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Proceedings, Highlights and Recommendations from the Workshop on Radiometric Calibration for European Optical Missions

Frascati (ESA/ESRIN), Italy, 30-31 August 2017

European Space Agency
Agence spatiale européenne

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1 SUMMARY

The European Space Agency (ESA) organized a Workshop on Radiometric Calibration for European Optical Missions held in Frascati (ESA/ESRIN), Italy, 30-31 August 2017.

The objectives of the workshop were to report on the status on the current calibration performance for the European Missions (Proba-V, Sentinel-2A, Sentinel-2B, Sentinel-3 OLCI and SLSTR, MERIS and ATSR), to compare the various approaches used by the different missions and to identify the open points and the issues. The discussions aimed at giving coherence between the various missions in term of radiometric calibration. This workshop was a European contribution to the CEOS WGCV/IVOS group on the calibration harmonisation discussion, in particular, the 'harmonisation of calibration coefficients' between missions and if and how we could agree on radiometric standard between missions.

An overview on the "operational calibration methods" (how the operational gains are derived) was given through this workshop. During this discussion the communalities and the differences between missions were identified. Moreover, the way to validate them (inter-comparison, vicarious methods) was discussed. Issues, open points and questions were also discussed. In the second day further discussions took place on the methods and issues related to the vicarious calibration techniques.

The participation was limited to European key actors in the calibration domain, with an invitation to NASA colleagues, in order to share their experiences.

All presentations are available online at the ESA SPPA website:
(https://earth.esa.int/web/sppa/meetings-workshops/expert-meetings/workshop-on-radiometric-calibration-for-european-optical-missions/programme).

1.1 Session Highlights

The key highlights from the main topical sessions are summarised in the tables below.

1.1.1 Missions Operational in-flight Calibration

Reference	Summary
Missions Operational in-flight Calibration	1. **The experience on MERIS calibration showed that increasing effort and budget should be allocated to instrument pre-launch characterization.** This includes both the measurements as well as the data analysis. Some instrument features observed during operations (e.g., spectral smile) are in fact difficult to be characterized in-flight and to correct within the geo-physical retrieval algorithms. 2. **The crucial issue for optical mission radiometric calibration and inter-sensor consistency verification is to agree on a community-accepted reference for L1 TOA radiances/reflectances. This topic is under discussion in the frame of CEOS.**

	3. The need to understand the effects of the incorrect Spectral Response Function (SRF) for S-2A was stressed. The current recommendation is to use the SRF derived for S-2B also for S-2A. The impact on vicarious calibration was also discussed. It is expected to be relevant for Rayleigh calibration method, while different SRFs would have less impact over spectrally uniform and bright desert site.

1.1.2 NASA Experience

Reference	Summary
NASA Experience	1. The moon is operationally used for MODIS and Landsat for stability monitoring. **The interest of the moon as stable vicarious target to monitor degradation trend is recalled, while uncertainty in the lunar irradiance model still prevents its usage as absolute calibration target.** 2. As lesson learned from MODIS/VIIRS experience, it is stressed the need for a comprehensive pre-launch characterization, though, **the calibration is a never-ending process and a dedicated effort should be allocated throughout the full mission lifetime (and beyond), this entails the need for regular reprocessing campaigns for the continuous improvements of the level 1 dataset.**

1.1.3 Radiometric Comparison

Reference	Summary
Radiometric Comparison	1. The impact of the differences between the SRFs of S-2A and S-2B was discussed. It was not clear why it affected only the bands B01 and B02. The impact of this change should be observed within the Rayleigh calibration results. 2. Multi-sensor (MERIS, MODIS, MSI, OLI, OLCI) radiometric inter-comparison over Pseudo-Invariant Calibration Sites (PICS) shows a group of sensors with consistent radiometry in the considered VNIR spectral range, the OLCI radiometry seems to be 2-3% brighter than this group, however, the uncertainty of the methods does not justify the conclusion that this group is correct. 3. **A harmonization of the definition of ROIs over desert sites (S-2/S-3) was proposed.** At the moment for S-2 smaller ROI sites for deserts are used. The S-2 MPC team suggested providing the list and specifications of the S-2 sites and then S-3 MPC team to extract these S-2 adapted ROI over desert sites. **4. It was pointed out the importance to break down the uncertainty in the various components and in particular the systematic and random component.**

1.1.4 Vicarious Calibration Methods

Reference	Summary
Vicarious Calibration	1. **The scene/pixel dependent uncertainty and the lack of standardisation/interoperability were among the challenges mentioned when**

