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MERIS

SMILE EFFECT

CHARACTERISATION

AND

CORRECTION

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1 INTRODUCTION

1.1 Purpose

MERIS is an imaging spectrometer aboard of ESA's ENVISAT environmental satellite. It operates in the reflective solar spectral range (390 nm to 1040 nm) with fifteen spectral bands. The instrument has a field of view of 68.5^o and covers a swath width of 1150 km. The field of view is shared between five identical optical modules arranged in a fan fan-shape configuration.
The instrument images the Earth's surface using the 'push broom' method where the spectral signal is dispersed to illuminate a 2-D detector array for each imaging line, on which one direction represents the across-track direction (along the imaged line) and the other the spectral dimension. The 15 spectral bands, that are programmable by ground command both in width and in position by steps of 1.25nm, are constructed by first binning spectral samples directly on the array into micro-bands, and further grouping them digitally into bands before transmission to ground.

If a row on the detector array should ideally correspond to a constant wavelength across the field-of-view, actual characteristics of the optics and slight misalignments of the sub-systems generally induce small variations, often referred to as the "smile effect".

This document intends to present the so called "smile effect"which is visible in MERIS Level 1 radiances and describes the "smile correction" applied in the Level 2 processing and available in the BEAM toolbox (envisat.esa.int/beam).

1.2 Scope

This document intends to provide the MERIS users with an overview of the instrument spectral characterisation, highlighting the in-field variations of the spectral bands central wavelengths – known as the "smile effect" – and of the applied "smile correction" in order to highlight the impact of the above effect on the MERIS Level 1 and Level 2 data quality.

1.3 Acronyms

CCD	Charge Coupled Device
ESA	European Space Agency
FOV	Field-of-view
FWHM	Full width at half modulation
MERIS	Medium Resolution Imaging Spectrometer
TOA	Top of Atmosphere

2 THE SMILE EFFECT

MERIS is an imaging spectrometer on board of the ENVISAT satellite put in orbit by the European Space Agency on the 1st of March 2002. MERIS is mainly devoted to the ocean colour remote sensing and measures the solar radiation reflected by the Earth in 15 spectral bands, programmable in width and position, in the visible and near infra-red. For more details about the instrument refer to the dedicated webpage:

http://envisat.esa.int/instruments/meris/

MERIS is composed of 5 cameras and measures the reflected sunlight using CCD technique; indeed each camera is equipped with spectrometer and a two-dimensional CCD array installed at the optics focal plane. The picture below illustrates the CCD sensor: each CCD horizontal line provides an image line of the swath covered by one camera; the other dimension provides the spectrally dispersed radiance for each pixel along the image line, with a spectral sampling of 1.25 nm.

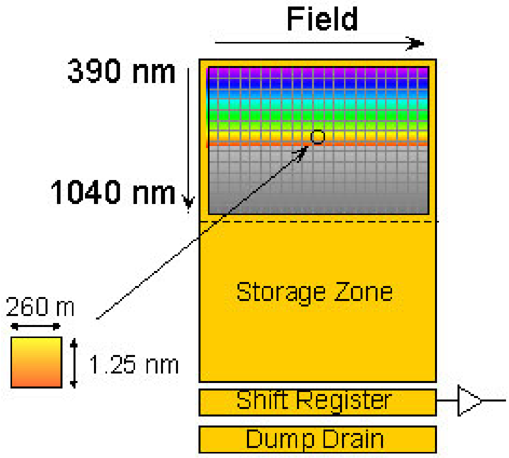

Figure 1: The CCD array. The pixel resolution on ground is 260m.

The current programming of MERIS bands constitute the so-called “SciHiO2” band set, introduced on December the 24th 2002 and still active to date. Its name refers to <u>Sci</u>entific band setting, <u>High</u> gains, and fine tuned for <u>O2</u> absorption measurements (band 11 was shifted by one spectral detector toward infrared with respect to previous SciHi band set). Its definition, in terms of detectors, as well as the corresponding spectral characteristics according to the theoretical spectrometer dispersion law are listed in.

The spectral measurements of each pixel along an image line are made by its own set of CCD sensors: this causes small variations of the spectral wavelength of each pixel along the image that constitute the so-called "smile effect". The variation of the wavelength per pixel can reach 1.7 nm from one camera to another, and 1.0 nm within one camera.

Table 1: MERIS current band settings (“SciHiO2” band set).

band	first spectral element	spectral width	central wavelength	start wavelength	stop wavelength	spectral width
	(detectors)		(nm)			
1	15	8	412.5	408.125	418.125	10
2	39	8	442.5	438.125	448.125	10
3	77	8	490	485.625	495.625	10
4	93	8	510	505.625	515.625	10
5	133	8	560	555.625	565.625	10
6	181	8	620	615.625	625.625	10
7	217	8	665	660.625	670.625	10
8	231	6	681.25	678.125	685.625	7.5
9	252	8	708.75	704.375	714.375	10
10	289	6	753.75	750.625	758.125	7.5
11	297	3	761.875	760.625	764.375	3.75
12	306	12	778.75	771.875	786.875	15
13	373	16	865	855.625	875.625	20
14	393	8	885	880.625	890.625	10
15	405	8	900	895.625	905.625	10

Even though this variation is small compared to the spectral bandwidth of a band, which is typically 10nm, and can hardly be seen in an image, it can cause disturbances in processing algorithms, which require very precise measurements, for example the retrieval of chlorophyll in the ocean or chlorophyll index over land. These disturbances can result in a visual artefact, "camera borders", or in a reduced accuracy of the Level 2 products.

