



# D2.2(MVIRI): Report on the MVIRI FCDR: Uncertainty

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## 1 Introduction

### 1.1 Scope

This document is one of the five documents that make up the D2-2 report on “traceability chains for FCDRs”. Since the original project proposal our thoughts have refined and while this document describes the “sequence of measurement standards and calibrations that is used to relate a measurement result to a reference” (the VIM definition of a traceability chain), it is not presenting this in the form of a chain.

This document provides an overview of the uncertainty analysis for the analysed sensors along with the methods to establish metrological traceability for the developed FCDRs.

This document is specifically about the MVIRI FCDR. The document D2-2a provides an overview of the effects tables.

### 1.2 Version Control

Version	Reason	Reviewer	Date of Issue
1.0	Initial release at end of project	EUM	August 2019
1.1	Update after Final Review	EUM/RP	09/10/2019

### 1.3 Applicable and Reference Documents

#### 1.3.1 D2-2 set of documents

D2-2a	Principles behind the FCDR effects table
D2-2(microwave)	Report on the MW FCDR: Uncertainty
D2-2(HIRS)	Report on the HIRS FCDR: Uncertainty
D2-2(AVHRR)	Report on the AVHRR FCDR: Uncertainty
D2-2(MVIRI)	Report on the MVIRI FCDR: Uncertainty (This document)

#### 1.3.2 References

P. Bretagnon; G. Francou (1988). "Planetary theories in rectangular and spherical variables. VSOP87 solutions". *Astronomy & Astrophysics*. **202**: 309–315.

Clark, Kliney and White (1997): Image Processing Software Detailed Design Document. Issue 2.2. EUMETSAT ref: MTP/BF/0901/SP/008

Keys (1981): Cubic Spline Interpolation for Digital Image Processing. IEEE ASSP Vol. 26 No. 6

Michel, Bleuez and Roche (1997): Meteosat Flight Operational Manual. EUMETSAT: MTP.88D.304

Nicodemus, F. E., J. C. Richmond, J. J. Hsia, I. W. Ginsberg, and T. Limperis. 1977. 'Geometrical Considerations and Nomenclature for Reflectance'. National Bureau of Standards.

Ralf Quast, Ralf Giering, Yves Govaerts, Frank R uthrich and Rob Roebeling, Climate Data Records from Meteosat First Generation Part II: Retrieval of the In-Flight Visible Spectral Response, *Remote Sens.* 2019, 11(5), 480; <https://doi.org/10.3390/rs11050480J>.

Unzalu (1987): Deformation Matrix for Rectification of Meteosat Images.

Moisson, X. & Bretagnon, P. Celestial Mechanics and Dynamical Astronomy (2001) 80: 205.  
<https://doi.org/10.1023/A:1012279014297>

EUMETSAT 2019, Product User Guide - MVIRI FCDR Release 1 Document reference: EUM/USC/DOC/17/906121

## 2 General overview

### 2.1 FIDUCEO effects tables

In FIDUCEO we have defined a standardized effects table which describes

- the uncertainty associated with a given effect
- the sensitivity coefficient required to propagate uncertainties associated with that effect to uncertainties associated with the measurand (Earth radiance, reflectance or brightness temperature)
- the correlation structure over spatial, temporal and spectral scales for errors from this effect

The concepts behind the effects tables are described in D2-2a. In this document we provide a discussion of the effects tables and uncertainty propagation for a single instrument series; here the MVIRI FCDR.

## 3 The MVIRI instrument

### 3.1 MVIRI on Meteosat

The Meteosat visible and infrared imager (MVIRI) is a radiometer that has been installed on all Meteosat spacecrafts of the first generation. The first satellite of this kind was launched in 1977, followed by a series of 6 successors. The orbit of the Meteosat satellites is geostationary and they were designed to provide one image of the earth every 30 minutes. Continuous data from the sub-satellite position of  $0^\circ$  are available since Meteosat 2, comprising now more than 24 years of data.

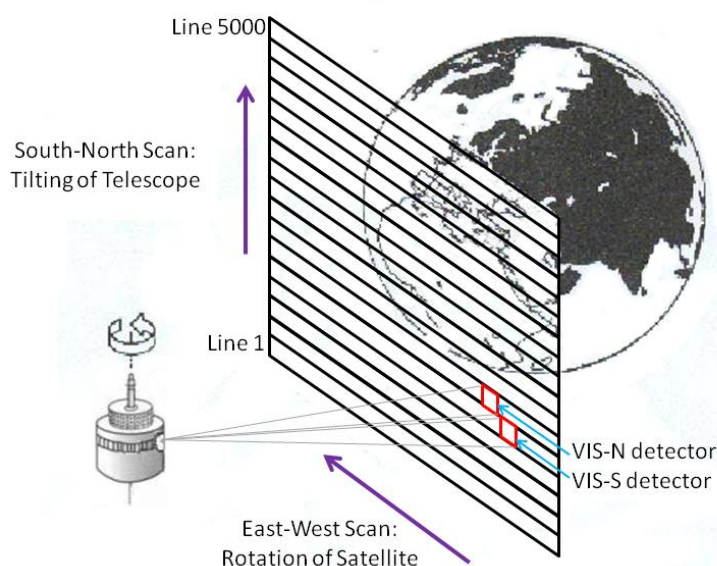


Figure 1: Scan concept of the MVIRI visible band on board the meteosat first generation spacecrafts. Own illustration, inspired by <https://directory.eoportal.org/web/eoportal/satellite-missions/m/meteosat-second-generation>.

The visible band of MVIRI essentially consists of 4 silicon photodiodes, 2 of which are active and 2 for backup, which respond to the light captured by the telescope. The position of the two active sensors is shifted relative to each other in north-south direction, so that they measure adjacent spots. Figure 1 shows the scan concept for the MVIRI visible band. Meteosat satellites are spin-stabilized and therefore, unlike other satellites, they

do not need a rotating scan-mirror. VIS-Images result from the interplay of the detectors measuring, the satellite rotating at a defined speed and the telescope tilting to a defined angle. During one revolution of the satellite, each of the two active sensors acquires one scan-line across the earth. The two scan-lines are sent to the ground station during that part of the revolution, during which the radiometer is not directed towards the earth (Michel, Bleuez and Roche, 1997; p. 96). For the next revolution the sensor is tilted slightly northward, so that the following scan-lines follow up north of the previous ones.

The detection system consists of a telescope and silicon photodiodes and therefore responds to Earth radiance in the spectral range from  $\sim 300$  nm to  $\sim 1100$  nm. Before a scan-line is sent to earth, it is converted into a digital count value. This A/D conversion was done at 6 bits for the early Meteosat-2 and -3 satellites and at 8 bits for later satellites.

The preprocessing of the raw data from the transmitted scan lines (level 0) into geo-rectified level 1.5 data is necessary to compensate for image distortions that are due to satellite wobbling. The pixels of the raw count images are transferred into a rectified grid based on a deformation matrix (Unzalu, 1987) that is optimized for each image. Interpolation is done using Key's cubic convolution (Keys, 1981). This method uses a symmetric kernel over 4 pixels in each dimension. Thus, a total of 16 surrounding pixels determine the value of one pixel in the rectified grid. This is illustrated in Figure 2. The ideal location of the kernel that has to be used for each rectified pixel is determined based on the "ideal pixel" concept in the image processing software (Clark, Kliney and White, 1997; p 191,639). Interpolation is first performed in line-direction. Therefore third-order polynomials are fitted to each row of 4 raw-pixel values. The interpolated values from each row of the kernel are then interpolated in y-direction (Figure 2). The rectified grid then is populated with the truncated integer results of the interpolation.