Methods	**using multi-sensor satellite data products.** The key issue is actually harmonisation not homogenisation, meaning that the sensor-specific issues will remain. 2. Some optimal new sites are identified among PICS, such as Namibia-1 and Arabia-4. Sand samples will be collected over these areas and sand spectral BRDF measurements will be performed at Onera. All the data will be hosted in Cal/Val portal, and free access will be guaranteed to interested users. 3. In order to monitor the stability of Libya-4 site, a normalised reflectance was computed with the help of the BRDF model computed using PARASOL data. An application over PICS-Libya-4 desert was shown for various data collections, i.e. FY-3, MERIS, VGT2, PROBAV, S2A/MSI, S2B/MSI. **4.** It was demonstrated the analysis of surface reflectance azimuthal dependencies due to sand dune topography for different regions-of-interest (ROIs) sizes using 3D Monte Carlo ray-tracing RTM. This investigation pointed out on **the need for 3D RTM if we want to achieve the radiometric accuracy of 1-3% with desert site vicarious calibration.** 5. GSICS is a system for the generation of inter-calibration coefficients for GEO/LEO meteorological sensors. The interoperability is the final goal of this project and all the GSICS products are free and open to the users. 6. It was expressed the need to define which is the right reference for absolute radiometric calibration, this discussion will be continued at the next CEOS/IVOS meeting. **A pragmatic approach for establishing a radiometric reference would be to use RadCalNet, as benchmark for HR sensors radiometry, in combination with the PICS, which allow transferring the radiometry to other sensors.** ***7.*** It is also essential to review the methodologies for vicarious calibration, in particular to agree on radiative transfer algorithms and associated atmospheric input parameters, on ancillary data (e.g., solar irradiance), on the adopted ground spectral BRDF modeling. **A table summarizing the results of vicarious calibration over PICS performed by the various groups (e.g., for S2 and S3) would be useful to agree on the commonly observed biases, as well as for investigating the remaining discrepancies.** 8. An alternative approach was finally presented, which is based on the assumption that Cal/Val data are available in any image. There is no need for collecting specific data over target sites and potential update of calibration coefficient in NRT. Basic statistical analysis is used to extract the various components of the signal and derive several parameters of interest for instrument characterization and calibration: e.g., relative gains, focus, SNR.

1.2 Recommendations

The key recommendations identified during the meeting are reported in the table below. The different frameworks in which these recommendations will need to be discussed are also reported.

Reference	Recommendation	Framework
[Rec-1]	To reinforce the focus on instrument pre-flight characterization activities during the mission development phase by allocating the required time and budget.	ESA
[Rec-2]	To ease access to instrument pre-flight characterization dataset for ensuring Level 1 full traceability during mission lifetime and beyond.	ESA
[Rec-3]	To support sensor in-flight radiometric calibration and inter-calibration activities and allocate the proper budget during mission operations (and beyond) for maintaining and continuously improving (re-processing) the relevant Level 1 dataset.	ESA
[Rec-4]	To work toward a community-agreed reference for Level 1 TOA radiances/reflectances and provide the relevant protocols and tools allowing different sensors to link to it. To propose and discuss this reference at the next CEOS WG Cal/Val Meeting.	CEOS
[Rec-5]	To further investigate and understand the impact of the incorrect SRFs for S-2A B01 and B02 bands both for vicarious calibration and for data exploitation.	S2-MPC
[Rec-6]	To continue investigation on S2 SRFs inter-detectors variability in collaboration with Landsat team.	S2-MPC
[Rec-7]	To redo the yaw manoeuvre, recently performed for S-3A in order to characterize OLCI sun diffuser BRDF, also for the S-3B unit.	S3-MPC
[Rec-8]	To further investigate the trend observed for Proba-V in-flight vicarious calibration over Libya-4, in particular the higher degradation rate in the SWIR as compared to VNIR channels.	Proba-V QWG
[Rec-9]	To harmonize definition of ROI for desert sites between S-2 and S-3 MPC teams in order to ease radiometric cross-calibration between MSI, OLCI and SLSTR sensors.	S-2 and S-3 MPC

[Rec-10]	To collect the results of vicarious calibration and inter-calibration over PICS from the different S-2, S-3 and Proba-V calibrations teams. To compile a table providing the estimated radiometric accuracy for each site with reference to the adopted methodology and ancillary data.	S-2 and S-3 MPCs, Proba-V QWG
[Rec-11]	To work toward providing uncertainty information for vicarious calibration results, discriminating between random and systematic component.	S-2 and S-3 MPCs, Proba-V QWG
[Rec-12]	To continue the work on harmonization of PICS both in terms of ROI definition as well as for the relevant protocols and procedures.	CEOS
[Rec-13]	To sustain the effort for the development of a community agreed RTM, able to model all the complexity of the surface-atmosphere coupled system, with the final goal to attain the required accuracy for sensor in-flight calibration (better than 3%).	ESA- CEOS

2 PROCEEDINGS

2.1 Day 1: 30 January 2017

2.1.1 Introduction

P. Goryl (ESA, Italy) welcomed the participants and mentioned the objectives of the workshop. In particular, he pointed out that the first goal was to review the status of the operational calibration for European optical sensors with focus on Sentinel-2, Sentinel-3 and Proba-V, reporting on the observed sensor-specific issues. The second objective was to report on the inter-comparison results and discuss on the cross-calibration methodologies. He also mentioned that the meeting was intended to contribute to the general discussion at CEOS level on calibration methods, traceability to the International System of Units (SI), inter-operability and harmonisation.

F. Gascon (ESA, Italy) raised specific points for discussion concerning Sentinel-2 (S-2) with a special emphasis to the difference between MSI-A and MSI-B SRFs. He also indicated the importance of sharing the experience on calibration using a sun-diffuser, i.e. technical limitations, possible improvements of in-flight methods and long-term monitoring of equalization coefficients.