2.1 The “smile effect” characterisation

The precise characterization of the spectral dispersion law called “smile effect”, for each of the 5 MERIS cameras, can be done using data acquired from the in-flight spectral calibration campaigns (see [1] or [2]).

The combination of the results from all the various campaigns (the Erbium doped diffuser on board calibration at 408 and 521 nm, the O2 absorption line calibration at 762 nm, the Sun’s Fraunhofer lines calibration at 394, 484, 587, 654, 853 and 864nm) allows covering almost all the MERIS spectral range and confirming the expected spectral slope, the so called “smile”, across the field of view for 4 of the 5 optical modules. See the figure below.

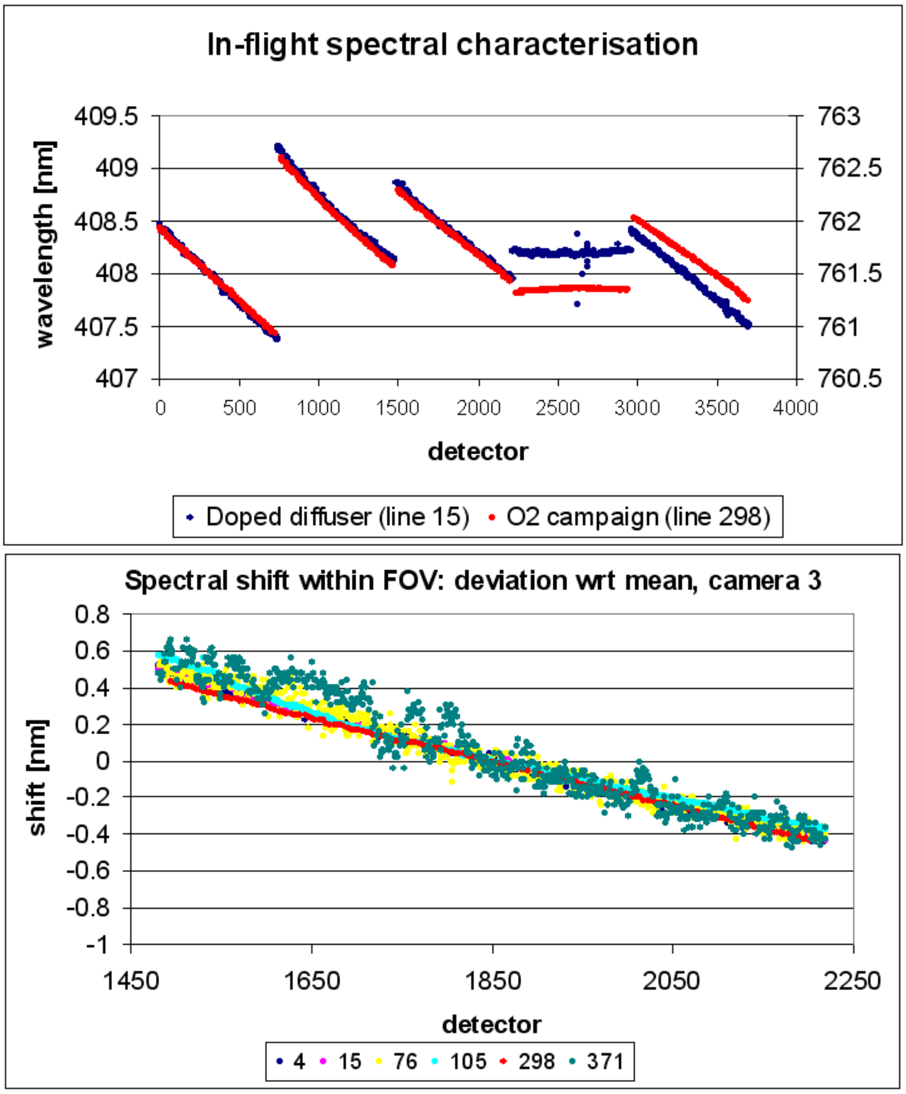

Figure 2: Top: Examples of in-flight spectral characterisation data highlighting the "smile effect". Bottom: Spectral shift within the FOV of camera #3 according to characterisation data at several detector rows spread over the whole spectral domain.

The spectrometer's "smile" has a very linear behaviour across the field of view of all cameras and this variation appears to be independent of the absolute wavelength.

The intra-camera "smile effect" has been characterised at several wavelength covering almost all the spectral domain of the MERIS nominal channels. The whole data set is summarised on the figure below.

