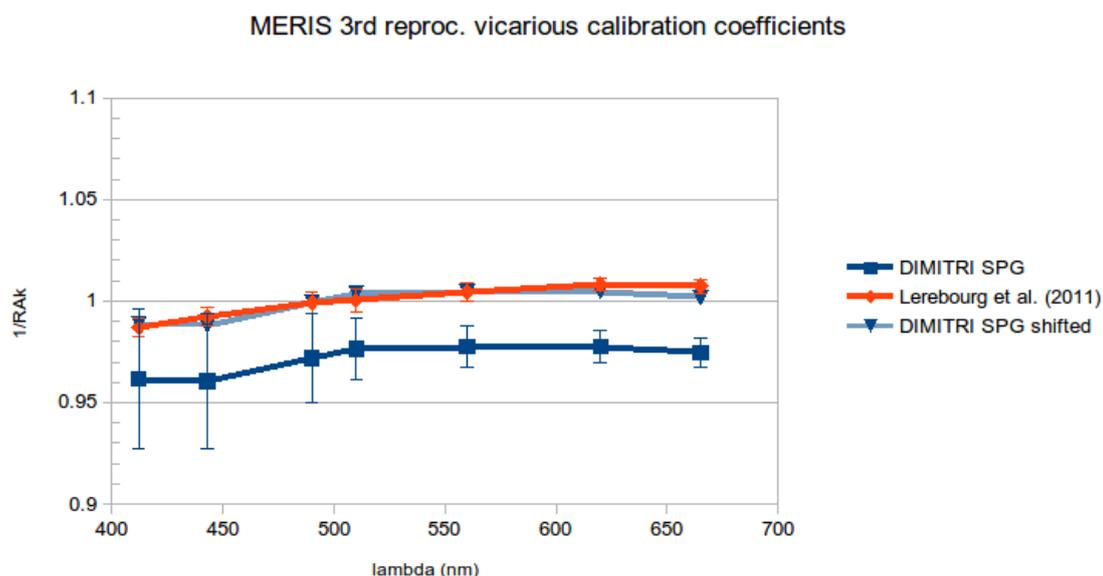


Figure 6: MERIS 3rd reprocessing mean gains (expressed in term of 1/RAK) as of DIMITRI Rayleigh calibration over SPG (dark blue) and for nominal MERIS vicarious calibration (red, from Lerebourg *et al.* 2011). Clear blue ligne represents DIMITRI gains shifted on the nominal gain at 490 nm

	<p style="text-align: center;">“Earth Observation Multi-Mission Phase-E2 Operational Calibration: assessment of enhanced and new methodologies, technical procedures and systems scenarios”.</p> <p style="text-align: center;"><b>FINAL REPORT</b></p>	<p><b>Reference:</b> MO-MAN-ARG-FR+ES</p> <p><b>Revision:</b> 1.0</p> <p><b>Date:</b> 28/05/2014</p> <p><b>Page:</b> 20</p>
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The total error budget of this implementation is about 5.9% at 412 nm and slightly lower than 4% at other bands. This high uncertainty at 412 nm is an extreme case, due to sensitivity of marine reflectance (see e.g. Figure 8 in Morel and Maritorena, 2001). If we consider that errors on the input parameters are random (around true pressure, ozone, chlorophyll, etc.), this error budget contains mainly (at first order) the random uncertainty, on punctual calibration points. However systematic input errors would produce systematic error on calibration coefficients.

Results of bias and  $\sigma$  present a smooth variation with wavelength and are roughly of same order of magnitude, from 8% at 412 nm to 1% at 665 nm. Extrapolating these numbers on a large number of targets, i.e. decreasing at maximum the random contribution, results into a bias of less than 6%.

Overall, results and analysis have shown the necessity to increase the number of calibration points as well as to perfectly characterize their chlorophyll concentration. In particular, the DIMITRI SIO site is not optimal because of high concentration and seasonal change.

