RECOVERY OF MVIRI/VIS BAND SPECTRAL RESPONSE

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Abstract

A new reverse engineering method for the recovery of the MVIRI/VIS band launch-time sensor spectral response and its spectral ageing is presented here. This method, developed in the framework of the H2020 FIDUCEO project, supports the generation of a fundamental climate data record from archived MVIRI data. This reverse engineering method relies on advanced radiative transfer modelling over PICS and inverse modelling techniques. It has been verified recovering the SEVIRI/HRVIS band that has been accurately characterized on ground and then applied on Met-7 MVIRI/VIS band data.

INTRODUCTION

The Meteosat Visible and Infrared (MVIRI) sensor on-board Meteosat First Generation (MFG) satellites (1982 - today) acquires radiances every 30 min in a single large spectral band, ranging approximately from 0.4–1.1µm, referred to as the visible (VIS) band. The primary objective of the MFG program is the acquisition of earth atmosphere images and their near real-time dissemination to the meteorological user’s community. Consequently, requirements on the accuracy of the pre-launch Sensor Spectral Response (SSR) characterization were rather loose. In addition to these limitations, degradations of the spectral response shape have already been reported. This spectral ageing process results from a faster degradation in the blue than in the near-infrared part of the VIS band (Decoster et al., 2013a).

Despite all these issues, the potential value of MVIRI data for climate monitoring should not be underestimated. During the late 1970s and early 1980s, space-borne observations of the Earth were very scarce, essentially limited to geostationary meteorological observations and a few polar platforms. The Fidelity and Uncertainty in Climate Data Records from Earth Observation (FIDUCEO) research project aims at reducing and quantifying the uncertainty on the instrument SSR characterisation to facilitate the creation of optimal consistent long-term data records. In the context of this project, a new reverse engineering method has been developed for the recovery of the MVIRI/VIS spectral response and its uncertainty, including the temporal ageing effects. This method allows thus the recovery of the SSR at launch time and the characterization of its spectral degradation. This method is based on observed count value spectral deconvolution over Pseudo Invariant Calibration Sites (PICS) such as deep convective clouds, bright deserts, and ocean targets viewed under different illuminating and atmospheric conditions. Top-of-atmosphere spectral radiances over these targets are accurately simulated to support this deconvolution. The improved radiance observations should permit to derive consistent ECVs like surface albedo and aerosol properties from MFG observations.

Early results of this method and its evaluation are presented in this paper. First, it has been applied for the recovery of the Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) high-resolution visible (HRVIS) band SSR, which in essence is similar to the spectral response of the MVIRI VIS band, but was accurately measured pre-launch. It is next applied on Meteosat-7 data.
EVIDENCE FOR MVIRI/VIS BAND SSR ANOMALIES

Anomalies and inconsistencies in the generation of a Fundamental Climate Data Record (FCDR) and a Climate Data Record (CDR) based on MFG MVIRI/VIS band data have already been reported. Performing calibration over sea and bright desert PICSs, Govaerts (1999) reported inconsistent calibration results of MVIRI/VIS band of Meteosat-5 and -6 when using the pre-launch SSR of these instruments. Such inconsistencies revealed inaccuracies of the SSR pre-launch measurement of these instruments resulting in the derivation of different calibration coefficients over spectrally different targets. Decoster et al. (2013b) also reported evidence of pre-launch SSR characterization problem of Meteosat-7 MVIRI/VIS band. In addition to this lack of a reliable pre-launch characterization, the systematic calibration of MVIRI/VIS band has shown a faster degradation over sea than over bright deserts that is due to a non-uniform degradation of the SSR (Govaerts et al., 2004).

As a consequence of this lack of pre-launch characterization, surface albedo CDR generated from the entire MVIRI/VIS archive revealed temporal inconsistencies (Löw and Govaerts, 2010). These authors proposed a post-processing method to remove suspicious biases and trends in this data set but did not report inconsistencies with the Meteosat-7 pre-launch SSR values. However, such approach is far from ideal for the generation of consistent CDR. Hence, the FIDUCEO Horizon 2020 project aims to reduce and quantify the uncertainty on the instrument spectral response characterisation to facilitate the creation of long-term consistent and high-quality data records of surface albedo and aerosol optical depth for climate applications. In this context, an innovative reverse engineering method has been developed for the MVIRI/VIS SSR recovery and its spectral degradation. This method is presented in the next section.