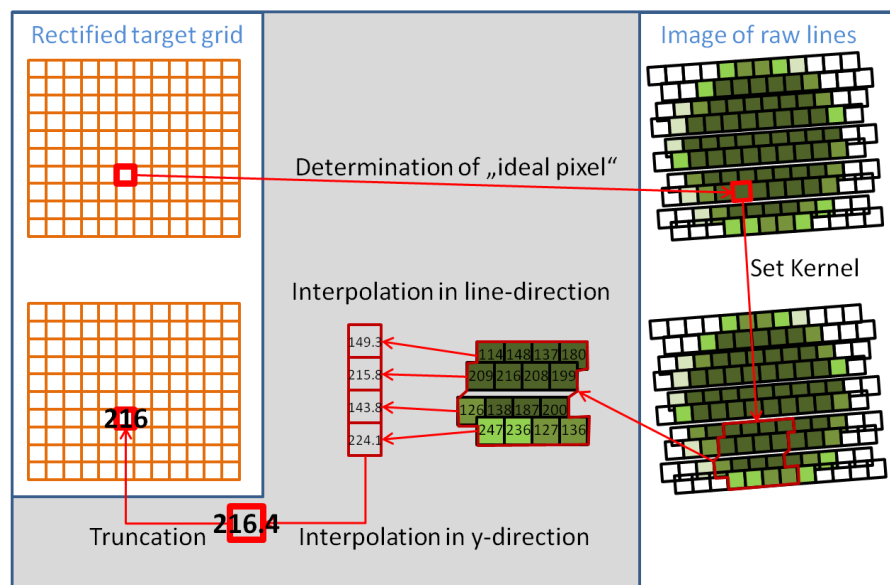


Figure 2: Flow chart on the rectification/interpolation algorithm as described in Keys (1981) and Clark, Kliney and White (1997) p 639. Example values are calculated using cubic spline interpolation with an assumed distance between rectified and ideal pixel of 0.1 pixels in both, x- and y-direction.

Corrections are also made, where necessary (Meteosat-3, -6) to correct for differences between the two different detectors. On the newer satellites (MET 3 onwards) the signal is dark corrected using the space-views in the four corners of the image.

MVIRI calibration is performed using calibration coefficients which express the relation between digital counts and corresponding radiance. To establish such a relation, in the absence of on-board calibration capability, reference top-of-atmosphere (TOA) radiances are necessary. These are obtained using radiative transfer modelling, combined with surface bidirectional reflectance function (BRDF) models, to derive modelled radiances above pre-defined bright desert and dark ocean target sites<sup>1</sup>. Atmospheric information required for these models is established using the latest set of ECMWF data, with aerosol type and total column ozone derived from monthly (NOAA) climatology tables. The modelled radiance above these sites is band integrated with the instrument spectral response function to establish a band-integrated TOA effective radiance.

This calibration can be determined at regular intervals throughout the sensor lifetime. The different individual calibrations are then used to establish a linear drift in the sensor calibration coefficient. The sensor calibration coefficient at any particular time is calculated from this drift function.

While MVIRI effectively measures the observed TOA radiance, the FCDR of interest is for band-integrated Bidirectional Reflectance Factor (BRF). The BRF is defined as the “ratio of the radiant flux actually reflected by a sample surface to that which would be reflected into the same reflected-beam geometry by an ideal (lossless) perfectly diffuse (lambertian) standard surface irradiated in exactly the same way as the sample.” (Nicodemus, 1977) This is calculated from the band-integrated radiance and the incident solar irradiance and the solar zenith angle.

### 3.2 The MVIRI measurement function

The MVIRI band-integrated BRF measurement function is given by:

$$\tilde{R} = \frac{\pi d^2}{\tilde{E}_{0,\text{sun}} \cos(\theta)} [(\bar{C}_E - \bar{C}_S)(a_0 + a_1 Y + a_2 Y^2)]. \quad \text{Eq 3-1}$$

The term  $\pi d^2 / (\tilde{E}_{0,\text{sun}} \cos \theta)$  represents the conversion from radiance (the instrument’s native measurement quantity) to BRF.  $d$  is the Earth-Sun distance in astronomical units (AU) and  $\tilde{E}_0$  is the band integrated solar irradiance for  $d=1\text{AU}$ .  $\theta$  is the solar zenith angle (see Section 3.2.1). The band-integrated solar irradiance is given by

$$\tilde{E}_{0,\text{sun}} = \int \xi(\lambda; t) E_{0,\text{sun}}(\lambda) d\lambda. \quad \text{Eq 3-2}$$

The rectified Earth counts,

$$\bar{C}_E = \sum_j w_j C_{E,j} \quad \text{Eq 3-3}$$

is calculated from a cubic spline, which acts as a local weighted sum of the measured Earth counts on neighbouring pixels (this is to perform the rectification, see Figure 2). The averaged space counts,

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<sup>1</sup> Within this project there is also work on the use of deep convective clouds as references.

$$\bar{C}_S = N_C^{-1} \sum_{c=0}^8 C_{S,c} \quad \text{Eq 3-4}$$

is a mean of the space-view pixel count in the eight<sup>2</sup> “space corners” of the image. Note that both the rectified Earth counts and the averaged space counts combine measured values from both of the two detectors (see Figure 1).

The instrument calibration (counts to radiance conversion) is given by  $a_0 + a_1 Y_t + a_2 Y_t^2$  evaluated from the linear fit to the calibration events (see Section 3.2.2).

The zero represents the suitability of this measurement function (see Section 3.2.4).

### 3.2.1 Solar zenith angle

The solar zenith angle is determined from the latitude, longitude and the time of acquisition.

$$\theta = \cos^{-1} \left[ \sin(\gamma) \sin(\varphi) + \cos(\gamma) \cos(h) \cos(\varphi) \right] \quad \text{Eq 3-5}$$

where,  $\gamma$  is the solar declination (calculated from pixel acquisition time),  $\varphi$  is the latitude and  $h$  is the local hour angle (from pixel acquisition time and longitude).

### 3.2.2 Calibration coefficients

The calibration coefficients  $a_0, a_1, a_2$  are determined from a time-series of observations and modelled band-integrated radiances over the target sites. From this time series, the coefficients are determined by fitting a 2nd order polynomial to the ratios between counts and radiances (Figure 3).

The individual calibration points (to which that polynomial is fitted) are determined from two quantities – the measured signal (rectified Earth Counts minus averaged Space Counts) over the target sites, and the modelled TOA band-integrated radiance over those sites.

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<sup>2</sup> For each detector 4 „space corners” are available in the non-rectified images. The combined mean space corner count will thus be estimated from 8 corners.



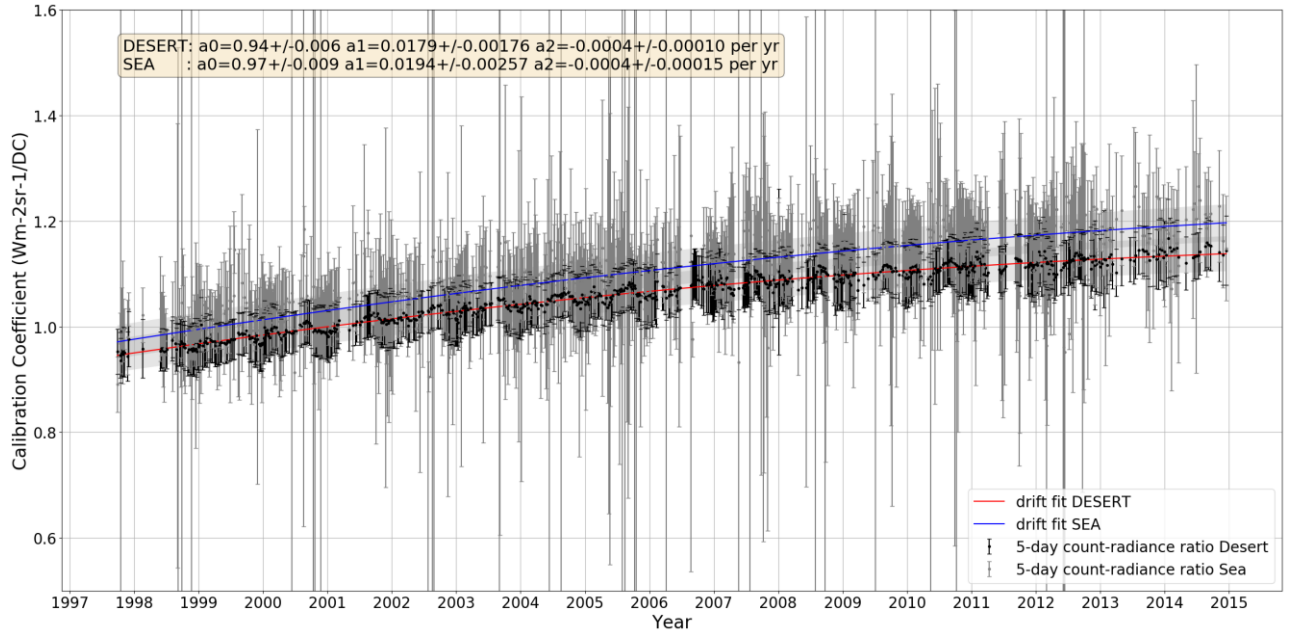


Figure 3: Time series of radiance-count ratios for Meteosat-7 over desert- and sea-sites with fitted polynomials. The radiance-count ratios are averaged over many sites of the same surface type and over 5 days. Note that the sea sites are used only for quality control and that the calibration coefficients used for the MVIRI FCDR are derived from the desert sites.