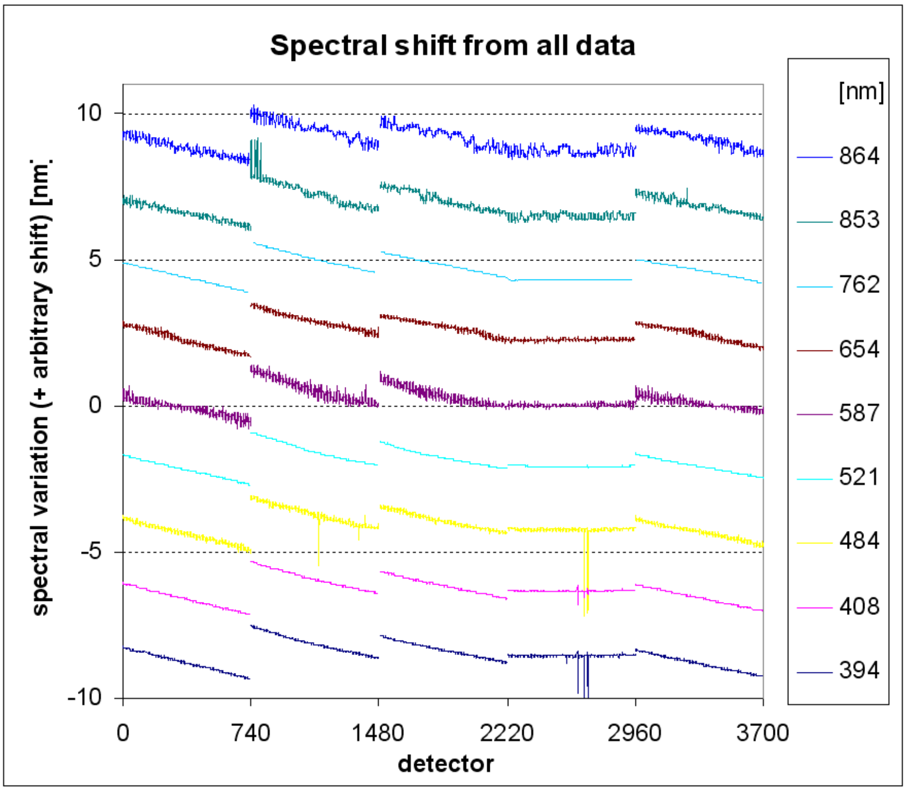

Figure 3: The “smile effect” at camera borders.

2.2 The MERIS Spectral Model

From the set of characterisation data presented above, and already available on-ground characterisation data, a model of the spectral behaviour of MERIS has been derived.
The Spectral Model of MERIS is aims at providing central wavelengths and spectral response curves for any of the MERIS elementary detectors, or any combinations of them. It thus allows to compute accurate spectral response curves at each MERIS band and for each spatial pixel.
This in turn allows to compute essential radiometric calibration parameters as e.g. in-band equivalent irradiances.

Even if the MERIS Spectral Model has a wider scope than the present document, it will be shortly presented here as it is the basis for the Smile Correction.

The set of in-flight spectral characterisation data allowed to

1. characterise central wavelength of several detector rows spread over the MERIS useful spectral range for every pixel
2. assess that the in-FOV variation of central wavelength does not vary significantly with absolute wavelength

From these characteristics it was decided to model the behaviour of detectors central wavelengths as a two terms: (a) the spectral dispersion law at each camera FOV centre as a function of the detector row and (b) the in-FOV variation around these values as a function of spatial pixel, or detector column. Those two terms are modelled as polynomials.

The on-ground characterisation of the spectral response of individual pixels allowed to assess that the resulting curve can be fitted by Gaussian curves to within an excellent accuracy. It also showed that the width of each curve vary with wavelength, i.e. with the detector row. This variation is also modelled as a polynomial.

The set of 3 polynomials constitute the Spectral Model of a MERIS camera. Combined with the MERIS channels definition, in terms of spectral rows to be combined into a given channel, allows to reconstruct the channel spectral response curve, form which one can derive the channel central wavelength (centre at half maximum) and the channel width (Full Width at Half Modulation).

The results of the latest version of the MERIS Spectral Model can be found in a Microsoft® Excel workbook at MERIS Spectral Characterisation - Wavelengths and Irradiances.
The Workbook contains 9 data sheets:

1. the central wavelengths of each FR pixel for each band (pixel 1 is East, pixel 3700 is west)
2. corresponding in-band irradiances (derived using above wavelengths, computed instrument response functions and reference irradiances from [3], scaled to Sun-Earth distance for MERIS reference day of year 95)
3. FWHM (full width at half modulation) of the instrument response functions for each band of each camera (each camera has 740 FR pixels – there is no FWHM variation for a given band within a given camera FOV -; camera 1 is east, camera 5 is west)
4. sheet 4 contains the reference Irradiance at 1 AU adopted for ENVISAT ([3])
5. sheets 5 to 9 hold the instrument response functions for cameras 1 to 5 (hence 5 sheets), for each band, computed at centre of FOV (between pixels 370 & 371). Each function is scaled to max=1.

It should be noted that, due to the regularity of the MERIS detectors spectral response, central wavelengths derived from the reconstructed channels response curves are very close to those directly given by the modelled dispersion law for the detector position corresponding to channel centre (differences are below 0.004 nm).
For the same reason, channels spectral response curves provided at FOV centre in the abovementioned Excel Workbook are valid for the whole field-of-view of each camera providing they are appropriately shifted according to the central wavelengths of the corresponding spatial pixels.

The following figure shows the spectral deviation, at camera FOV centre, with respect to theoretical channels central wavelengths provided in Table 1, for each camera as a function of spectral band.