REVERSE ENGINEERING METHOD

Overview

The objective of the retrieval method is the recovery of the MVIRI/VIS band SSR $\xi(\lambda, t)$ as it would have been characterized pre-launch and to monitor its spectral ageing. The following simple instrument model expressing the digital count value $K$ as a function of the incoming spectral radiance $R(\lambda)$ is used

$$ K = \gamma(t) \frac{\int \xi(\lambda, t)R(\lambda) d\lambda}{\int \xi(\lambda, t) d\lambda} + K_0 + \epsilon_K $$

where $\gamma(t)$ is the instrument gain in [Wm$^{-2}$sr$^{-1}$µm$^{-1}$DC$^{-1}$], $R(\lambda)$ is the spectral radiance [Wm$^{-2}$sr$^{-1}$µm$^{-1}$] at the telescope entrance, $K_0$ the digital count offset and $\epsilon_K$ the radiometric noise. $K_0$ and $\epsilon_K$ are known from the telemetry and other ancillary information (Rüthrich et al, 2016). Its estimation is detailed in the next section. Digital count values $K$ is extracted from Level 1.5 images over well-characterised pseudo-invariant sites. Over these sites, it is therefore possible to simulate the spectral radiance $R(\lambda)$ at the entrance of the telescope. Hence, the instrument gain $\gamma(t)$ and the SSR $\xi(\lambda, t)$ are unknown in Equation (1). A specific inverse modelling method has been developed for that purpose which relies on prior information on the SSR and its spectral ageing.

Simulated spectral radiances

Top-of-atmosphere (TOA) spectral radiances in the MVIRI/VIS band spectral interval need to be simulated with a method that can be applied to the entire MFG era from 1982 up to now. Consequently, parameters that characterise the state of the surface and atmosphere have to rely essentially on climatology or reanalysis data, but cannot rely on products like those derived from MODIS. Three types of targets with different spectral signature are used, namely, bright desert, open ocean and Deep Convective Clouds (DCCs).

CEOS Libya-4 PICS has been selected for the TOA radiance simulation over bright desert targets. Surface and atmospheric properties have been documented according to Govaerts et al. (2013). Cloud and sand storm cases are identified by analysing daily variations of the observed count values. Clear-sky pixel detection is performed by fitting a second order polynomial to the daily cycle of observations. Any deviations from this polynomial is interpreted as a cloud contamination, cloud shadow, or sand storm. Observations of
that day are disregarded when the remaining number of clear-sky slots is too low after this daily filtering. Surface reflectance is represented with the RPV model (Rahman et al., 1993). Simulations are performed according to the method described in Govaerts et al., (2013). Error! Reference source not found. The accuracy of these simulations has been verified against well-calibrated instruments such as MODIS and MERIS. On the average, these simulations agree within ±2% with observations from these instruments when the sun and viewing zenith angles are limited to 40 degrees.

Sea targets are defined by large search areas in which cloud- and aerosol-free potential targets are identified, looking at uniform and very low digital count values outside the sun-glint regions (Govaerts et al., 2004). This procedure is used to ensure a very low aerosol optical thickness. The values of the surface wind speed and the total column water vapour are extracted from European Centre for Medium-Range Weather Forecasts (ECMWF) data, and a potential target is disregarded when the wind speed exceeds 7 m s⁻¹. Surface reflectance is simulated with the Cox-Munk model where surface wind direction and intensity are taken from ECMWF reanalysis data (Cox and Munk, 1954). Salinity and pigment concentration are kept constant.

Potential DCC pixels are identified looking at the brightness temperature in the thermal infrared band. Only uniform DCC with a temperature lower than 205 K are selected as potential DCC pixels. Spectral radiances are simulated over land and sea African tropical regions according to the description provided by Sohn and Choi (2015). The lower part of the cloud up to 7 km, is composed of water droplets with a constant effective radius. Above 7 km, the clouds are composed of ice particles with a vertical effective radius of 20 µm. The total Cloud Optical Thickness typically varies between 70 and 120.

An example of simulated spectral radiances over these three types of target is shown on Figure 1. The derivatives (Jacobian columns) of the simulated spectral radiance with respect to the state variables are calculated in order to estimate the corresponding uncertainties.

![Figure 1: Example of simulated TOA radiances over bright desert, sea and DCC in the Meteosat VIS band spectral interval.](image)

SSR prior information

The MVIRI/VIS band spectral response is composed of three main components:

- The Telescope Scan Assembly (TSA);
- The Focal Plane Optical Benches (FPOB);
- The Silicon detectors without spectral filter.