The modelled TOA band-integrated spectral radiance for a pixel  $(i, j)$  at time  $t$  is obtained by spectrally integrating a hyperspectral TOA radiance model weighted by the normalised (to unit area) instrument spectral response function, thus:

$$\tilde{L}_{\text{TOA};t,i,j} = \int_{\lambda_{\min}}^{\lambda_{\max}} \xi_t(\lambda; t) L(\lambda; \Omega_{t,i,j}, \chi_{t,i,j}) d\lambda \quad \text{Eq 3-6}$$

where,  $\xi_t(\lambda; t)$  is the instrument spectral response function (at time  $t$ ) and the modelled radiance  $L$  is a function of the geometric conditions,  $\Omega$  (sun and satellite zenith angles and the sun-satellite relative azimuth angle) and the surface and atmospheric conditions  $\chi$ , both of which change with observation time and location. In practice this integral is determined numerically and replaced with a summation.

$$\tilde{L}_{\text{TOA};t,i,j} = \sum_{\lambda_k=\lambda_{\min}}^{\lambda_{\max}} \xi_t(\lambda_k; t) L(\lambda_k; \Omega_{t,i,j}, \chi_{t,i,j}) \delta\lambda_k + 0. \quad \text{Eq 3-7}$$

Here the 0 represents the appropriateness of this numerical integration.

### 3.2.3 Spectral response function

The normalised (to peak 1) spectral response function  $\xi_t(\lambda; t)$  has been determined for this project also using reference sites whose radiance is determined from radiative transfer functions, and also Eq 3-7. While the radiometric gain term is determined from two types of reference site (several desert and ocean sites), three types of reference site are used to estimate the spectral response function (one desert site, ocean sites and deep convective clouds). The method to determine the spectral response function is described in detail in [Quast and Giering, 2019].

The spectral response function is modelled by a linear combination of Bernstein basis polynomials combined with a degradation model that defines a temporal drift of the spectral response function, with a stronger

degradation for short wavelengths than for longer wavelengths. The linear combination is established to minimise the differences between the measured and radiative transfer modelled radiances over the three types of test site. This linear combination changes as a function of time as the instrument degrades.

### 3.2.4 Zero

The term zero in the expression  $(a_0 + a_1Y_t + a_2Y_t^2 + 0)$  comes from the following effects:

- The suitability of  $a_0 + a_1Y_t + a_2Y_t^2$  as obtained from the reference sites to represent the true instantaneous instrument gain. For example the annual cycle of the satellite interior temperature induces an annual cycle of the responsivity of the sensor. Therefore there are seasonal patterns to the residuals of the polynomial fit (compare Figure 3).
- The assumption in the measurement equation that the instrument is linear in Earth counts

## 3.3 Measurement Function Diagram

As illustrated in Figure 4, many effects cause errors in the parameters of the measurement equation and subsequently in the calculated BRF. As the errors cannot be known in reality, they are described by uncertainties that can be thought of as probability distributions around the measured value. The most renowned effects are the noise sources that impact the digital counts acquired by the instrument during Earth-views. Noise comes from the sensor electronics (like the amplifier), from the digitisation and from the Earth signal itself. As the error that is caused by this effect is different for each pixel, it can be considered independent. The same effects are also present while the sensors are pointed into deep space to determine the dark signal. As the dark signal is determined from the mean of all available space observations of an image, a good part of the noise averages out. This averaging for one image in turn has the effect that the error is present in all calibrated pixels of that image. The image navigation process in the ground segment also has remaining errors in terms of the geolocation as well as the acquisition time. They affect the measurement as they create an error of the viewing geometry, particularly of the solar zenith angle. The SRF reconstruction approach and the vicarious calibration involve radiative transfer modelling above selected sites. Both are susceptible to errors in the determination of the surface parameters, of the atmospheric parameters, of the solar spectrum and of the model itself. SRF reconstruction and calibration both relate Earth counts ( $\bar{C}_E$ ) to simulated radiances after subtracting the dark signal. Therefore the dark signal, approximated by the mean space count ( $\bar{C}_S$ ), its error, as well as the noise level of the detection chains have an impact on the error of the SRF reconstruction and the calibration. The SRF reconstruction error again propagates into: *i*) the convoluted effective solar irradiance and *ii*) the calibration coefficients.

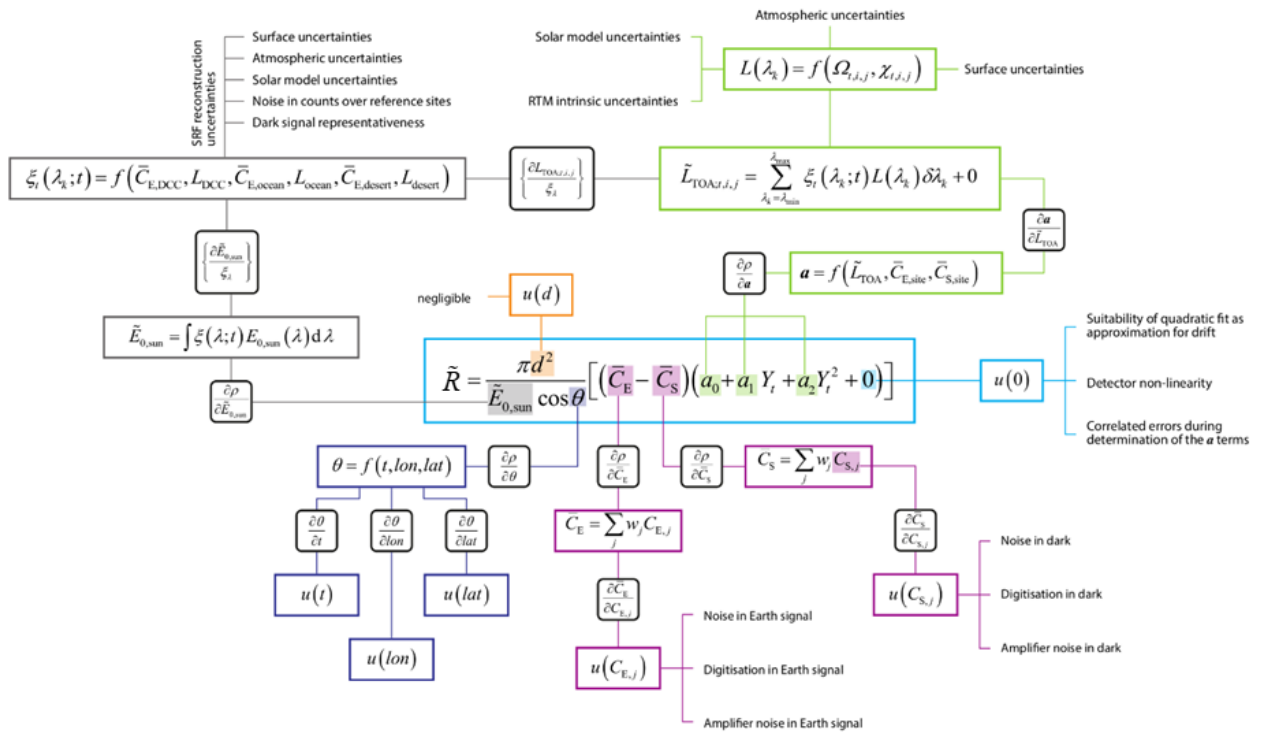


Figure 4: Uncertainty diagram of the MVIRI reflectance measurements. In the centre of the diagram is the measurement equation. From there, branches reach out to the different effects that cause errors?in each parameter of the measurement equation. The branches describe the transformation of the effect causing the error into the uncertainty of a parameter (e.g. averaging or application to a radiative transfer model). The black boxes represent the sensitivity coefficients that are used for the propagation.