The updated implementation of DIMITRI gives the user a straightforward access to new auxiliary data and derive updated results.

### **Sunglint**

The glint calibration method implemented in DIMITRI\_v3.0 also follows Hagolle *et al.* (1999), with (as for the Rayleigh method) several adaptations taking into account more recent and well-tried ocean colour modelling in marine reflectance and aerosol contribution. A noticeable difference is that the aerosol optical thickness cannot be computed from simultaneous off-glint observations and is therefore fixed; the present methodology further screens the pixels after glint estimates to only keep those with consistent aerosol modelling in the near-infrared.

Vicarious coefficients presented for MERIS, were a bit above the 2% expected L1b calibration uncertainty (Bourg and Delwart, 2012) at 865 and 885 nm (2.3 and 3.6% respectively). On the other hand we have retrieved excellent comparison with Lerebourg *et al.* (2011) when making same assumption in the interband calibration (i.e. 779 nm perfectly calibrated). This shows that the 665 nm reference band used in other cases is possibly not well calibrated. Also taking into account water vapour absorption would probably improve the results at those bands. It appears that the glint coefficients in the red and near-infrared are extremely stable along the years (very low standard-deviation), contrary to the Rayleigh vicarious calibration in the visible. This probably comes from the very strong and well-modelled glint signal at the reference band, contrary to the off-glint marine signal in the visible bands highly sensitive to the chlorophyll content.

Comparison with nominal vicarious coefficients of MERIS 3<sup>rd</sup> reprocessing (Lerebourg *et al.*, 2011) is shown on Figure 40 where the DIMITRI Rayleigh vicarious calibration at 665 nm is expressed in term of  $A_k=1/RA_k$ . Both methods disagree in term of shape towards near-infrared; however tests with MERIS RTM LUTs would again produce different results and conclusion. Furthermore, both approaches differ by a major interband assumption: Lerebourg *et al.* (2011) assumes that bands 779 nm and 708 nm (this latter not considered in DIMITRI) are perfectly calibrated (coefficients set to 1), for calibrating other near-infrared bands, in particular 865 nm.

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In all cases the standard deviation are excellent, as already stated (if not visible on the plot), contrary to those of the Rayleigh calibration, and even better than the nominal MERIS vicarious in the near-infrared.