S. Dransfeld (ESA, Italy), informing about Sentinel-3 (S-3), mentioned that the SLSTR calibration of SWIR bands and of oblique view need to be addressed. It is also important to improve in-flight calibration methods, maybe by considering lunar calibration, and vicarious methods, by using RadCalNet sites.

F. Niro (ESA, Italy) reported for Proba-V that there is not specific issue and the radiometric accuracy is well within the requirements set in the MRD, though the experience and lessons learnt with vicarious methods will be reported with emphasis on the results obtained with the yaw manoeuvre and with the moon.

2.1.2 Missions Operational On-flight Calibration

L. Bourg (ACRI, France) presented "MERIS/OLCI Calibration". An overview of MERIS and OLCI instruments was given, in order to point out their similarities. The radiometric and spectral calibration, is based on on-board diffusers. There are two diffusers on-board: operational and "pristine" (or ageing), the latter one is exposed less frequently for assessing operational diffuser ageing. The spectral calibration on-board is achieved by using: i) Erbium-doped diffuser spectrum, ii) solar Fraunhofer lines, iii) atmospheric absorption O2-A lines. The results of the calibration with the diffuser ageing for MERIS and OLCI were shown. The results were quite similar and it was observed that ageing is mostly linear with time; for MERIS ageing was a bit more than 2% after 10 years in orbit, for OLCI it is less than 0.2% after 1.4 years.

As lessons learned from the calibration of MERIS and OLCI it was pointed out that extreme care should be paid to the pre-launch characterization of the diffusers and particularly the BRDF. It was stressed that the two diffusers should have very similar BRDF, for OLCI a slight difference in the BRDF of the two diffusers is observed. According to MERIS instrument degradation results, its degradation depends on the camera. In general, there is a strong dependency with Sun azimuth due to limitations in the diffuser BRDF model. **For OLCI a dedicated yaw manoeuvre was planned in order to acquire consecutive diffuser measurements at varying Solar Azimuth Angle (SAA). This manoeuvre allows to better characterizing sun diffuser BRDF resolving the remaining dependency on SAA. Re-doing this exercise for the B-unit is seen as an absolute must.** The spectral calibration results were also presented with similar results between MERIS and OLCI.

As a general lesson from MERIS experience, increasing effort and budget should be allocated to instrument pre-launch characterization. This includes both the measurements as well as the data analysis. Some instrument features observed during operations (e.g., spectral smile) are in fact difficult to be characterized in-flight and to correct within the geo-physical retrieval algorithms.

D. Smith (RAL, UK) presented "(A)ATSR and SLSTR VIS/SWIR Channels Calibration". The key differences of SLSTR and the legacy ATSR instrument, which could affect the calibration, were pointed out. These differences do not allow a smooth transition/adaptation from one system to the other and this is important to be carefully addressed in the pre-launch calibration. In-flight calibration is performed with the Viscal unit for the solar bands, while two Blackbodies (BB) are used for the upper and lower range of the TIR bands. The pre-launch calibration of SLSTR and OLCI is achieved with the support of the National Physical Laboratory (NPL). NPL have performed measurements using spectroradiometers and reference source at host institution. The measurements results between (Rutherford Appleton Laboratory) RAL and NPL had good agreement for channels S1-S3, S5, while some discrepancies were observed for channels S4 and S6.

The availability and discoverability of on-ground Calibration/characterization database (CCDB) was discussed at this point among all the participants. **It was stated that CCDB should be accessible to users during the mission lifetime, and beyond for preservation and potential re-analysis. The availability of**

these data is key for Level 1 traceability. However, potential restrictions may apply and need to be agreed with the instrument providers.

Then, it was mentioned that SLSTR experienced contamination effects, as already observed for AATSR, due to outgassing and the subsequent build-up of a thin condensation layer. A regular decontamination is needed in this case.

The Pseudo Invariant Calibration Sites (PICS) are used for radiometric validation. The results of the calibration of ATSR series over Libya-4 were shown, demonstrating good stability and consistency after applying BRF correction. Moreover, the cross-comparisons of SLSTR with OLCI and MODIS indicated significant bias (10-20%) in the SWIR channels that is not fully explained. Generally, the radiometry for the nadir view is more consistent, while some remaining issues are observed for the oblique view.

A discussion followed on what is the right "reference" for radiometric calibration. The discussion will be ongoing in the frame of CEOS-IVOS.

B. Lafrance (CS, France) presented "Sentinel-2 L1 Radiometric Calibration". The radiometric calibration is performed on-board with a sun diffuser. The radiometric uncertainty is below 5% considering a combination of absolute calibration with sun diffuser, dark signal calibration over ocean at night and vicarious calibration.