## 4 A discussion of different terms

In this section we consider the different sources of uncertainty and discuss the error correlation structure for each effect in the different dimensions using the Effects Tables that have been described in D2-2a.

### 4.1 Noise in Earth Counts and Space Counts

Earth pixel counts in georectified images are interpolated values. This reflects the fact that the pixels in the rectified grid have modified locations. The interpolation is a cubic spline, using the 4 x 4 closest non-rectified pixels. This results in correlations of the errors within this pixel range. Since a spline involves a weighted average, this could be treated as a truncated-Gaussian correlation structure. As the effect of this correlation is marginal and the computation costly, the FCDR considers the Earth count noise as uncorrelated.

The space-count value is taken by averaging all four space corners for both individual detectors (=in total 8 space corners are evaluated) to get a single dark signal applied throughout the image, despite the fact that the noise levels of the two detectors are different. This is necessary, because in the georectification of the Earth image, data from both individual detectors are combined, and for different pixels there is a different

relative weighting of the two detectors. The single image dark count is subtracted from this georectified Earth count.

Because a single space count value is used for all pixels, there are two possible correlation structures for the space count error. If the dominant uncertainty is in the estimation of the dark count from the space corners, then this would be a fully systematic effect. On the other hand, if the dominant uncertainty is the representativeness of the dark count determined from the space corners to the actual dark count for an individual measurement, then this would be a random effect. In theory it would thus be necessary to consider, for each pixel, how the two detectors are weighted. The error would then be fully correlated with pixels that have a similar weighting, and less correlated with pixels with different weightings. This is in reality not possible. In the FCDR the dark signal estimation error is considered as a structured effect. This reflects that the estimation of the dark signal is done once per image, but it neglects the fact that the weighting of the two detectors is variable. The error of the dark signal is thus regarded as fully correlated within one image, but it is independent from the dark signal estimation in the images before and after. The uncertainty of the dark signal estimation can be quantified by the standard deviation between the means of the two detectors as depicted in equation 4-1. The dark signal not only differs for the detectors but also changes over time, which becomes apparent in differing averages for the different space corners even for the same detector. To consider the resulting uncertainty, the standard deviation of the four space corner averages means has to be considered as well (equation 4-2). The same evaluation needs to be done for both detectors individually (equation 4-3). The three above described uncertainty effects can be combined into one single measure of the dark signal uncertainty according to equation 4-4.

$$u(\bar{C}_{S,d}) = \sqrt{((\bar{C}_{S1} - \bar{C}_S)^2 + (\bar{C}_{S2} - \bar{C}_S)^2)} \quad \text{Eq 4-1}$$

$$u(\bar{C}_{S,s1}) = \sqrt{\frac{\sum_{c=1}^4 (\bar{C}_{S1}(c) - \bar{C}_{S1})^2}{3}} \quad \text{Eq 4-2}$$

$$u(\bar{C}_{S,s2}) = \sqrt{\frac{\sum_{c=1}^4 (\bar{C}_{S2}(c) - \bar{C}_{S2})^2}{3}} \quad \text{Eq 4-3}$$

$$u(\bar{C}_S) = \sqrt{u(\bar{C}_{S,d})^2 + u(\bar{C}_{S,s1})^2 + u(\bar{C}_{S,s2})^2} \quad \text{Eq 4-4}$$

The uncertainty in the Earth counts is determined by combining the uncertainties associated with electronics (white) noise and the effect from the detector difference. The electronics noise is estimated from the Allan deviation of the space corner counts and combined with the difference of the means of the two detectors (Equation 4-5).

Another effect on the Earth counts is the digitisation noise. It can be described as the standard deviation of a uniform (rectangular) distribution with a half width of 0.5 counts (Equation 4-6).

Our evaluation of the photon shot noise, a source of noise common for optical instruments, has revealed that it is below  $5.4 \times 10^{-9}$  counts and therefore insignificant.

$$u_e(\bar{C}_E) = \sqrt{\frac{1}{2}(\sigma_\tau(C_{S1})^2 + \sigma_\tau(C_{S2})^2) + \left(\frac{\bar{C}_{S1} - \bar{C}_{S2}}{2}\right)^2} \tag{Eq 4-5}$$

$$u_d(\bar{C}_E) = \frac{b}{2\sqrt{3}} \tag{Eq 4-6}$$

Table 1 Effects tables for the Earth, averaged-Space and averaged-IWCT counts

Table descriptor				
Name of effect		Earth Count Error	Digitisation Noise	Space count error
Affected term in measurement function		$\bar{C}_E$	$\bar{C}_E$	$\bar{C}_s$
Instruments in the series affected		All	All	All
Correlation type and form	<b>Pixel-to-pixel [pixels]</b>	Random (Bell shaped)	Random	Rectangular_absolute
	<b>from scanline to scanline [scanlines]</b>	Random (Bell shaped)	Random	Rectangular_absolute
	<b>between images [images]</b>	Random	Random	Random
	<b>Between orbits [orbit]</b>	N/A	N/A	N/A
	<b>Over time [time]</b>	Random	Random	Random
Correlation scale	<b>Pixel-to-pixel [pixels]</b>	[0]	[0]	[5000]
	<b>from scanline to scanline [scanlines]</b>	[0]	[0]	[5000]
	<b>between images [images]</b>	[0]	[0]	[0]
	<b>Between orbits [orbit]</b>	N/A	N/A	N/A
	<b>Over time [time]</b>	[0]	[0]	[0]
Channels/bands	<b>List of channels / bands affected</b>	N/A	N/A	N/A
	<b>Correlation coefficient matrix</b>	N/A	N/A	N/A
Uncertainty	<b>PDF shape</b>	Digitised Gaussian	Uniform	Digitised Gaussian
	<b>units</b>	Counts	Counts	Counts
	<b>magnitude</b>	Provided per pixel, Eq 4-5	Provided per instrument, Eq 4-6	Provided per pixel, Eqs 4-1 to 4-4
Sensitivity coefficient		$\frac{\partial \rho}{\partial \bar{C}_E}$ , Eq 4-7	$\frac{\partial \rho}{\partial \bar{C}_E}$ , Eq 4-7	$\frac{\partial \rho}{\partial \bar{C}_s}$ , Eq 4-8

The sensitivity coefficients can be determined as the first derivatives of the measurement equation (middle term) or as the relative sensitivity by dividing both sides by reflectance (right term):

$$\frac{\partial \tilde{R}}{\partial \bar{C}_E} = \frac{\pi d^2}{\tilde{E}_{0,\text{sun}} \cos \theta} (a_0 + a_1 Y_t + a_2 Y_t^2) = \frac{\tilde{R}}{(\bar{C}_E - \bar{C}_S)} \quad \text{Eq 4-7}$$

$$\frac{\partial \tilde{R}}{\partial \bar{C}_S} = \frac{-\pi d^2}{\tilde{E}_{0,\text{sun}} \cos \theta} (a_0 + a_1 Y_t + a_2 Y_t^2) = \frac{-\tilde{R}}{(\bar{C}_E - \bar{C}_S)} \quad \text{Eq 4-8}$$

## 4.2 Spectral response function, band-integrated solar irradiance

The spectral response function (SRF) is determined through a minimisation routine which minimises the differences between the modelled and measured top-of-atmosphere reflectance values over different calibration reference sites. The SRF for processing the FCDR is stored as a tabulated list of values at different wavelengths, along with a covariance matrix which provides the covariance associated with the different wavelength pairs. Note that because of the fitting process there is significant correlation between the SRF values for different wavelengths.