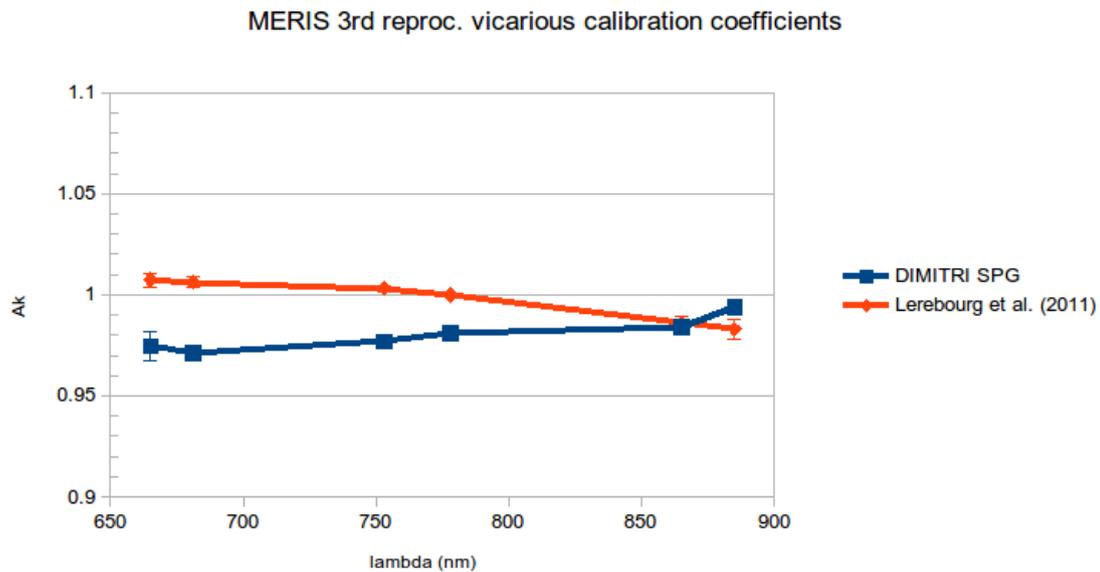


Figure 7: MERIS 3rd reprocessing mean gains as of DIMITRI Rayleigh calibration (blue line from 412 to 665nm, expressed in term of  $1/RA_k$ ) and DIMITRI glint intercalibration relative to 665 nm (blue line from 681 to 885 nm) over SPG and for nominal MERIS vicarious calibration (red line, from Lerebourg et al., (2011)).

The total error budget is less than 0.6% from 681 to 865 nm and 1.3% at 885 nm due to extreme tests (coastal model at SPG). A maximum 1% uncertainty is assigned to all bands in DIMITRI interface. Because error on the input parameters can be considered as random (around true pressure, ozone, chlorophyll, etc.), this error budget contains mainly the random uncertainty, on punctual calibration points.

Results of bias and  $\sigma$  are very low, from 0.3% at 681 nm to 1.4% at 885 nm. Extrapolating these numbers on a large number of targets results into a bias of less than 1%. This is very consistent with Hagolle *et al* (1999) estimates.

Results and analysis have shown the necessity to increase the number of calibration points and we recommend enriching the DIMITRI database with oceanic targets studied in Fougnie *et al.* (2002) and used in Fougnie *et al.* (2012).

#### 1.5.4 Cloud screening

In addition to the current cloud screening methodologies, two new approaches have been implemented in DIMITRI\_v3.0 and are described here.

During the development of the new methodologies, it was found that the current version of the database has many misclassified manually screened scenes. It is believed that one possible reason for the misclassifications of the manually screened scenes is that

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DIMITRI\_v2.0 drew a red shaded box over the ROI. This made it difficult to see by eye, especially at DomeC where there was the largest found number of misclassified images. DIMITRI\_v3.0 subverts this problem with the new ingestion routine, which simply draws an un-shaded box around the ROI making it possible to see into the ROI. It is therefore recommended that the manual cloud screening be redone; as the database is getting quite large, it is recommended that a standard subset be defined and the manual cloud screening be redone. The subset should include a more even number of images across the different sites and sensors than the current manually screened set.

1. **Spatial Scale Variability (SSV):** measures the statistical variance of the per-pixel values from the mean top of atmosphere value over the area of interest. If the variance is above an empirically derived threshold then the scene is considered cloudy. It was discovered in the SSV method that the power law that was fitted to the standard deviation as a function of window size may not be the best function to fit to. In fact, a linear fit may be more appropriate. It was found that for the very low resolutions that the variance is mostly noise and this can be a challenge for the fitting routine to fit to accurately. The curve very quickly converges to a straight line. For this reason it may be better to simply take the absolute standard deviation over the entire scene because the changing window size doesn't appear to give any more information about the scene. It is recommended that this be investigated further in future evolutions of DIMITRI. The SSV method has very high computational requirements. Training the model can take quite some time and so does classifying the images. The method often has trouble discriminating between cloudy and partly cloudy, particularly over marine targets. The method can however, provide information on whether or not the image has some cloud in it. As a binary classifier it performs quite well on the test dataset. However, the advantage that was foreseen for this method was that it was a ternary classifier.
  
2. **BRDF Variability Threshold (BRDFVT):** measures how closely the BRDF of a satellite measurement over a site complies with an empirically derived model of the BRDF for that site. If the BRDF deviates beyond a certain threshold from the modelled BRDF the scene is considered cloudy. The BRDF method works better and faster than the SSV approach if a binary classifier is sufficient, and is very useful at identifying scenes with cloud. The BRDF method is able to detect very small amounts of cloud in an ROI and contrary to the SSV cloud screening, it can identify scenes erroneously labelled as manually clear in the database.