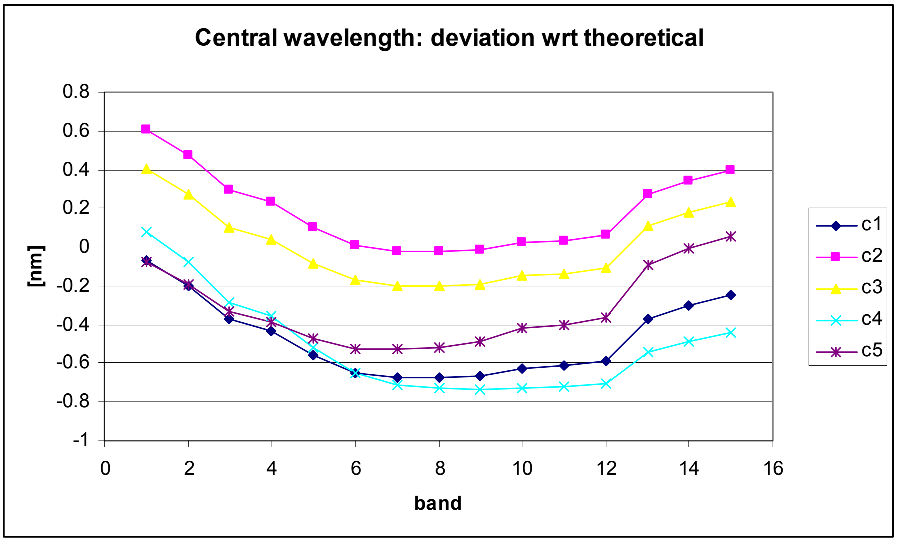

Figure 4: Spectral deviation of band central wavelength with respect to theoretical values for the current MERIS Spectral Model.

Examples of normalised Spectral Response Curves are shown below, for a set of bands representative of the most common (10 and 7.5 nm) and extremes (3.75 and 20 nm) bandwidths of the MERIS nominal band set.

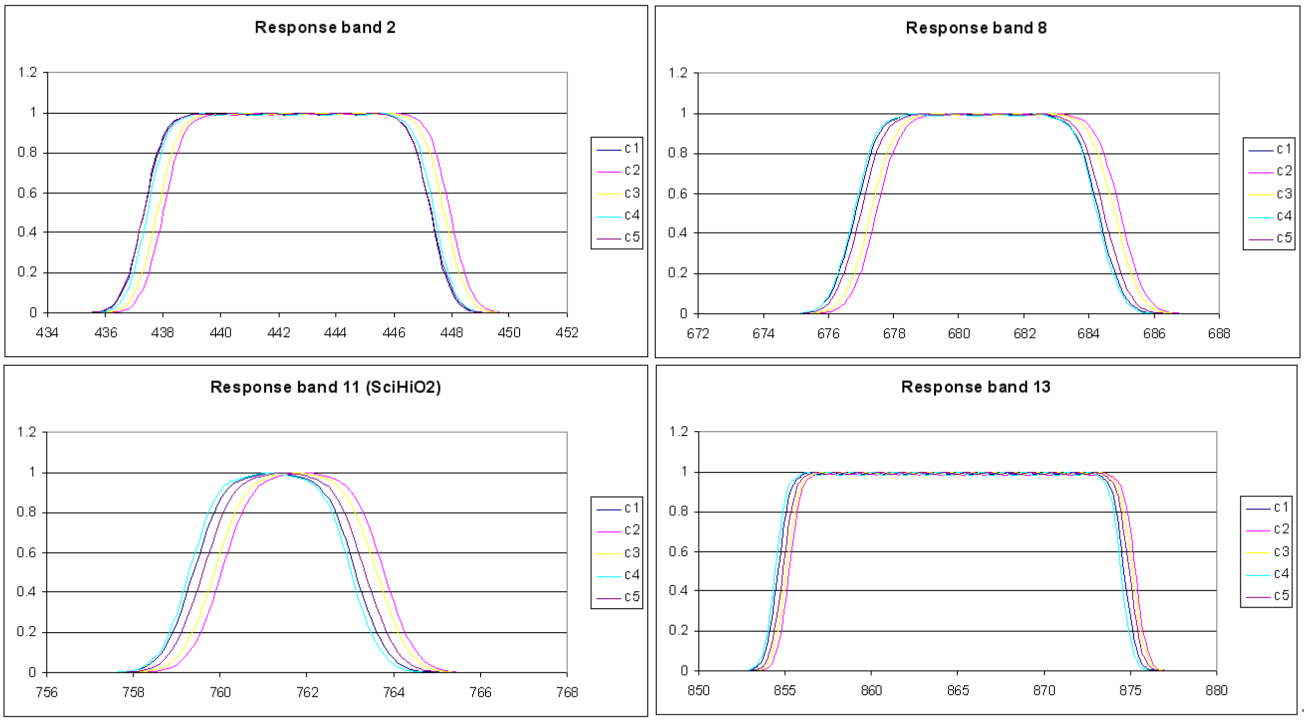

Figure 5: examples of MERIS bands normalised Spectral Response curves for typical (10 and 7.5 nm, top left and right) and extremes (3.75 and 20 nm, bottom left and right) bandwidths.

3 THE SMILE EFFECT CORRECTION

The “smile effect” correction is performed in order to correct the MERIS TOA reflectance for the small scale variations due to the non-constant central wavelength of a given band across the spectrometer field of view. The “smile effect” correction is implemented in the MERIS Level 2 processor and is available to users in the BEAM toolbox[1].

The Level 1 product is not “smile” corrected, because this product shall provide the user with exactly what the instrument is measuring, and that is in fact the radiance at the given wavelength of each pixel. While the Level 1 product provides the radiance measurement for individual wavelengths within one spectral band, the “smile” corrected product has normalised the wavelengths within one spectral band to one reference wavelength. Table 2 provides the reference wavelength and the reference solar irradiance for each band; the reference solar irradiance is not corrected for the daily variation.