The importance of having an accurate pre-launch BRDF characterization for the sun diffuser was underlined by several participants. In the presented results, variations (up to 0.6%) were observed for B01 and B08 bands between the currently operational and the improved BRDF models of S2. The improved BRDF model smooths the irregularities within the detectors and enhances linearity and stability. Moreover, contamination effects were observed in the SWIR channels (B10, B11, B12), which were caused by outgassing and build-up of condensation thin layer. For this reason regular (6-months) decontaminations are planned. Some sensitivity degradation (0.6-1% depending on the band) was also observed for VNIR bands. Additionally, the evolution of gains variation correlates well with variation of SAA, a fact that demonstrates the need to refine the BRDF model.

A discussion was initiated at this point on the recently discovered **erroneous S-2A Spectral Response Function (SRF) for B01 and B02.** An investigation is on-going by the instrument provider to understand the issue and conclusions will be made public towards the end of the year. The impact of this issue on vicarious calibration was discussed. It is expected to be relevant for Rayleigh calibration method, while different SRFs would have less impact over spectrally uniform and bright desert site. Another issue on the **S2 SRFs inter-detector module variability** was reported (causing the so-called spectral noise). For this issue, it was suggested to contact Landsat team, since they faced similar issues.

S. Sterckx (VITO, Belgium) presented "Proba-V Radiometric Calibration". In Proba-V there is not on-board calibration device and the in-flight calibration is uniquely based on vicarious methods. In particular, observations over desert sites and oceans are used for the absolute calibration and the accuracy requirement is 5%. For the inter-band calibration, observations over deep convective clouds (DCC) are used, while for the multi-temporal calibration, observations over the desert sites are again used together with one observation every month of the moon. In both cases the accuracy requirement of the relative calibration is 3%. The calibration methods used for Proba-V were recalled and briefly explained.

The evolution of the band degradation over Libya-4 was shown. There was no obvious degradation for VNIR bands, while for the SWIR band a slight decreasing trend of about 1%/year was observed. Moon observations at a phase angle of 7° are used for the radiometric stability monitoring. The lunar calibration results were presented for the VNIR bands. The DCC method is used to derive inter-band calibration coefficients.

In the following discussion, the instrument's degradation over Libya-4 was analysed. For VNIR channels the observed trend is not statistically significant and well within the accuracy of the method. It is odd though that SWIR band degrades more that VIS channels, while one would expect increasing degradation when moving towards the blue channel. This issue will need to be addressed in the frame of Proba-V Quality Working Group (QWG). An explanation for the observed trend in the SWIR channel should also be identified.

Then, S. Sterckx presented the calibration results using Raylroad Valley site, which is part of RadCalNet. This site is suitable for Proba-V bands with 100m spatial resolution. It was suggested that also the newly included Gobabeb site could be used for Proba-V 100m pixel, while the other sites are mainly suited for HR sensors. Overall, the radiometry is very consistent with the TOA signal provided by RadCalNet, though, some bias is observed in the SWIR. This fact should also be further investigated.

A reference was also made to 90^{o} yaw manoeuvre performed by Proba-V, in order to characterize pixel-to-pixel gains. The first attempt allows to effectively characterizing the SWIR band for the center camera. For the side views camera additional pitch is required to reduce BRDF effects. It was mentioned Landsat also performed that similar manoeuvre.

J. Ackermann (EUMETSAT, Germany) presented "AVHRR operational calibration". An overview of AVHRR instrument was given with a reference to its spatial resolution of 1 km, lower than the earlier presented instruments, and the absence of any on-board visible (VIS) calibration target. The operational AVHRR/3 sensor calibration for the VIS channels relies on vicarious calibration (Libyan Desert) updated on a monthly bi-monthly basis by NOAA. In particular, the operational gains are derived by NOAA and directly applied by EUMETSAT in the operational chain. Regarding the IR channels, they use measurements of space and of internal warm BBs sampled during each scan. The results of the desert calibration for Channel 1 and Channel 2 are shown. Seasonal variations are observed with a slight degradation trend.

For AVHRR/3 Channel 1, GOME-2 instrument is also used to build simulated pseudo-AVHRR radiance. GOME-2 is used as reference for assessing AVHRR radiometry. For TIR channels a similar approach is used, where IASI hyper-spectral sensor is used as reference.

2.1.3 NASA Experience

J. Xiaxiong (NASA, USA) presented "Inflight Radiometric Calibration: NASA Experience". A brief description was given on MODIS, VIIRS, and OLI Instruments and their spectral coverage. The on-orbit calibration for MODIS (Terra/Aqua) and VIIRS was reported. It was referred that an issue with the solar diffuser door of

MODIS (Terra) caused significant increase on diffuser degradation rate. The assessment of the consistency of MODIS (Terra/Aqua) over PICS was shown and it was within the range of 2%.

For stability monitoring, the moon is operationally used for MODIS and Landsat. **It was pointed out that polarization effects need to be carefully addressed, which may have impact on long-term trend analysis.**

Concerning L8-OLI calibration, in addition to on-board diffusers calibration, additional yaw manoeuvre is planned every 4 months to characterize pixel-to-pixel gain and their changes during mission lifetime. The degradation for the different channels is presented, the strongest degradation is observed in the deep-blue Band-1 used for coastal aerosol. **The experience on OLI's calibration demonstrated the effectiveness of using multiple and complementary calibration methods**; the different methods for OLI are very consistent, while this was not the case for ETM+.