### 1.5.5 Human Machine Interface

The updated implementation of DIMITRI gives the user a straightforward access to new auxiliary data and immediately gives updated results. The DIMITRI\_v3.0 HMI (Figure 8) allows users to easily choose all main parameters of the calibration (thresholds, chlorophyll concentration, aerosol model, etc.). Automated handling of auxiliary files also gives users the possibility to immediately test other parameterisations of the signal modelling, both for the marine contribution (e.g. chlorophyll climatology, coefficients of the Morel and Maritorena (2011) model) and atmospheric component (e.g. new look-up tables with different geometrical discretisation or aerosol models).

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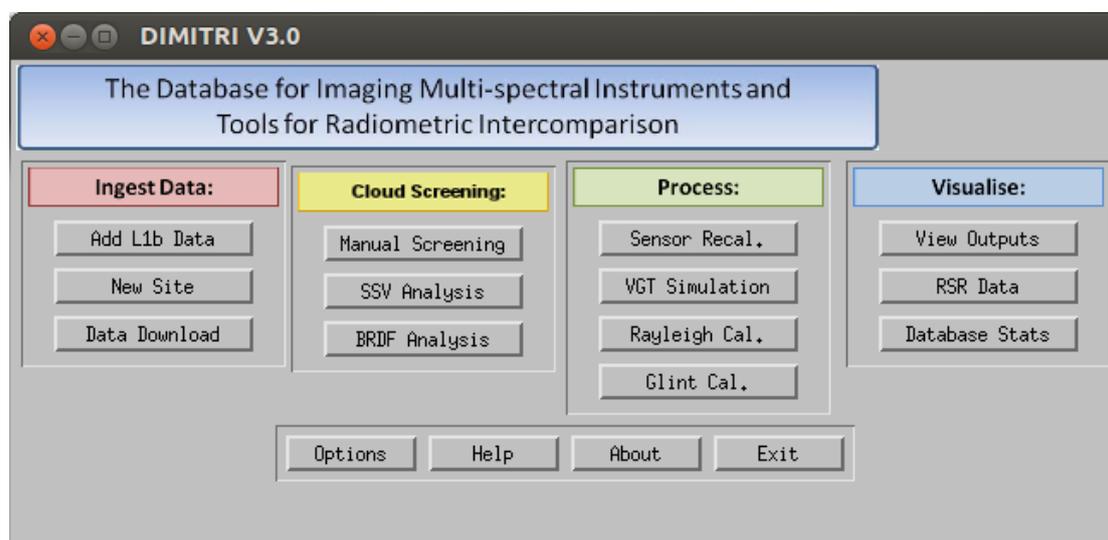


Figure 8: Main DIMITRI window updated for Rayleigh scattering and sunglint vicarious calibration methods, and the cloud screening tool

### Modules and functions

The calibration methodologies are implemented as individual IDL modules, called by a new HMI module (or directly in command line); this then calls several separated routines for specific jobs (e.g. computation of Rayleigh reflectance, of marine models, etc.). Schematically, the main glint calibration module:

- Interfaces with the DIMITRI database to identify appropriate L1b extractions with respect to chosen region, sensor, processing version and year;
- Screens data for ROI cloud and region coverage; in the pixel-by-pixel mode, pixels are further screened by the cloud mask;
- Finds all pixels within other user defined parameters specific to the calibration method;
- Reads all Radiative Transfer Model (RTM) LUT;
- Performs the Rayleigh or sunglint (user chosen) calibration band per band;
- Post-processes the coefficients (averaged, statistics);
- Outputs the individual and averaged calibration coefficients for each band in several text and image file.