The SRF is used to determine the band-integrated solar spectral irradiance using a discretised version of Eq 3-2:

$$\tilde{E}_{0,\text{sun}} = \sum_i \xi(\lambda_i) E_{0,\text{sun}}(\lambda_i) \delta \lambda_i + 0 \quad \text{Eq 4-9}$$

Note that we consider the uncertainty associated with the band-integrated solar irradiance to be dominated by the uncertainty associated with the SRF. Uncertainties associated with the solar spectral model are small and minimised when the same model is used for the calibration sites.

The Plus Zero term in Eq 4-9 represents the extent to which the summation is an approximation to the original integral. We have tested the sensitivity of this summation to the wavelength spacing used and it is insignificant, therefore we consider the uncertainty associated with the plus zero term to be negligible.

The SRF is also used in the calibration process to determine  $a_0, a_1, a_2$ , using Eq 3-7.

Because it is used in both, calibration and irradiance, there is an error correlation between the solar irradiance and the calibration coefficients in the measurement function which must be considered in uncertainty propagation. A Monte-Carlo approach, based on an ensemble of disturbed SRFs, is used to determine the correlation. The ensemble of SRFs is generated using the eigenvectors of the error covariance matrix of the SRFs in order to map the wavelength dependent error correlation through the entire process.

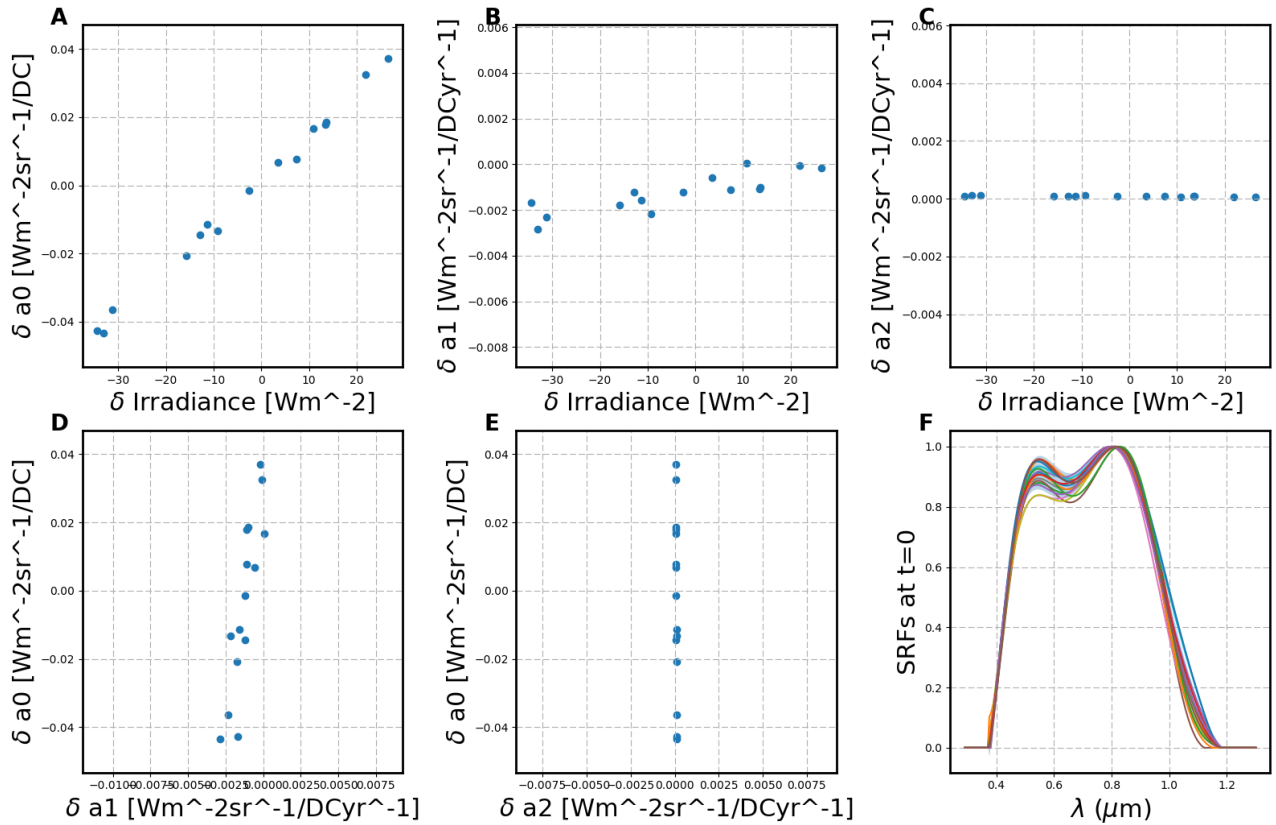


Figure 5: Co-deviations from the normal calibration of the solar irradiance with calibration parameters  $a_0$  (A),  $a_1$  (B) and  $a_2$  (C) as well as of  $a_0$  with  $a_1$  and  $a_2$  (D and E), when using a member of an ensemble of spectral response functions (F). The generation of the SRF ensemble considers the covariance matrix of the reconstructed SRF. The correlation matrix of all effects is provided in the Annex (Figure 6).

The SRF varies with time, but this variation is defined explicitly by the degradation model. The errors in the SRF are therefore fully correlated across time for each instrument, with a sensitivity coefficient defined by the degradation model.

Table 2 Effects tables for the SRF

Table descriptor			
Name of effect		Spectral response function effect on solar irradiance	Spectral response function effect on calibration
Affected term in measurement function		$\tilde{E}_{0,\text{sun}}$	$[a_0, a_1, a_2]$
Instruments in the series affected		All	All
Correlation type and form	<b>Pixel-to-pixel [pixels]</b>	Rectangular_absolute	Rectangular_absolute
	<b>from scanline to scanline [scanlines]</b>	Rectangular_absolute	Rectangular_absolute
	<b>between images [images]</b>	Rectangular_absolute	Rectangular_absolute
	<b>Between orbits [orbit]</b>	N/A	N/A
	<b>Over time [time]</b>	Rectangular_absolute	Rectangular_absolute
<b>Pixel-to-pixel [pixels]</b>		$[-\infty, +\infty]$	$[-\infty, +\infty]$

Table descriptor		Spectral response function effect on solar irradiance	Spectral response function effect on calibration
Name of effect			
Correlation scale	<b>from scanline to scanline [scanlines]</b>	$[-\infty, +\infty]$	$[-\infty, +\infty]$
	<b>between images [images]</b>	$[-\infty, +\infty]$	$[-\infty, +\infty]$
	<b>Between orbits [orbit]</b>	N/A	N/A
	<b>Over time [time]</b>	$[-\infty, +\infty]$	$[-\infty, +\infty]$
Channels/bands	<b>List of channels / bands affected</b>	N/A	N/A
	<b>Correlation coefficient matrix</b>	N/A	N/A
Uncertainty	<b>PDF shape</b>	Gaussian	Gaussian
	<b>units</b>	$\text{W m}^{-2}$	$\text{W m}^{-2}\text{sr}^{-1}/\text{count}$
	<b>magnitude</b>	Provided per instrument	Provided per instrument
Sensitivity coefficient		Depends on degradation state	Depends on degradation state

### 4.3 Earth-sun distance

The maximum error of the Earth-sun distance  $d$ , calculated using the VSOP87 (French: Variations Séculaires des Orbites Planétaires; Bretagnon and Francou, 1988) concept, is one arcsecond [Moisson and Bretagnon, 2001], equalling around 725281 m. The sensitivity coefficient of  $d$  can be written as:

$$\frac{\partial \rho}{\partial d} = \frac{2\pi(C_E - C_S(a_1 D_t + 0 + a_0)d}{E_0 \cos(\theta)} \quad \text{Eq 4-10}$$

An example typical measurement could be:

$C_E$	50 [counts]
$C_S$	5 [counts]
$a_0$	0.92 [ $\text{W m}^{-2}\text{sr}^{-1}/\text{count}$ ]
$a_1$	0 [ $\text{W m}^{-2}\text{sr}^{-1}/\text{count}/\text{year}$ ]
$a_2$	0 [ $\text{W m}^{-2}\text{sr}^{-1}/\text{count}/\text{year}^2$ ]
$Y_t$	1.0 [years since launch]
$d$	1 [AU]
$E_0$	690 [ $\text{W m}^{-2}$ ]
$\theta$	0.44 [radians]



For this scenario an uncertainty of 725281 m ( $4.85 \times 10^{-6}$  AU) would have an impact of only  $1.99 \times 10^6$  reflectance points (= 0.0009 % of the BRF value of 0.208). Therefore we consider  $d$  a negligible uncertainty effect.