2.1.4 Radiometric Comparison I

V. Lanjou (CNES, France) presented "Sentinel-2 absolute calibration monitoring". The different vicarious calibration methods over natural targets, which are used by CNES, were presented. Over oceanic sites, Rayleigh calibration method is adopted with global RMS error ranging from 3 to 4% depending on the band. Over deserts and snow sites, only cross-calibration is performed, with a reference sensor. The inter-band calibration based on DCC was also described as a very reliable method, with an error for multi-temporal calibration around 0.5% and for inter-band calibration around 1%.

In particular, for Sentinel-2 absolute calibration, the results of the **cross-calibration over PICS with different reference sensors (MERIS, MODIS and Landsat-8) showed that S-2 is very consistent with MERIS radiometry (1-2%). The results between S-2 and MODIS and Landsat-8 are in good agreement as well, around 3-4%.** The inter-calibration between S-2A and S-2B was also performed showing that both instruments are consistent within 1-2%, although the official spectral response function (SRF) was used, which is considered incorrect and needs to be corrected. This fact triggered a discussion on the impact of the differences between the SRFs. It was not clear why it affects only the bands B01 and B02. The impact of this change should be more pronounced within the Rayleigh calibration results. Concerning the inter-band calibration on DCC all bands are consistent within 3%, apart from band B8A with 4%.

M. Bouvet (ESTEC, Netherlands) presented "Assessment of the OLCI radiometric performance" and "S3-A/SLSTR radiometric assessment". The first results were the comparison between OLCI radiometry and a 'TOA model' reconstructed from 10 years of MERIS data. OLCI seems to be slightly brighter than MERIS over Libya-4. Overall band-to-band consistency is in-line with MERIS. The following results of OLCI observations to simulations of TOA signal over ocean showed that there is a bias between observations and simulations, whose source has still to be identified.

The same methodology and sites were used for SLSTR sensor. The radiometry of nadir and oblique views seem different, this is in-line with results observed at RAL. The validation over Libya-4 showed that SLSTR is 3% brighter than MERIS in the VNIR channels.

2.2 Day 2: 31 January 2017

2.2.1 Radiometric Comparison II

C. Desjardins (CNES, France) presented "Radiometric comparison: Validation of the Sentinel-3A OLCI/SLSTR radiometric calibration". Regarding the S3 OLCI and SLTRSR, all the methods performed by CNES and presented the previous day by V. Lanjou, are implemented, apart from DCC that is only implemented on OLCI. The cross-calibration results between OLCI versus MERIS and SLTR versus MODIS showed very good consistency over desert sites.

In the following discussion the comparison over desert sites was analysed. **F. Gascon (ESA, Italy) suggested that it would be interesting to have inter-comparison results (actual values) over PICS computed by the different institutes in the form of a table to compare results for similar sites and similar methods (e.g., deserts, Rayleigh).** This summary table would give insight on the overall consistency between OLCI-SLSTR and help to converge to common conclusion. A collection of the inter-comparison results of S-2 and S-2 with vicarious methods from the different institutes was agreed.

The results of the SLTSR vicarious calibration over desert showed a bias for the SWIR (10-20%) with respect to MODIS/S2MSI/AATSR/MERIS. The residual bias for OLCI VNIR bands is in the order of 2-3%.

In the discussion that followed, N. Fox (NPL, UK) mentioned that there is a group of consistent sensors, though the uncertainty of the methods does not justify the conclusion that this group is correct. **A proposal came from CNES to harmonize the definition of ROI for desert sites (S-2/S-3).** At the moment for S-2 smaller ROI sites for deserts are used. The S-2 MPC team suggested providing the list and specifications of the S-2 sites and then S-3 MPC team to extract these S-2 adapted ROI over desert sites.

B. Alhammoud (ARGANS, UK) presented "Level-1 radiometry Inter-comparison from multi-sensors: MERIS-MSI-MODIS-OLCI-OLI". An overview of MERIS, MODIS, MSI, OLCI and OLI features was given, together with a brief description of the vicarious calibration methods of DIMITRI toolbox. The PICS CEOS Cal/Val sites used in the project were shown; pointing out the different size of ROIs selected for HR and MR sensors. The results for MERIS 3rd reprocessing radiometric validation over desert sites were very stable in time. A known limitation of Dimitri for two O2 absorption bands was observed, but apart from these two bands, the other bands were within 2% variation. For OLCI's radiometry validation over PICS desert sites, the results seemed to be improved with time, although initially a small bias was observed. The uncertainty in the plot presented was fixed to 5% as the uncertainty of the method.

In the following discussion on uncertainty, **N. Fox (NPL, UK) suggested that it would be important to break down the uncertainty in the various components and in particular the systematic and random component.** M. Bouvet (ESA, The Netherlands) mentioned that the error bars of 5% for desert calibration is a combination of systematic and random uncertainty. The random contribution was estimated as the RMSE of time series of the ratio model/observation and it was in the order of 2-3%, depending on the wavelength. In terms of systematic uncertainty, the bias was in the order of 1-2%. N. Fox (NPL, UK) closed the topic mentioning again the importance to provide information on systematic and random error components.