### User Options

The Rayleigh calibration and sunglint calibration methodologies allow both HMI and command line activation. All processing parameters specific to the chosen calibration methodology are selectable by the user through a new window (Figure 8):

- Case study (region, sensor, processing version, year, output directory);
- Cloud and region coverage percentage; note that scenes having a manual cloud screening set to 0 will be selected whatever the automated cloud screening value;

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- Pixel-by-pixel mode;
- Chlorophyll concentration, either by monthly climatology put in the DIMITRI auxiliary folder or by a fixed values;
- Maximum wind speed.

#### Specific to Rayleigh calibration:

- Maximum Rayleigh corrected normalised radiance at 865 nm;
- Aerosol model, among an automated list built on all models existing in DIMITRI auxiliary folder, sensor per sensor.

#### Specific to Sunglint methodology:

- Maximum angle between viewing and specular directions;
- Reference band for the calibration;
- Absolute calibration coefficient for the reference band;
- Aerosol optical thickness at 865 nm;
- Aerosol model, among an automated list built on all models existing in DIMITRI auxiliary folder, sensor per sensor.

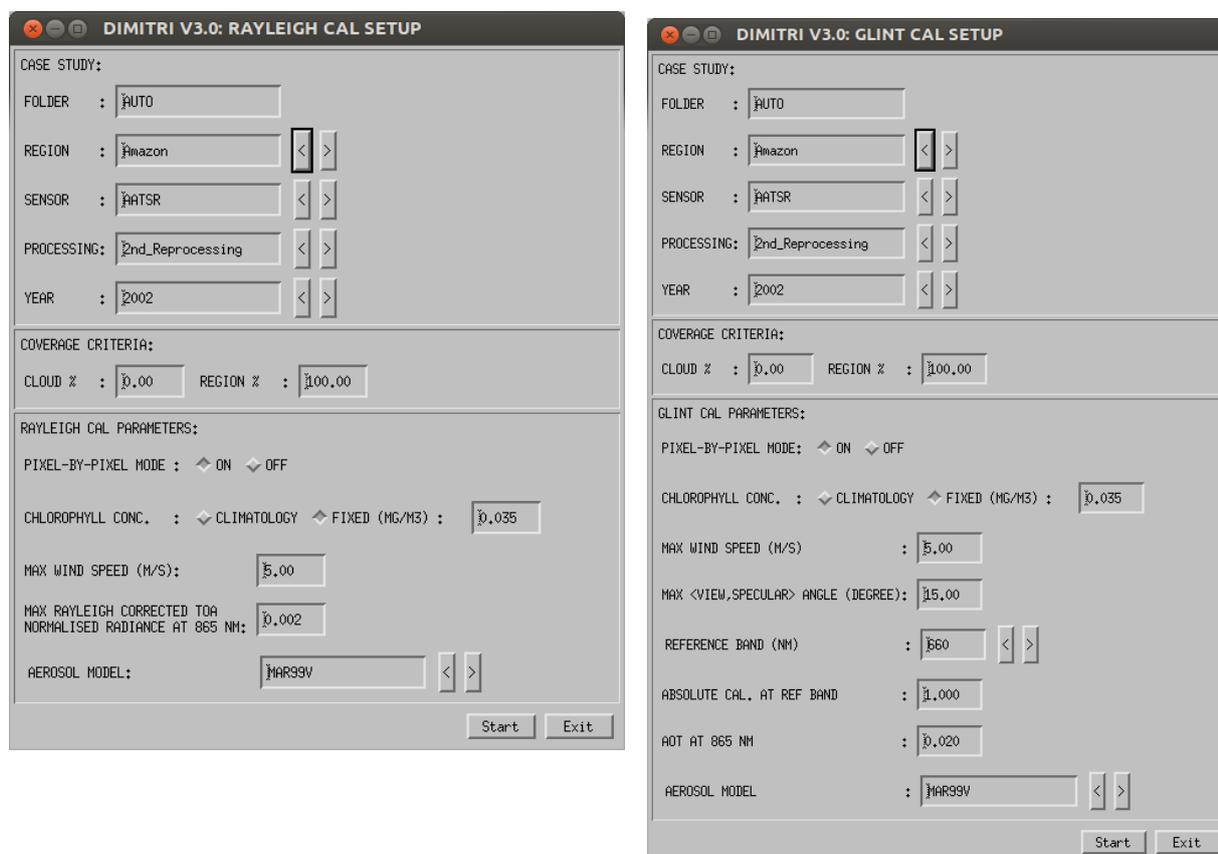


Figure 9: New DIMITRI\_v3.0 windows for parameterising: LEFT: Rayleigh scattering vicarious calibration; and RIGHT: glint vicarious calibration