Unlike for SEVIRI, no information is available on the pre-launch characterization of these individual elements for MVIRI. For Meteosat-7, the primary mirror (TSA) is made of BK7 glass coated with evaporated aluminium and a protective SiO₂ layer. Figure 2 left panel shows an example of reflectance of a vacuum evaporated aluminium mirror before and after ageing (Nostell et al., 1998). The TSA is expected to be the most important component contributing to the spectral ageing. The FBOP, thought not pre-launch characterised, is not
supposed to exhibit important ageing effects. There is no unique responsivity of silicon detectors as can be seen on Figure 2 right panel but it can vary depending on its purity, thickness, temperature, etc. All possible TSA, FPOB et silicon optical properties have been combined to generate a prior value for the MVIRI/VIS band SSR. This prior information is only used in the near-infrared spectral region where less spectral contrast is available from the simulated spectral radiances.

![Figure 2: Left panel: Reflectance of a vacuum evaporated aluminium foil before (dashed line) and after 7 years of ageing (dash-dotted line) after Nostell et al. (1998). Right panel: typical normalized responsivity of silicon detectors.](image)

**Inverse modelling**

Using observations to infer the values of some model parameters corresponds to solving an inverse problem, which is usually stated as an optimisation problem (e.g. Tarantola 2006): which values of the model parameters yield the best fit to the observations? The generic FastOpt inverse modelling framework used to infer the Meteosat visible spectral response implements a probabilistic inverse problem theory (Tarantola 2005) that describes the state of information on any physical or empirical quantity by means of a probability density function (PDF). Prior information on model parameters is quantified by a PDF in parameter space and the observational information by a PDF in the space of observations.

To generically model the MVIRI/VIS band SSR, linear combinations of generalised Bernstein basis polynomials are appropriate. The response degradation of the visible channel is modelled by equations motivated in terms of physics (e.g. Krijger et al. 2014 and references therein) and is able to reproduce the results of empirical studies (e.g. Xiong et al. 2015). Possible biases arising from small unknown systematic errors in the spectral radiance simulation of mutually different target types can be included in the modelling. Typically, solving the inverse problem involves the optimisation of 10-20 model parameters, depending on the degradation model and bias correction chosen.

The cost function to be minimised includes two terms, which represent prior information and quantify the misfit between model and data, respectively. The minimisation of the cost function yields a maximum posterior probability estimate (mean, uncertainty and spectral error covariance matrix) of the absolute sensor spectral response. Computationally, the minimisation is carried out by a limited-memory variant of the Broyden-Fletcher-Goldfarb-Shanno algorithm that evaluates the gradient of the cost function and iteratively approximates the Hessian matrix (Gilbert and Lemaréchal 1989).

For calculating posterior error covariance matrix, Hessian and Jacobian matrices are computed by means of algorithmic differentiation (AD) of the source code through Transformation of Algorithms in Fortran (TAF) (Giering and Kaminski 1998, 2000, 2003). AD allows the accurate evaluation of exact derivatives at machine precision, with only a small constant factor of overhead and ideal asymptotic efficiency. Cost function and derivatives are evaluated in multiple parallel threads. A recent application of TAF has been described by Blessing et al. (2014) and references therein.

TAF decomposes the source code that evaluates the cost function into elementary functions, the derivatives (local Jacobian matrices) of which are known. The derivative code of the composite function is generated by applying the chain rule of calculus to the sequence of local Jacobian matrices. The multiple matrix product can either be evaluated in forward or reverse (or adjoint) order. Both modes yield identical gradient results,
but differ in performance. While reverse mode requirements grow in proportion to the number of output variables, forward mode requirements increase in proportion to the number of input parameters. The cost function gradient is evaluated in adjoint mode, while Hessian code (second derivatives) to calculate the error covariance matrix is generated by AD of the previously generated adjoint code in forward order. Jacobian code to propagate the error covariance is generated and evaluated in (vector) forward mode.

METHOD EVALUATIONS

The method reliability has been first evaluated against SEVIRI/HRVIS data. The SSR of this band has been accurately measured pre-launch and has characteristics very similar to the MVIRI/VIS one. In both cases no spectral filter is applied on the silicon detector. However, a relevant difference might be that the TSA of SEVIRI, unlike that of MVIRI (see above), is made of silver coated Zerodur with a thin protective SiO$_2$ layer. It is also expected that SEVIRI exhibits less degradation than MVIRI due to well specified requirements on that matter.

Data acquired by MSG-1 (MET-8) in 2005 have been used for that evaluation. Over Libya-4 and sea, digital count values and associated uncertainties have been extracted with the SEVIRI Solar Channel Calibration (SSCC) facility (Govaerts et al., 2004). Respectively 950, 721 and 676 observations have been extracted and simulated over Libya-4, ocean and DCC targets.

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Results are shown on Figure 3. A visual inspection of the left panel reveals that the HRVIS band can be reconstructed fairly accurately. The corresponding uncertainties are displayed on the right panel. The SSR error is calculated as the absolute difference between the pre-launch SSR (considered here as the truth) and the retrieved one. The corresponding root mean square error is 0.029. The root mean square uncertainty of the pre-launch measurement is about 0.017. The estimated root mean square uncertainty is much larger with a value of 0.093. On the average, our method is therefore capable to recover the SSR with an accuracy almost similar to pre-launch characterization.