#### 4.4 Solar zenith angle

The solar zenith angle is calculated using Eq 3-5 from the longitude, latitude and acquisition time. Maximum uncertainty of the acquisition time is around 30 seconds. For acquisition time variations of this order, the SZA has almost not measurable sensitivity. therefore we consider it to be a negligible uncertainty effect. Uncertainties associated with longitude and latitude have been analysed by looking at errors in the positioning of ground landmarks. These errors show that landmark errors in longitude direction can roughly be assumed to be correlated across 50 lines and pixels, while those in latitude direction are correlated across 1000 pixels and 200 lines (Figure 7 and Figure 8 in Appendix 0). There is no significant autocorrelation in the landmark errors, and therefore the temporal error correlation form and error correlation form between images is random.

Table 3 Effects tables for the Solar Zenith Angle

Table descriptor			
Name of effect		Longitude	Latitude
Affected term in measurement function		$\theta$	$\theta$
Instruments in the series affected		All	All
Correlation type and form	Pixel-to-pixel [pixels]	Bell-shaped	Bell-shaped
	from scanline to scanline [scanlines]	Bell-shaped	Bell-shaped
	between images [images]	Random	Random
	Between orbits [orbit]	N/A	N/A
	Over time [time]	Random	Random
Correlation scale	Pixel-to-pixel [pixels]	[-50,+50]	[-1000,+1000]
	from scanline to scanline [scanlines]	[-50,+50]	[-200,+200]
	between images [images]	[0]	[0]
	Between orbits [orbit]	N/A	N/A
	Over time [time]	[0]	[0]
Channels/bands	List of channels / bands affected	N/A	N/A
	Correlation coefficient matrix	N/A	N/A
Uncertainty	PDF shape	Gaussian	Gaussian
	units	Degrees	Degrees

Table descriptor			
Name of effect		Longitude	Latitude
	magnitude	Provided per pixel	Provided per pixel
<b>Sensitivity coefficient</b>		$\frac{\partial \rho}{\partial lon} = \frac{\partial \rho}{\partial \theta} \frac{\partial \theta}{\partial h} \frac{\partial h}{\partial lon}$ , Eq 4-11, Eq 4-12	$\frac{\partial \rho}{\partial \varphi} = \frac{\partial \rho}{\partial \theta} \frac{\partial \theta}{\partial \varphi}$ , Eq 4-11, Eq 4-

The sensitivity coefficients are:

$$\frac{\partial \rho}{\partial \theta} = \frac{\pi d^2}{\tilde{E}_{0,\text{sun}} \cos^2 \theta} \left[ (\bar{C}_E - \bar{C}_S) (a_0 + a_1 Y + a_2 Y_t^2 + 0) \right] \frac{\sin \theta}{\cos^2 \theta} = \rho \tan \theta \quad \text{Eq 4-11}$$

$$\frac{\partial \theta}{\partial h} = \frac{\cos(\gamma) \cos(\varphi) \sin(h)}{\sqrt{1 - (\sin(\gamma) \sin(\varphi) + \cos(\gamma) \cos(h) \cos(\varphi))^2}} \quad \text{Eq 4-12}$$

$$\frac{\partial \theta}{\partial \varphi} = - \frac{\sin(\gamma) \cos(\varphi) - \cos(\gamma) \cos(h) \sin(\varphi)}{\sqrt{1 - (\sin(\gamma) \sin(\varphi) + \cos(\gamma) \cos(h) \cos(\varphi))^2}} \quad \text{Eq 4-7}$$

$\frac{\partial \theta}{\partial lon}$  has to be and  $\frac{\partial \theta}{\partial \varphi}$  can also be determined using Monte-Carlo iterations. The results of the Monte carlo runs are, for both sensitivities, provided inside the so called lutFCDR – file [EUMETSAT, 2019].

## 5 Calibration coefficients (harmonisation)

Unlike the other FIDUCEO FCDRs, there is not a direct harmonisation using matchups to a reference sensor for the MVIRI FCDR. However, the determination of the calibration coefficients,  $a_0, a_1, a_2$  shares much in common with the process of harmonisation. The calibration coefficients are determined by orthogonal distance regression to fit a 2<sup>nd</sup> order polynomial model to results obtained by comparing the sensor measured radiance to that of a reference, here a modelled spectrally-integrated TOA radiance value for several desert and several ocean sites. Each datapoint is a successful five-day calibration run. The fit is described in section 3.2.2 and illustrated in Figure 3. It is important to note that the five-day calibration runs for the fit are weighted by the inverse of their squared combined uncertainty.

From the residuals of the calibration process we obtain the uncertainties associated with  $a_0, a_1, a_2$  and the covariance between them. The errors in these terms are constant for the whole sensor. The term +0 in the main measurement function, Eq 3-1, represents the extent to which the polynomial calibration equation applies to the whole sensor. In practice, when the residual is plotted over time, a seasonal effect is seen (Figure 9, Appendix).

This can come from three effects:

- A responsivity effect due to satellite warming or cooling. The exposition of a geostationary satellite to the sun changes with a yearly cycle, affecting the thermal environment inside the spacecraft. The sensitivity of a silicon photodiode in turn changes with the temperature of the material. Since the silicon responsivity increases with temperatures, the calibration coefficients in the presence of high temperatures (usually winter) need to be smaller. This is a real seasonal effect that needs to be accounted for in the uncertainty analysis.
- An impact of the seasonal cycle of the satellite temperature on the noise level. Generally, electronics noise (white noise) increases with the temperature of an electronic assembly. In MVIRI instruments this effect is masked by a thermal behaviour of the A/D converters. This behaviour superimposes an artificial seasonal cycle of the dark-signal and of its noise level. However, the increasing noise level of the dark signal sufficiently covers the effect of the artificially increased dark signal (Figure 10, appendix).
- An effect due to errors in the radiative transfer model's determination of the TOA reflectance over the sites due to an increased sensitivity to SZA (which have a significant uncertainty) and inaccuracies in the BRDF model of the site which provide a seasonal variation. This would be an artificial effect that will not affect the measurement of the instrument.

It is likely that the majority of the observed deviation is due to the latter effect and therefore the errors in the model (the zero term) are considered to be smaller than the observed variation. They are, however, considered fully systematic. As systematic effects are fully correlated between all five-day calibration runs, they cannot be determined from the residuals of a polynomial fit. In spite, they have to be propagated separately using equation 5-1, where the sensitivity matrices (C) are, as in the orthogonal distance regression model described above, represented by the inverse of the squared combined uncertainty of each run. The one-dimensional uncertainty matrix (U) holds the correlated uncertainty component of each five-day run. As such, the size of the U-matrix depends on the number of successful five-day calibration runs that are available for a satellite. The correlation matrix (R) is two dimensional. As the error of the SRF reconstruction is fully correlated for the lifetime of a satellite, R is set to unity.