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### Cloud screening modules:

The DIMITRI SSV cloud screening window is shown in Figure 10. Options are:

- Case study (region, sensor, processing version, time range)
- Coverage criteria. This applies both for the training stage (if activated) and the screening stage.
- Cloud screening option: skip the training stage or not and select the band used for standard-deviation computation. Skipping the training stage can be of interest when the fitting coefficients already exists from a previous run because computation may take a relatively long time, depending on number of classes and number of scenes per classes.

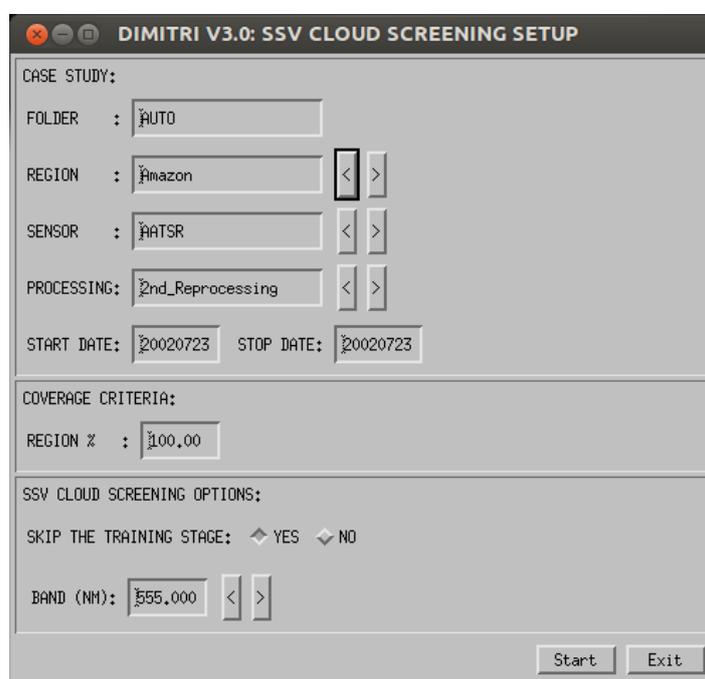


Figure 10 DIMITRI SSV cloud screening window

### 1.5.6 Conclusions and Roadmap/recommendations

DIMITRI\_v3.0 has undergone significant testing and the implementations of the methodologies have been found to be scientifically sound. It was observed during development that the pixel-by-pixel data extractions, and cloud mask flagging, may have implications for data storage and ingestion because S2 and S3 require Rayleigh Calibration/validation. The pixel-by-pixel extraction has significantly increased the size of extracted datafiles from the old version (v2.0) to the new version (v3.0, with Rayleigh method implemented).

In the first instance we recommend to initiate a consolidated QA and QC protocol. To date this has not existed for DIMITRI development, on neither the source code, nor its output and should be considered before operational application in the S2 and S3 MPC. DIMITRI follows QA4EO to some extent, in the uncertainty definition; this can be built upon further in future developments, for consistency with the direction and goals of the CEOS/IVOS working group.