Going back to the presentation, the results of the OLCI radiometry validation showed about 2% positive bias. Concerning the S2-MSI validation, the results over PICS were within 3% for all bands. The case of S2A/MSI validation using RadCalNET over Railroad Valley was then presented. The results showed that for all bands the agreement was within 3-5%. The results were really good also for SWIR bands, this was not the case for the initial validation at this site. For the inter-comparison results of MSI-OLI over PICS sites, the two instruments were in good agreement to within 3%. There was a remaining bias for band B02, an issue that can be justified by the error in S-2A SRF used. To conclude, all the results for S-2A MSI were within 3%, while the inter-calibration results between S2A and S2B over PICS were for VNIR bands within 1% and for SWIR bands within 2-3%. For all sensors, the inter-comparison results were as following: MERIS close to 1 (reference), OLCI ≈2-3% positive bias, and for all the others within 1%.

2.2.2 Vicarious Calibration Methods

L. Bourg (ACRI, France) presented "Radiometric validation using Deep Convective Clouds observations for Sentinel-2 and Sentinel-3/OLCI" (SEOM project). A remaining uncertainty was observed in the DCC method linked to micro-/macro-properties of clouds (ice/water content and properties), which needs to be further investigated. It was pointed out that using different cloud models, you can get 1-2% difference, a fact that should be stressed when presenting DCC results. There is an uncertainty in the retrieval of cloud optical thickness (COT), which is retrieved from Red band that is then used as a reference band.

N. Fox (NPL, UK) presented "RadCalNet to PICS an interoperability framework". The scene/pixel dependent uncertainty and the lack of standardisation/interoperability were among the challenges mentioned when using satellite multi-sensors data products. The first step in order to have consistent information is at least to be sure that there is interoperability of L1 TOA radiance/reflectance. To achieve that goal, CEOS/IVOS proposes a key Infrastructure to be established and maintained independent of sensor specific projects and/or agencies. Their vision actually is **to establish community agreed references allowing for L1 TOA inter-comparison and the associated means of how the different sensors can link with it.** The idea is about harmonisation not homogenisation, meaning that the sensor-specific issues will remain and the 'reference' will not be used to force sensor X to appear as sensor Y. The applications of such a service could be data-cubes, FCDR and CDR. What can be done now is to start collecting information on inter-comparison of current and future sensors in common format. This information could be stored potentially on the Cal/Val portal, but with caution and in a controlled database (DB), because the users may be confused looking at different results. In order to share the comparison results a single repository would be preferable, where all the necessary information would be stored. It was pointed out that the time is right to start collecting data by filling this DB, at least for European optical sensors. The key issues for radiometric calibration are reported, they include: a comprehensive pre-launch characterization, the presence of an on-board system (at least on some sensors) to understand how the sensor performs in all parts of the orbit, the need to consistently evaluate and communicate the differences (ideally SI traceable) between sensors and to evaluate/improve vicarious Cal/Val methods.

A way to start implementing this idea is **to use RadCalNet to do the transfer to the PICS and allow this transfer calibration to other sensors.** As an example S2 radiometry validated over RadCalNet sites can be transferred to S3 (or another MR sensor) radiometry through the PICS. The priority sites for cross-comparison of L1 are already defined from the CEOS reference standard sites. There are still some open issues/questions, i.e. if we need to agree on all the physics behind, radiative transfer, and spectral response adjustment.

X. Briottet (ONERA, France) presented "PICS characterisation – New development". The main goals of this work are the revision of the PICS list over desert areas defined 20 years ago and the definition of certain selection criteria to identify sites suitable for vicarious calibration. The intention of this project is also to define a shortlist of PICS and collect some sand samples, in order to characterize them in the laboratory, in terms of micro-physics and optical properties.

The site selection criteria were mentioned and the decision tree for their choice was shown. The results confirm Cosnefroy' sites selection for most sites, but also some optimal new sites are identified, such as Namibia1 and Arabia4. Some sand samples will be collected over these areas and sand spectral BRDF measurements will be performed at Onera. All data will be hosted in Cal/Val portal, and free access will be guaranteed to interested users.

In the discussion that followed, K. Thome (NASA, USA) asked if there is any plan to provide protocols on how to use these sites. X. Briottet (ONERA, France) mentioned that for the moment this is not foreseen, but at the end of this work the possibility to provide such guidelines will be evaluated. F. Gascon (ESA, Italy) whether dark sites will be also included to explore the possibility of having calibration sites at low radiance. This option is not foreseen within the project, selection is limited to bright sites.

B. Berthelot (Magellium, France) presented "PICSCAR status". The goal of this project is to survey the usage of PICS within the user community; in order to do that a questionnaire was distributed to the users. The main result of the questionnaire showed that the CEOS PICS sites are the most used ones, in particular Libya-4 site. The ROIs selected by different users for various PICS were shown. The interesting conclusion at this point was that the **users do not use the same ROI over a PICS site; an example was demonstrated here over the most popular site of Libya-4.** This means that although they refer to site with the same name, they do not use the same site at all. Therefore, a harmonisation is definitely needed.