Correction is made for a predefined subset of bands for which (a) those variations can induce significant distortions when used in algorithms based on a fixed wavelength scheme. This subset of bands, which is specific to each land and water surface type, should ensure smoothness of reflectance local variations with wavelength and allow a good estimation of the reflectance derivative using neighbour bands. Table 2 presents the selection of subsets for water and land as used currently in the Level 2 processing and as delivered with BEAM. In BEAM, these settings can be changed by the user.

3.1 Algorithm description

The “smile” correction has been defined for Level 2 processing purposes. It is split in two distinct steps:

Step 1. use of per pixel in-band equivalent irradiance in the conversion of radiance into top-of atmosphere (TOA) reflectance:

$$\rho\left(\lambda_{b,pixel}\right)=\pi\cdot\frac{L\left(\lambda_{b,pixel}\right)}{E_0\left(\lambda_{b,pixel}\right)\cdot\cos(\theta_S)} \qquad \text{Eq. 1}$$

where L is the measured radiance at pixel wavelength, E_0 the in-band irradiance corrected for daily variations, and θ_S is the Sun zenith angle at the pixel location

Step 2. correction of TOA reflectance from pixel wavelength to nominal one, using a first order Taylor expansion:

$$\rho_{corr}\left(\lambda_0\right)=\rho_{meas}\left(\lambda_{pixel}\right)+\frac{\partial\rho}{\partial\lambda}\cdot\left(\lambda_0-\lambda_{pixel}\right) \qquad \text{Eq. 2}$$

where the local reflectance spectral derivative is estimated by finite differences:

$$\frac{\partial\rho}{\partial\lambda}\approx\left[\frac{\rho_{meas}\left(\lambda_{2,pixel}\right)-\rho_{meas}\left(\lambda_{1,pixel}\right)}{\left(\lambda_{2,pixel}-\lambda_{1,pixel}\right)}\right] \qquad \text{Eq. 3}$$

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[1] The smile correction in the standard L2 processor is applied to reflectance already corrected for stratospheric aerosols and gaseous absorption. The BEAM smile correction tool works on the L1b product, i.e. top of atmosphere radiances.

It should be noted that Step 2 of the “smile” correction applies to reflectance already corrected for stratospheric aerosols and gaseous absorption.

Since the BEAM smile correction tool works on the Level 1b product, it applies Step 1, then Step 2 directly on the outputs of Step 1 (i.e. without correction for gaseous absorption or stratospheric aerosols) and a third step to convert corrected reflectance back into radiance:

Step 3. (BEAM tool only) back conversion of corrected reflectance into radiance:

$$L_{corr}\left(\lambda_0\right)=\frac{\rho_{corr}\left(\lambda_0\right)\cdot E_0\left(\lambda_0\right)\cdot\cos(\theta_S)}{\pi} \qquad \text{Eq. 4}$$

Step 1, the irradiance correction, is systematically applied to all 15 bands and requires the use of the same spectral model than the one used during Level 1 processing, in order to remain coherent with instrument calibration. This is ensured by the selection of the appropriate auxiliary data. Apart from that it does not require particular applicability conditions.

Step 2, reflectance correction, on the other hand, requires to be carefully tuned to ensure that the local spectral variation around a given channel position can be estimated with sufficient accuracy by a linear approximation. If such conditions cannot be met, e.g. for bands located inside absorption lines like bands 11 and 15 or for sharp spectral features like phytoplankton chlorophyll fluorescence, the reflectance correction can be disabled, thanks to the dedicated switches. For these reasons, the activation switches as well as the band pairs selected for the spectral slope estimates are specified according to the underlying surface type, namely water or land, via auxiliary data parameters. Table 2 presents the current setting of the operational Level 2 processing.

In BEAM this table is available as an auxiliary data set and it can be changed by the user.

Table 2: Standard configuration of the "smile" correction (equal to the current setting in the Level 2 processor). The activation switch defines if the reflectance correction is applied or not. The lower and upper band indices specify the adjacent bands, which are used in the reflectance correction. The reference wavelength is the wavelength to which all pixels of a band are normalised, and the E_{0_ref} column lists the solar irradiances (not day-corrected), which are used in BEAM for back conversion into radiance. Those solar irradiances are integrated over the spectral widths of the band.

	Land			Water				
band	activation switch	lower band	upper band	activation switch	lower band	lower band	reference wavelength	E_{0_ref}
1	1	1	2	1	1	2	412.5	1713.69
2	1	1	3	1	1	3	442.5	1877.57
3	1	2	4	1	2	4	490	1929.26
4	1	3	5	1	3	5	510	1926.89
5	1	4	6	1	4	6	560	1800.46
6	1	5	7	1	5	7	620	1649.70
7	1	6	9	1	6	9	665	1530.93
8	1	7	8	0	*7*	*9*	681.25	1470.23
9	1	9	10	1	8	9	708.75	1405.47
10	1	10	12	1	10	12	753.75	1266.20
11	0	N/A	N/A	0	N/A	N/A	761.875	1249.80
12	1	10	12	1	10	12	778.75	1175.74
13	1	13	14	1	13	14	865	958.763
14	1	13	14	0	*13*	*14*	885	929.786
15	0	N/A	N/A	0	N/A	N/A	900	895.460

4 DISCUSSION

The smile effect is small in absolute values. As shown above, the spectral variation between cameras is in the order of 1.5 nm, and variation inside cameras in the order of 1nm. However, the effect of such a variation is important, if the spectral bandwidth is small and/or if the slope of the measured spectrum is high. The largest impact of the smile effect is therefore in band 11, which is very narrow (3.75nm) and which is tentatively located in an absorption band. This band cannot be corrected by the procedure described above, and algorithms using this band, like pressure algorithms, have to use the exact wavelength per pixel.