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A selection of recommendations, expanded upon in the full final report, are provided here and include conclusions from the Final Meeting (ESA/ESRIN, 28<sup>th</sup> May 2014):

- **Add Morel and Gentili BRDF in the marine reflectance model;** this is relevant for S3
- **Define standard pressure, ozone, wind, etc., in auxiliary files** instead of hardcoding in view of future RTM LUT evolution.
- **Rayleigh Scattering methodology:**
  - Generate the XC polynomial from the  $\rho_{\text{path}}/\rho_{\text{R}}$  LUT: DIMITRI\_v3.0 makes use of XC generated by forcing the  $\rho_{\text{path}}/\rho_{\text{R}}$  to 1 for  $\tau_a = 0$  (this approach was shown not to be appropriate).
  - Review the literature on Rayleigh optical thickness to make use of the latest/most advanced modelling for the generation of the LUTs.
  - ROT formulation to be used in LUT RT generation needs to be the latest and correct version of the ROT.
  - Include the f/Q correction in the LUT generation as a priority
- **In case of multiple-direction acquisition (e.g. PARASOL), analyse the vicarious coefficients variation with respect to each direction** and possibly do not average over all directions.
- **Change selection methodology for SPG and SIO in order to have more targets**, as in the MERIS vicarious adjustment with optimal windows selection.
  
- **Development**
  - **Add an option for adjusting  $L_{\text{TOA}}$**  by given calibration factors and then applying the inter-sensor comparison, or the vicarious calibration; this should bring new vicarious gains close to 1 when taking vicarious gains.
  - **Add an interface to manage the database more easily** (view number of sensor, files per sensors, etc.).
  - **Improve the software development approach:**
    - include rigorous quality assurance and quality control procedures and unit testing (standard in software development), versioning using Git, as introduced during MOSAEC, formalise a long-term development plan which takes into accounts and plans ahead for operational application of DIMITRI in S2 and S3 Mission Performance Centres (MPCs).
    - Employ an Agile development approach; this is a framework for developing software and goals assessment, and addressing and coordinating with other developers. Consider how this could fit with ESA’s way of working (i.e. the tendency to contract in short timescales in the coming months, for forthcoming SoWs).

	<p style="text-align: center;">“Earth Observation Multi-Mission Phase-E2 Operational Calibration: assessment of enhanced and new methodologies, technical procedures and systems scenarios”.</p> <p style="text-align: center;"><b>FINAL REPORT</b></p>	<p><b>Reference:</b> MO-MAN-ARG-FR+ES</p> <p><b>Revision:</b> 1.0</p> <p><b>Date:</b> 28/05/2014</p> <p><b>Page:</b> 27</p>
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- **Add new sites for more robust vicarious calibration** (Fougnie *et al.* 2002). This should be addressed in the ESA contract “Pseudo Invariant Calibration Sites”, and in the S2 MPC (CS Prime; ARGANS leading DIMITRI vicarious radiometric validation).
- **Extensions to include other sites:**
  - Another snow site is a priority,
  - Fully exploit BOUSSOLE with the Rayleigh scattering methodology by making use of the in-situ data available.
  - Dark water could be preferable to dark land (e.g a lava field, which are not yet characterised anyway). Example of dark waters: the Baltic Sea because of the CDOM absorption, and use a boundary condition of 0 instead of the Maritorea marine reflectance model.
  - S2 MPC sites will be included anyway. These are yet to be finalised but Greenland, Libya-4 and other PICS and BOUSSOLE are all mooted.
  - Include RadCalNet in-situ data, when available.
- **Extensions to include other methodologies:**
  - *Deep Convective Cloud* methodology could be considered; this may have application in the S2 MPC, but may be limited by the dynamic range for some channels of some sensors.
  - *$\rho_{toa}$  simulations approach* (e.g. like VITO/Y. Govaerts OSCAR method): This involves simulated TOA signals through forward modelling, and is to be included in DIMITRI in the ESA/ESTEC/ARGANS contract “Exploitation of the Pseudo-Invariant Calibration Sites (PICS) for Radiometric Intercomparison of Optical EO Sensors”.
- **Extensions to other sensors**
  - Priorities should be the Sentinels and Landsat (as precursor to MSI).
- **Improve the cloud screening by introducing feature clustering techniques.**  
For example, DomeC is a difficult target to accurately detect clouds but by using information about ozone absorption, relative humidity and possibly other features, performance of cloud screening over DomeC can be further improved (demonstrated in Figure 11 and explained further in the Full Final Report).