$$u(+0) = C \cdot U \cdot R \cdot U^T C^T \quad \text{Eq 5-1}$$

Table descriptor			
Name of effect		Harmonisation coefficients	Plus Zero
Affected term in measurement function		$[a_0 \ a_1 \ a_2]$	+0
Instruments in the series affected		All	All
Correlation type and form	Pixel-to-pixel [pixels]	Rectangular_absolute	Rectangular_absolute
	from scanline to scanline [scanlines]	Rectangular_absolute	Rectangular_absolute
	between images [images]	Rectangular_absolute	Rectangular_absolute
	Between orbits [orbit]	N/A	N/A
	Over time [time]	Rectangular_absolute	Rectangular_absolute
Correlation scale	Pixel-to-pixel [pixels]	$[-\infty, +\infty]$	$[-\infty, +\infty]$
	from scanline to scanline [scanlines]	$[-\infty, +\infty]$	$[-\infty, +\infty]$
	between images [images]	$[-\infty, +\infty]$	$[-\infty, +\infty]$
	Between orbits [orbit]	N/A	N/A
	Over time [time]	$[-\infty, +\infty]$	$[-\infty, +\infty]$
Channels/bands	List of channels / bands affected	N/A	N/A
	Correlation coefficient matrix	N/A	N/A
	Covariance	N/A	N/A
Uncertainty	PDF shape	Gaussian	Gaussian
	units	Units of $a_0, a_1, a_2$ [W m <sup>-2</sup> sr <sup>-1</sup> /DC, W m <sup>-2</sup> sr <sup>-1</sup> / DC / year ...]	W m <sup>-2</sup> sr <sup>-1</sup> /DC
	magnitude	Determined per instrument	Determined per instrument
Sensitivity coefficient		$\frac{\partial \rho}{\partial a_0}, \frac{\partial \rho}{\partial a_1}, \frac{\partial \rho}{\partial a_2}$ , Eq 5-1 to Eq 5-3	$\frac{\partial \rho}{\partial '+0'}$ , Eq 5-4

$$\frac{\partial \rho}{\partial a_0} = \frac{d^2 \pi (C_E - C_S)}{\tilde{E}_{0,\text{sun}} \cos(\theta)} \tag{Eq 5-1}$$

$$\frac{\partial \rho}{\partial a_1} = \frac{d^2 \pi (C_E - C_S) Y_t}{\tilde{E}_{0,\text{sun}} \cos(\theta)} \tag{Eq 5-2}$$

$$\frac{\partial \rho}{\partial a_2} = \frac{d^2 \pi (C_E - C_S) Y_t^2}{\tilde{E}_{0,\text{sun}} \cos(\theta)} \quad \text{Eq 5-3}$$

$$\frac{\partial \rho}{\partial ' + 0'} = \frac{d^2 \pi (C_E - C_S)}{\tilde{E}_{0,\text{sun}} \cos(\theta)} \quad \text{Eq 5-4}$$

## A Appendix on detailed information about uncertainty components

### A.1 Error correlation between effects

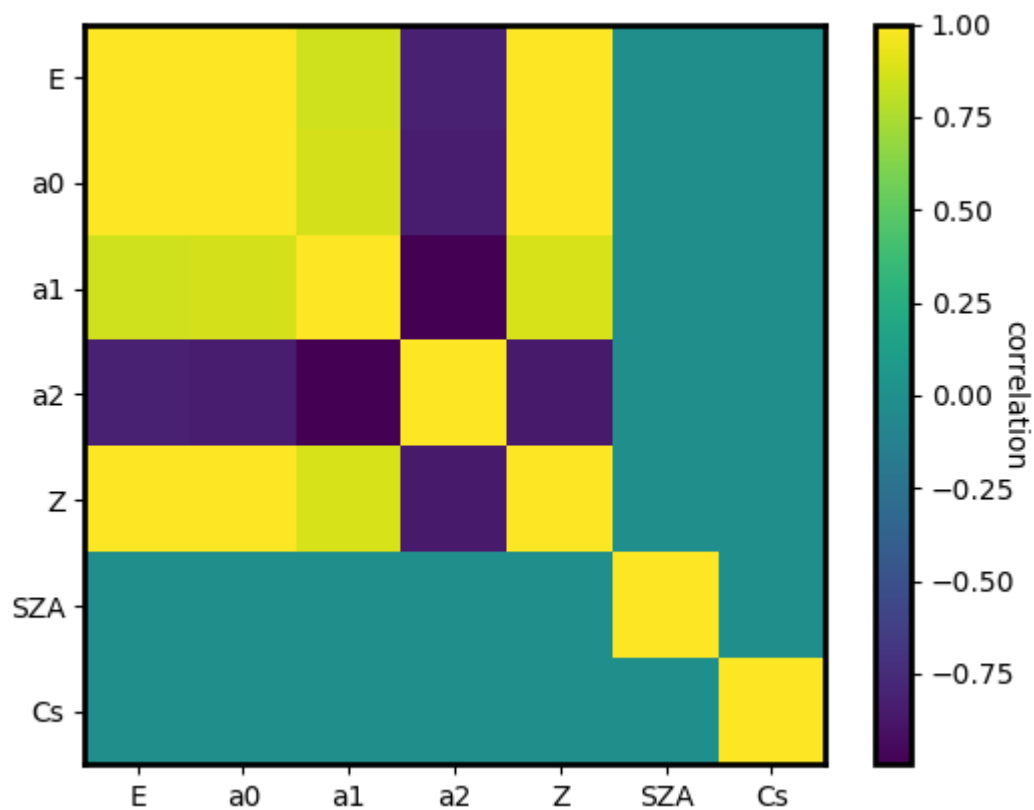


Figure 6: Error correlation matrix between the different uncertainty effects of the measurement equation. The correlations were determined by MonteCarlo iteration of the FCDR generation using a set of 15 different SRFs. Z refers to the uncertainty effects contained in the +0 term.

## A.2 Error correlation in longitude and latitude from landmark analysis

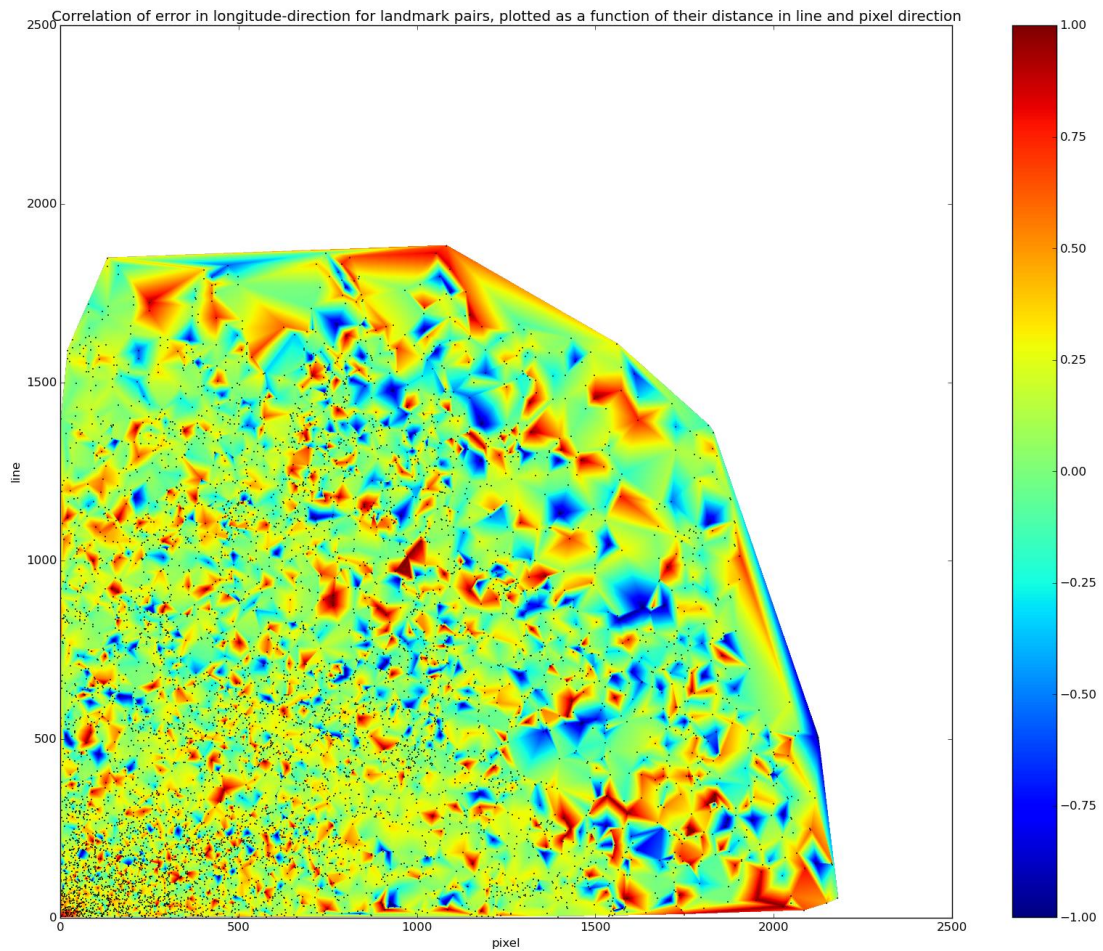


Figure 7: Correlation of landmark errors across all landmark pairs in longitude direction, plotted as a function of their distance in pixel- and line-direction. Landmark errors can be strongly negatively or positively correlated even if they have large distances. However, landmarks with distances of up to 50 pixels are commonly positively correlated (lower left corner).