Bands which are also strongly affected are the short wavelength bands because of the spectral slope of the solar irradiance and the strong wavelength dependence of the Rayleigh scattering.
As an example, the radiance in band 1 (412.5nm) and corresponding smile correction terms are shown in Figure 6, for a scene including parts of Scandinavia and the North Sea. The measured radiances are between 40 and 90 mW/m²sr nm (excluding the clouds), see top image of Figure 6. The smile correction is in the order of 0.05 mW/m²sr nm or 0.1% of the measured signal. The bottom part of Figure 7 shows the two components of the smile and its total impact: the irradiance variation (left), the reflectance variation (centre) and the total smile effect (right) in relative units:

1. irradiance variation:

$$\frac{\Delta E_0}{E_0} = \frac{E_0\left(\lambda_{pixel}\right) - E_0\left(\lambda_0\right)}{E_0\left(\lambda_0\right)} \qquad \text{Eq. 5}$$

2. reflectance variation:

$$\frac{\Delta\rho}{\rho} = \frac{\rho(\lambda_{pixel}) - \rho(\lambda_0)}{\rho(\lambda_0)} \approx \frac{(\lambda_{pixel} - \lambda_0)\cdot\frac{\partial\rho}{\partial\lambda}}{\rho(\lambda_0)} \qquad \text{Eq. 6}$$

3. total smile correction on radiance:

$$\begin{aligned}\frac{\Delta L}{L} &= \frac{L(\lambda_0) - L(\lambda_{pixel})}{L(\lambda_{pixel})} = \frac{\rho(\lambda_0)\cdot E_0(\lambda_0)}{\rho(\lambda_{pixel})\cdot E_0(\lambda_{pixel})} - 1 \\ &= \frac{E_0(\lambda_0)}{E_0(\lambda_{pixel})}\cdot\frac{\rho(\lambda_{pixel}) + \frac{\partial\rho}{\partial\lambda}\cdot\left(\lambda_0 - \lambda_{pixel}\right)}{\rho(\lambda_{pixel})} - 1 \\ &= \frac{E_0(\lambda_0)}{E_0(\lambda_{pixel})}\cdot\left(1 + \frac{\frac{\partial\rho}{\partial\lambda}\cdot\left(\lambda_0 - \lambda_{pixel}\right)}{\rho(\lambda_{pixel})}\right) - 1\end{aligned} \qquad \text{Eq. 7}$$

The relative irradiance correction does not depend on the measured signal but is an expression of the irradiance variation across the field of view of each camera. Therefore, the five cameras can clearly be identified, and the white vertical line in each camera (no correction) indicates that pixel on the CCD which actual wavelength corresponds to the reference wavelength.

The reflectance correction is expressed as an additive deviation term, it depends strongly on the measured signal, as can be seen in the middle image of Figure 6. It is worth noting that the sign of the reflectance correction is inverse to the irradiance correction, which is a typical situation. Consequently, the total smile correction is weaker than each of the two components.