In order to monitor the stability of the site, a normalised reflectance was computed with the help of the BRDF model computed using PARASOL data. An application over PICS-Libya desert was shown for various data collections, i.e. FY-3, MERIS, VGT2, PROBAV, S2A/MSI, S2B/MSI. According to the results of the normalisation of the BRDF on FY-3, the Bottom-Of-Atmosphere (BOA) normalized reflectances show strong reduction of spread. For MERIS data acquisitions of ten years, when the ROIs are of different areas, the variation of the BOA reflectances is the same but the actual values differ. After the BRDF normalization these values converge. The corrected for BRDF results of VGT2 and Proba-V seem to be very consistent in radiometry all along the full time series. All the results of this project will be provided on PICSCAR portal. AATSR was missing in this analysis, but RAL is interested in providing data. In general, the survey is still open to additional contribution.

Y. Govaerts (Rayference, Belgium) presented "Recent developments in Lybia-4 spectral and directional characterization". The comparison of three Radiative Transfer Models (RTM) simulations, i.e. 6SV

(Hitran96), RTMOM (Hitran96), LibRadTran (Hitran04), with respect to MERIS observations in the visible range over Libya-4 was demonstrated. The relative standard deviation of the results was in the range of 1%, though some problems were observed when moving toward the blue edge, where it can reach 2%.

To understand these differences, a comparison with GOME data was performed over Libya-4. At short wavelength there was larger discrepancy between observations and simulations. The various RTMs have in general different behavior, with LibRadTran performing slightly better that the others at short wavelength. It was mentioned also that all models were implemented on band-mode and not line-by-line. It was also stressed that there is not NO_2 absorption in RTMOM and 6SV, because it is not included in the used spectroscopic database (Hitran96), similarly for O_4. This fact explains some of the observed differences with respect to LibRadTran, which uses Hit04. On the other hand, the 6SV model is the only one to include polarization. All these differences on the models could explain also the differences on the results. The RTMs agree within 1% where gas transmittance is close to 1.

Then, BRF simulations over LIBYA-4 were presented. The goal of this work is to analyze surface reflectance azimuthal dependencies due to sand dune topography for different regions-of-interest (ROIs) using 3D Monte Carlo ray-tracing RTM. It was mentioned that Libya-4 dunes are pretty stable in time. The BRF calculated for Libya-4, was considering only sand dunes topographic effects, while the sand in itself is considered as Lambertian. It was observed also that the dunes are introducing directional effects, which can vary when comparing morning and afternoon orbits. If the atmosphere will be added, the scattering will reduce this effect.

The recommendations referred at the end of the presentation included the need to develop a 3D RTM to solve issues related to topographic effects, this will allow to reach the required 1-3% accuracy in the vicarious methods. For Libya-4 site, it was pointed out that it has a lot of topographic complexity, but it is pretty stable. Generally, a ROI of 50km was recommended. Libya-4 site is probably not the best site for High Resolution sensors, except if there is an accurate representation of the topography. The sand dunes may have an effect reaching 1% between morning and afternoon orbits.

In the following discussion, the sources of uncertainties were questioned when using this kind of 3D model. Pathfinder mission was also proposed in order to further characterize some sites.

Y. Govaerts stressed that the new required RTM accuracy driven by vicarious calibration of Sentinel satellites (better than 3%) will necessitate the development of a new generation of RTM, able to handle 3D effects of any complexity and scale for a non-flat Earth; this new RTM should allow accurate simulation of satellite TOA signal over any land surfaces and water bodies and for all atmospheric media; furthermore, this new RTM should include full radiative coupling between these media (surface-atmosphere) and be able to model polarization and IR emission. Y. Govaerts mentioned that a project will start next year with the aim to develop this RTM as a community open source code; contribution from a large scientific community within Europe will be fostered and gathered.

2.2.3 GSICS experience

T. Hewison (EUMETSAT, Germany) presented “Introduction to GSICS and inter-calibration monitoring at EUMETSAT”. GSICS stands for Global Space-based Inter-Calibration System. It is actually a system for the generation of inter-calibration coefficients for GEO/LEO meteorological sensors. The interoperability is the final goal of this project and World Meteorological Organization (WMO) was the initiator. The GSICS products are free and open to the users. The IR channel was the first to be calibrated, and then the algorithms for VIS/NIR channels followed and today UV and MW domains are involved in the calibration corrections. At the beginning only Near-Real-Time (NRT) correction functions were available, while today re-analysis corrections have been added.

Concerning the IR channels corrections, an overview of the correction, based on SNO of GEO-LEO sensors with IASI Hyper-spectral sensor, was given. The spectral convolution of IASI radiance with the SRF of GEO imagers was shown. Generally, it resulted in a linear correction of the radiances. The SLSTR-IASI IR comparison was also presented. The results though were only for nadir, but some SLSTR straighlight effects are still visible. For the calibration of the GEO-LEO VIS channels the DCC method is implemented and the PICS are used to transfer calibration from reference sensor. In addition, Eumetsat is leading the Moon project for improving the lunar calibration model. Actually, GSICS implementation of the ROLO model (GIRO) reaches 1% relative uncertainty. The moon is used as a pseudo-invariant target for stability monitoring. The GSICS Lunar Observation Dataset (GLOD) contains basically Moon observations from all instruments using GIRO and it helps that way to arrive to an agreed absolute calibration of GIRO and develop inter-calibration methods. The 2nd Lunar Calibration Workshop will be in Xi’an (China on 13-16 November 2017.