METEOSAT-7 RESULTS

The Meteosat-7 spacecraft became operational in July 1998 and was operated over the zero degree position until early 2006 when it has been moved over the Indian Ocean. The MVIRI/VIS band SSR has been characterised pre-launch from 0.5 up to 0.9µm. Values outside this interval have been extrapolated. The launch-time SSR of MVIRI/VIS band has been recovered with our method. Results are shown in Figure 4, top panels. Within the 0.5-0.9µm interval, the retrieved SSR at launch time (1998) follows quite accurately the pre-launch value. The limited number of Bernstein basis polynomials used for the inversion prevents the retrieval of fine scale SSR variations such as the one presents around 0.55µm in the pre-launch curve.
However, there is no evidence that this bump is real as there is no uncertainties associated to these pre-launch measurements.

Seven years later, the spectral degradation of the VIS band response is noticeable (Figure 4, lower panels). This degradation occurs essentially in the 0.4 – 0.6µm spectral interval as can be seen on Figure 5.

Figure 4: Retrieval results for Meteosat-7 MVIRI/VIS recovery in 1998 (top row) and 2005 (lower) row. Left column: prior (grey), pre-launch (blue) and retrieved (red) SSR. Right panel: associated uncertainties. Horizontal dashed lines are the corresponding root mean square value.

Figure 5: Spectral ageing between 1998 and 2005 is shown is grey.
Table 1 summarizes the impact of the SSR on the calibration coefficient derived over the three target types. As can be seen, differences between the coefficients derived with the prelaunch SSR and the retrieved one are limited for MSG-1. With the prelaunch SSR, the coefficient derived over sea is about 3.5% (1%) lower than the one derived over desert (DCC). Assuming that the error on the MSG-1 SSR characterization is not significant and that SEVIRI response to intensity is linear, this 3.5% difference might result from inaccuracies in the simulated spectral radiances. There is no significant difference in the coefficients derived over the three spectral target types with the retrieved SSR.

For Meteosat-7, there are no significant differences (<1%) between the calibration coefficients derived over desert and sea with the pre-launch SSR in 1998. Seven years later, the coefficient derived over sea exceeds by more than 4% the one derived over desert or DCC with the prelaunch SSR as a result of the instrument spectral ageing. In our early results, the coefficient derived over sea with the retrieved SSR in 1998 is about 4% (2-3%) lower than the one derived over desert (DCC). In 2005, this difference is only of 1.4% and not significant with respect to DCC.

Table 1: Derivation of the calibration \([\text{Wm}^{-2}\text{sr}^{-1}\text{μm}^{-1}\text{DC}^{-1}]\) coefficients over the three target types from the pre-launch SSR and the recovered one. DDC (DDC) is for the DC pixels extracted over land (sea).

<table>
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<th>Year</th>
<th>Desert</th>
<th>Sea</th>
<th>DCC&lt;sub&gt;L&lt;/sub&gt;</th>
<th>DCC&lt;sub&gt;S&lt;/sub&gt;</th>
<th>MEAN</th>
<th>Desert</th>
<th>Sea</th>
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<th>DCC&lt;sub&gt;S&lt;/sub&gt;</th>
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<tr>
<td>MET-8</td>
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DISCUSSION AND CONCLUSIONS

This paper presents early results of a method developed to recover MVIRI VIS band SSR and its spectral ageing. The proposed inversion method generalises and enhances existing vicarious calibration concepts to fully trace all uncertainty information from end to end. For instance, merely using the diagonal elements of the spectral response error covariance matrix underestimates the actual total uncertainty by a factor of more than three. Therefore, the inversion calculates the full error covariance matrix of the reconstructed spectral response function to facilitate a complete propagation of uncertainties to subsequent calibration steps and to meet a main aim of FIDUCEO: to set new standards of accuracy and rigour in the generation of fundamental and thematic climate data records.

The application of our method on MSG-1 data has demonstrated that it provides reliable results. A similar evaluation will also be performed against MSG-3 data which has a better characterised HRVIS band SSR. This reliability is however limited by the accuracy of the simulated spectral radiances. Nonetheless, the possibility to quantify the spectral ageing of the SSR has clearly been demonstrated.

It is expected that these results will significantly contribute to FIDUCEO objectives and allow the generation of long-term consistent FCDR and high-quality data records of surface albedo and aerosol optical depth for climate applications.

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1 Pierre Olivier, personal communication.