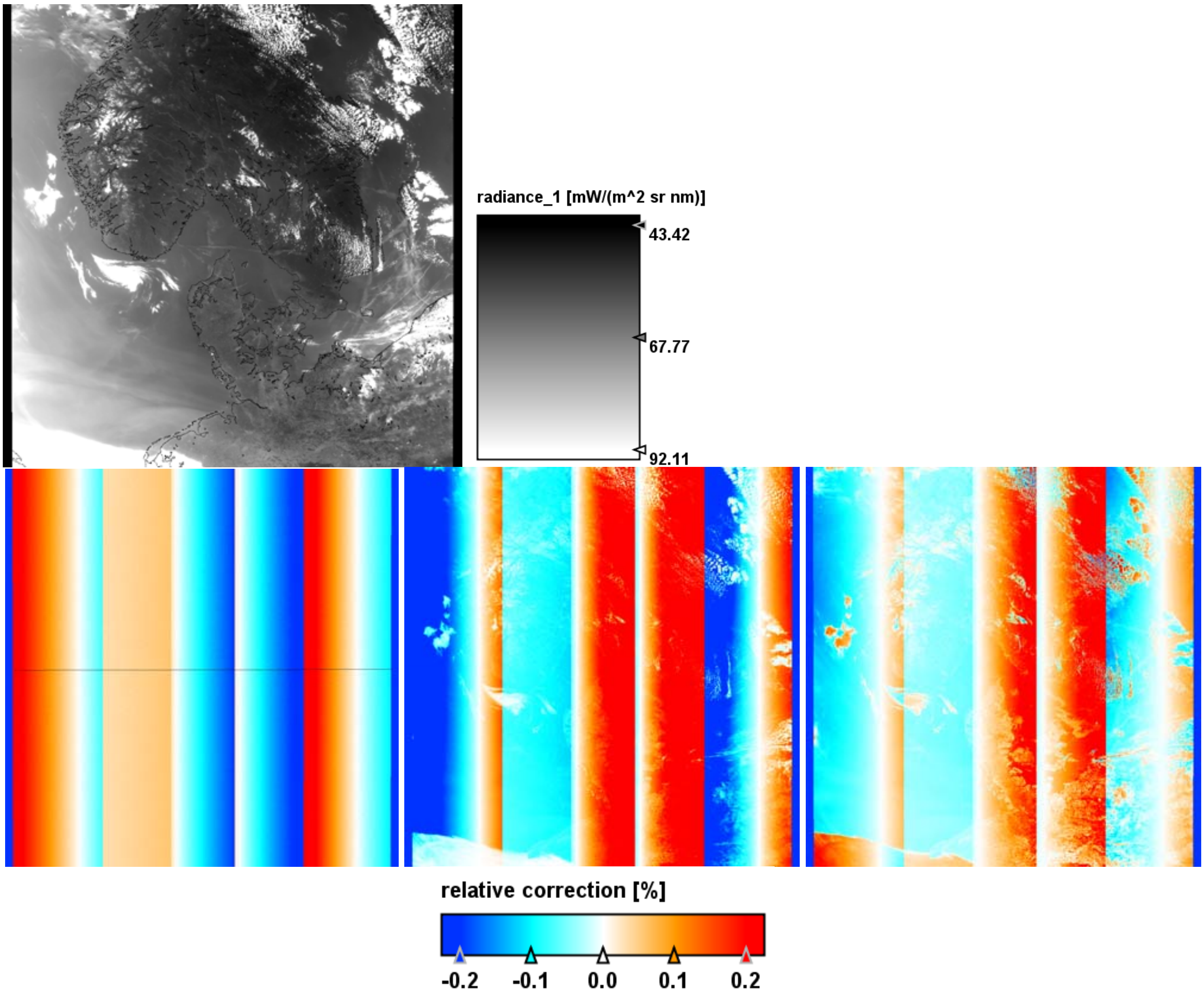

Figure 6: Example of the smile correction, MERIS RR scene of 9.8.2003, orbit 7534. Top: uncorrected radiance in band 1 (412.5nm). Bottom: left - irradiance correction, middle: reflectance correction, right: total smile correction on radiance. The horizontal line in bottom left image shows the location of the transect plotted on **Figure 7** .

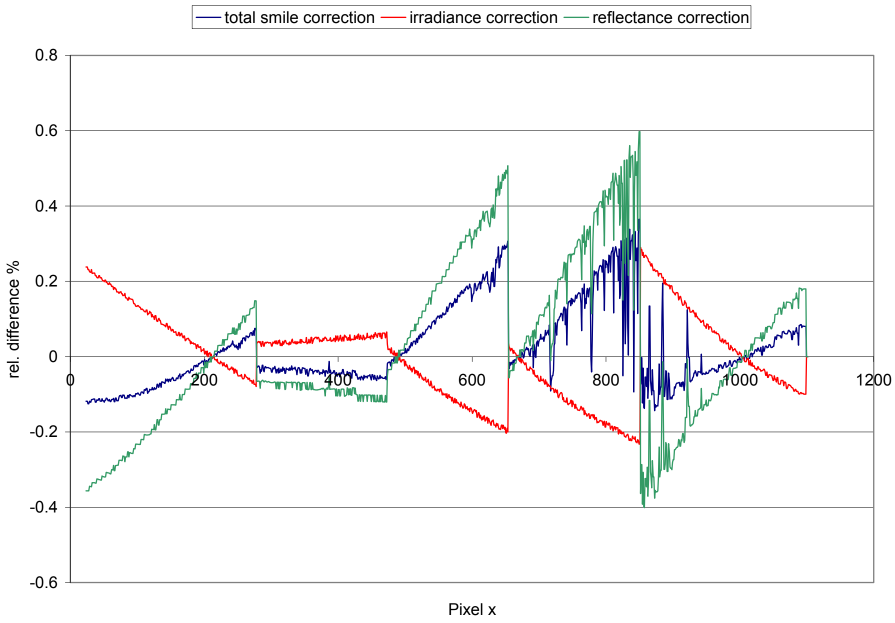

Figure 7: Terms of the smile correction along the transect shown in Figure 6.

A transect has been extract from the images (see left image in Figure 6) and is shown in Figure 7. The five different cameras can clearly be identified. The smile correction can reach up to 0.2% of the measured signal at camera borders. In other bands, where the reflectance correction is not activated, i.e. only the irradiance correction is applied, the correction can even reach a magnitude of 0.5%. In a first approximation, the solar irradiance is a linear function of the wavelength for very small wavelength intervals, which is the case here. Therefore, the shape of the relative irradiance correction, which is independent of the measured signal but depends on the ratio of irradiance at each pixel and the reference irradiance, is very similar to the spectral shift shown in Figure 2 (top figure, note that the pixel ordering is reversed).

Even though the effect of the smile of the measured is below 0.5%, which seems to be very small, it has a significant effect on higher level products, which depend on very small variations of the signal, and specifically those algorithms, which include differences or ratios of two bands, which amplify such small variations.

An example is shown in Figure 8 and Figure 9, which presents the MERIS Terrestrial Chlorophyll Index, MTCI. The border between cameras 1 and 2 on the left side of the image is removed after applying the smile correction. In absolute terms, the effect reaches 5% of the MTCI.