In the following discussion, N. Fox (NPL, UK) pointed out that a priori there is no need of having a reference sensor, although for GSICS this was assumed. This is specific case, but going more generic this assumption is not always needed. But what we still need is to define which is the right reference for radiometric absolute calibration, this question will be specifically addressed at the next CEOS/IVOS meeting. Y. Govaerts (Rayference, Belgium) mentioned that we could maybe already define the requirements for a reference. F. Gascon (ESA, Italy) agreed on that and he proposed that we should start already from what we have, e.g. starting with RadCalNet. N. Fox (NPL, UK) indicated at this point the need to review the methodologies for vicarious calibration.

2.2.4 Alternative Methods

Steve Mackin (EOSense, UK) presented “Alternative Methods for the assessment of radiometry and image data quality”. The basic principle of his approach is that Cal/Val data are available in any image. The advantage in this case is that there is no need of collecting specific data over target sites and it is potentially possible to update the calibration coefficient in NRT. Basic statistical analysis is used to extract the various components of the signal and derive several parameters of interest for instrument characterization and calibration: e.g., relative gains, focus, SNR. An example of AATSR gain evolution during the whole mission is shown; the results match really well the RAL results over PICS. The results for S2B relative gains were also presented. An issue with one detector was spotted, which was largely solved with the first on-board calibration. The corresponding results for MERIS demonstrate an abrupt change in the signal corresponding to a specific orbit. It seems something has changed during the mission, but the root cause of the problem is not clear.

3 APPENDICES

3.1 Appendix A: Agenda

The European Space Agency (ESA) organized a Workshop on Radiometric Calibration for European Optical Missions held in Frascati (ESA/ESRIN), Italy, 30-31 August 2017.

The presentations are available online at: https://earth.esa.int/web/sppa/meetings-workshops/expert-meetings/workshop-on-radiometric-calibration-for-european-optical-missions/programme.

Agenda

Day 1: Wednesday, 30th August 2017 - James Cook Room			
Introduction			
09:00 - 09:05	Philippe Goryl	ESA	Welcome and Introduction
09:05 - 09:15	Steffen Dransfeld/ Ferran Gascon/ Fabrizio Niro	ESA	Objectives
Missions Operational On-flight Calibration			
09:15 – 09:45	Ludovic Bourg	ACRI	MERIS/OLCI calibration
09:45 – 10:15	Dave Smith	RAL	(A)ATSR and SLSTR VIS/SWIR Channels Calibration
10:15 – 10:45	Bruno Lafrance	CS	SENTINEL-2 L1 RADIOMETRIC CALIBRATION
10:45 – 11:00	Coffee		
11:00 – 11:30	Sindy Sterckx	VITO	Proba-V calibration
11:30 – 12:00	Jörg Ackermann	EUMETSAT	AVHRR/3 Operational Calibration
12:00 – 13:00	ALL		DISCUSSION
13:00 – 14:00	Lunch		
NASA Experience			
14:00 – 14:45	Jack Xiaxiong	NASA	Inflight Radiometric Calibration: NASA experience
Radiometric Comparison			
14:45 - 15:30	Vincent Lonjou and Camille	CNES	Sentinel-2 and Sentinel-3 absolute calibration monitoring

	Desjardins		
15:30 – 16:00	Bahjat Alhammoud	ARGANS	Level-1 radiometry Inter-comparison from multi-sensors: MERIS-MSI-MODIS-OLCI-OLI
16:00 – 16:30	Marc Bouvet	ESA	Assessment of the OLCI radiometric performance & S3-A/SLSTR radiometric assessment
16:30 – 18:00	ALL		DISCUSSION: Open points, issues
Day 2: Thursday, 31st August 2017 - James Cook Room			
Vicarious Calibration Methods			
08:30 – 09:15	Nigel Fox	NPL	RadCalNet to PICS an interoperability framework
09:15 – 09:45	Xavier Briottet	ONERA	PICS characterisation–New development
09:45 – 10:15	Yves Govaert	Rayference	Recent developments in Lybia-4 spectral and directional characterization
10:15 – 10 :30	Béatrice Berthelot	Magellium	PICSCAR Status
10:30 – 11:00	Yves Govaert	Rayference	Verification of MSI Low Radiance Calibration Over Coastal Waters, Using AERONET-OC Network
11:00 - 11:15	Coffee		
GSICS experience			
11:15– 11:45	T. Hewison/B. Bojkov	EUMETSAT	Introduction to GSICS and inter-calibration monitoring at EUMETSAT
11:45 – 13:15	ALL		DISCUSSION Open points, issues
13:15 – 14:00	Lunch		
Alternative Methods			
14:00 – 15:00	Stephen Mackin	EOsense	Alternative Methods for the assessment of radiometry and image data quality
15:00 – 17:00	ALL		DISCUSSION and CONCLUSION
17:00	END		

3.2 Appendix B: Participants

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