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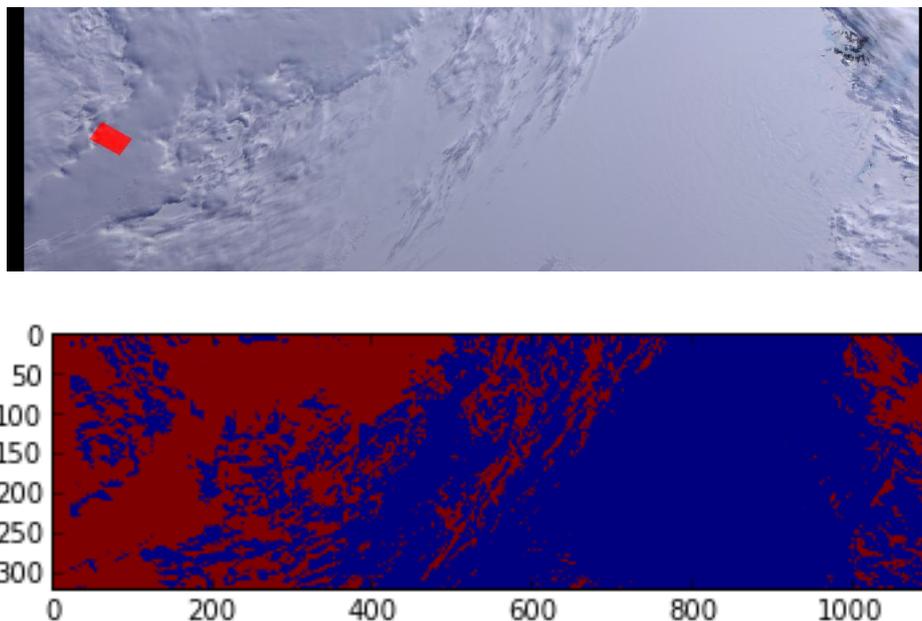


Figure 11: Spectral feature clustering algorithm over DomeC with the inclusion of Ozone. 37.5% Cloud Coverage  
- More accurate estimate

- **Longer-term (Post-MOSAEC CCN):**

- **Uncertainties:** Investigate the non-random uncertainties, for instance with the meteorological data, one could assign the random and system uncertainties and then propagate through the methodologies & add to the modelling uncertainties.
- **Intercomparisons with other Agencies:** Initiate contact with CNES and VITO to see if they would apply their methods to the reference dataset, and compare results.

**Recommendations in the wider context of the CEOS/IVOS**

**(NIGEL)**

- Characterise input systematic and random uncertainties in all radiometric intercomparison methodologies and propagate these uncertainties through the methodologies to the the outputs (be they rho\_obs/rho\_sim or rho\_sensor\_1 vs. rho\_sensor\_2)
- Participate to or support intercomparison exercises within CEOS/IVOS WG2 and WG3

**1.5.7 Access to DIMITRI\_v3.0**

DIMITRI\_v2.0 and v3.0 are freely (without L1b data) available. DIMITRI\_v2.0 is available following registration at [www.argans.co.uk/dimitri](http://www.argans.co.uk/dimitri). DIMITRI\_v3.0 is a larger file (approx. 55GB) so is available upon request; ARGANS or ESA will make it available on an FTP server.

	<p style="text-align: center;">“Earth Observation Multi-Mission Phase-E2 Operational Calibration: assessment of enhanced and new methodologies, technical procedures and systems scenarios”.</p> <p style="text-align: center;"><b>FINAL REPORT</b></p>	<p><b>Reference:</b> MO-MAN-ARG-FR+ES <b>Revision:</b> 1.0 <b>Date:</b> 28/05/2014 <b>Page:</b> 29</p>
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