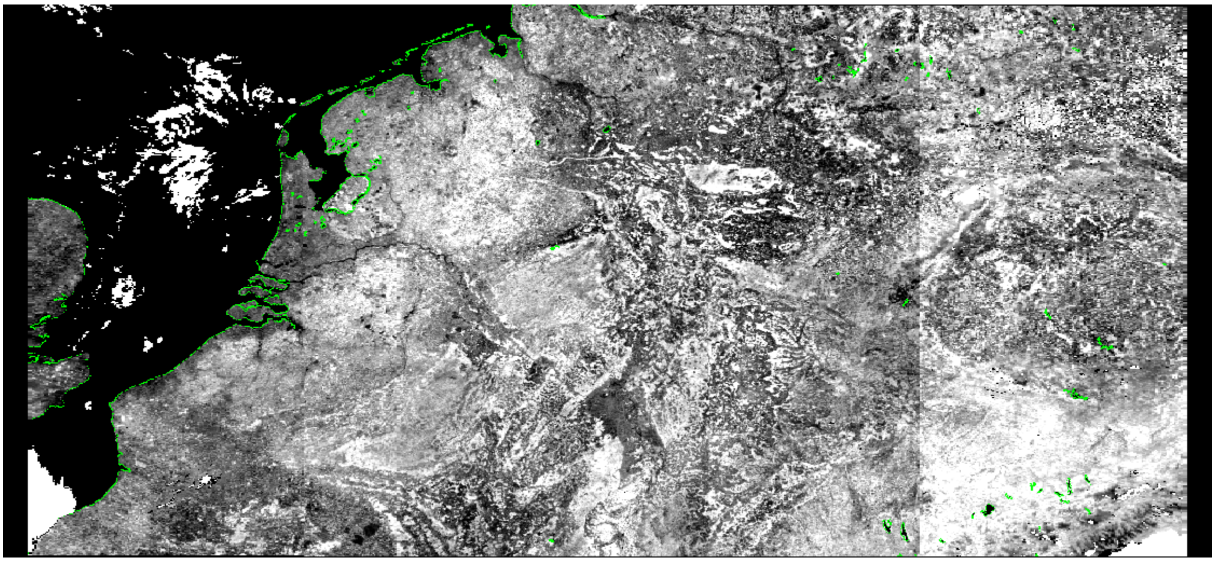

Figure 8: MTCI without smile correction for
MER_RR__1PNACR20030806_100726_000000902018_00423_07491_0000.N1

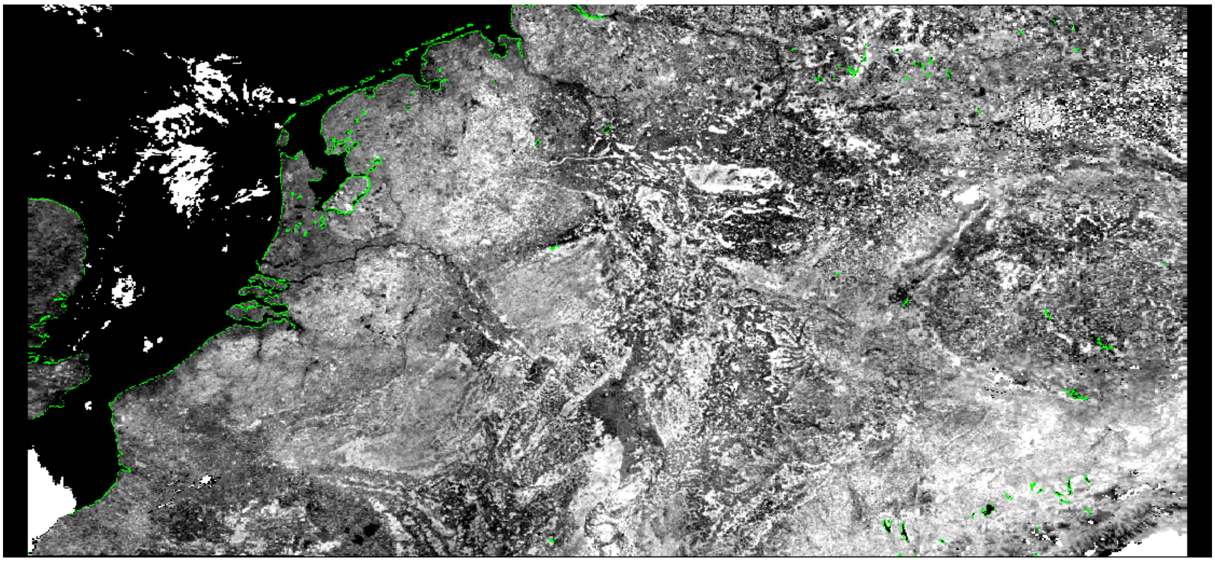

Figure 9: MTCI with smile correction for
MER_RR__1PNACR20030806_100726_000000902018_00423_07491_0000.N1

5 REFERENCES

[1] Delwart, S., R. Preusker, L. Bourg, R. Santer, D. Ramon and J. Fischer, 2005. MERIS in-flight spectral calibration, International Journal of Remote Sensing, MERIS Special Issue, Volume 28, Numbers 3 - 4, January 2007

[2] S. Delwart, R. Preusker, L. Bourg, R. Santer, D. Ramon & J. Fischer, MERIS In-flight Spectral Calibration, Proceedings of the Second working meeting on MERIS and AATSR Calibration and Geophysical Validation, "MAVT-2006", available on-line at: http://envisat.esa.int/workshops/mavt_2006/papers/60_delwa.pdf

[3] Thuillier, G., M. Hersé, D. Labs, T. Foujols, W. Peetermans, D. Gillotay, P. C. Simon, and H. Mandel, 2003, "The solar spectral irradiance from 200 to 2400 nm as measured by the SOLSPEC spectrometer from the ATLAS and EURECA missions", Sol. Phys., **214:** 1-22.