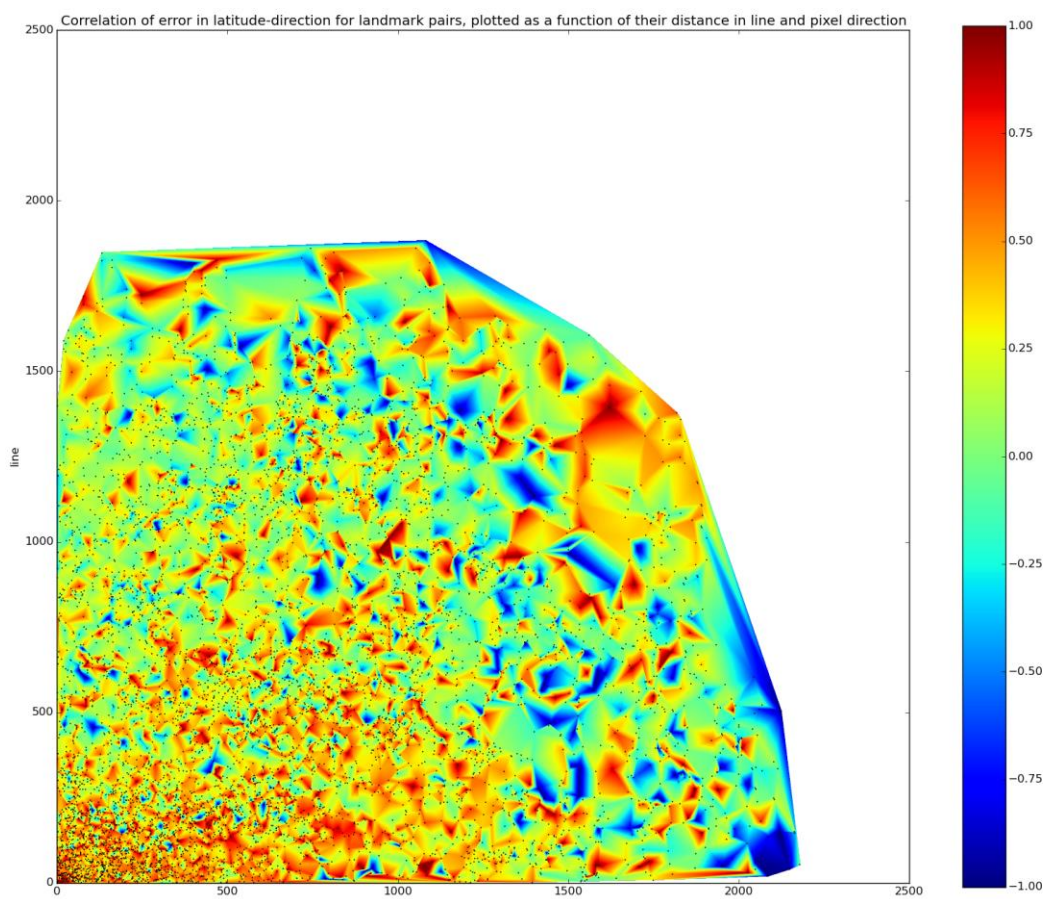


Figure 8: Correlation of landmark errors across all landmark pairs in latitude direction, plotted as a function of their distance in pixel- and line-direction. Landmark errors can be strongly negatively or positively correlated even if they have large distances. However, landmarks with distances of up to 200 pixels in line direction or 1000 pixels in pixel direction are commonly positively correlated (lower left corner, stretching towards the lower right corner).



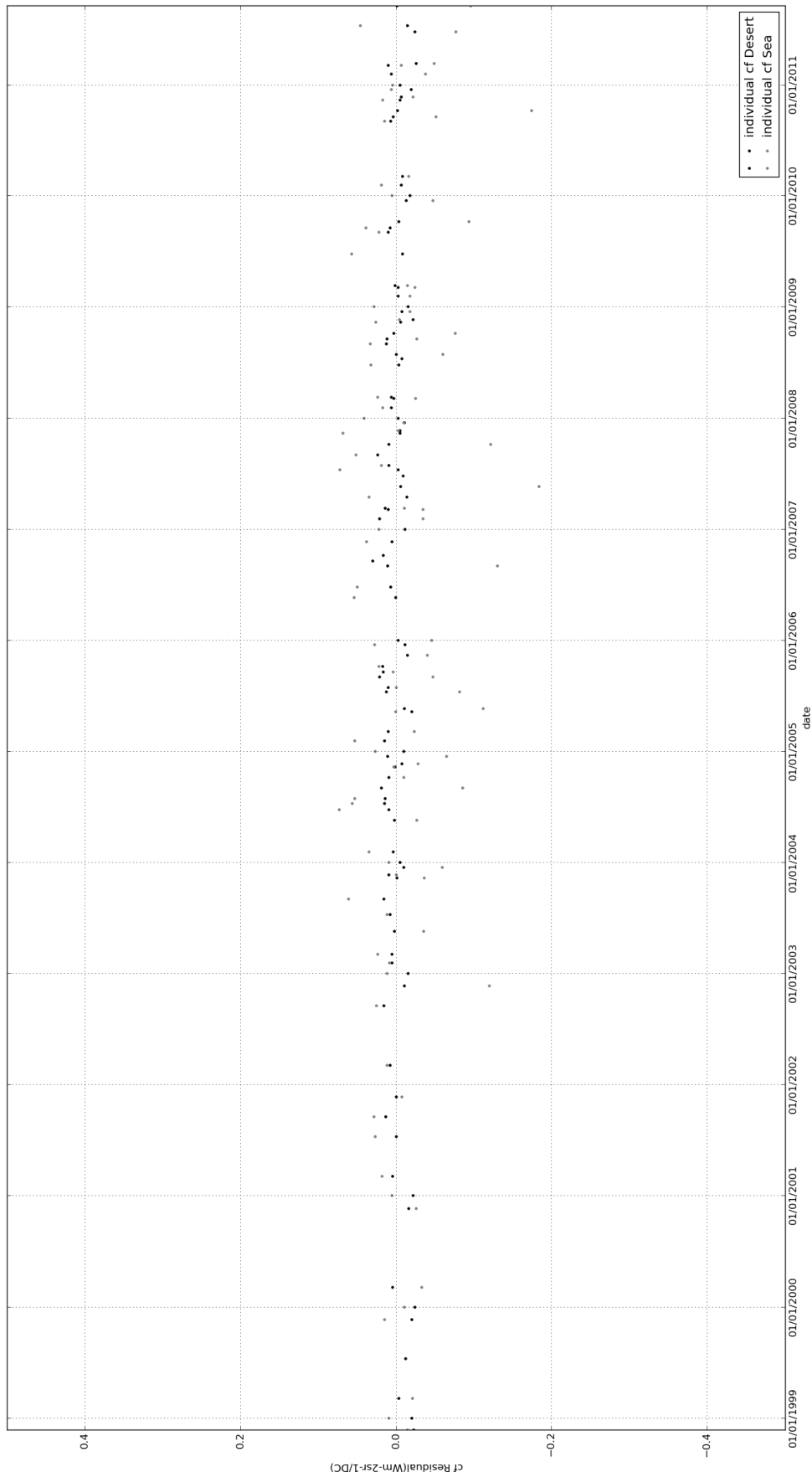


Figure 9: Residuals from the linear fit shown in the Figure above.

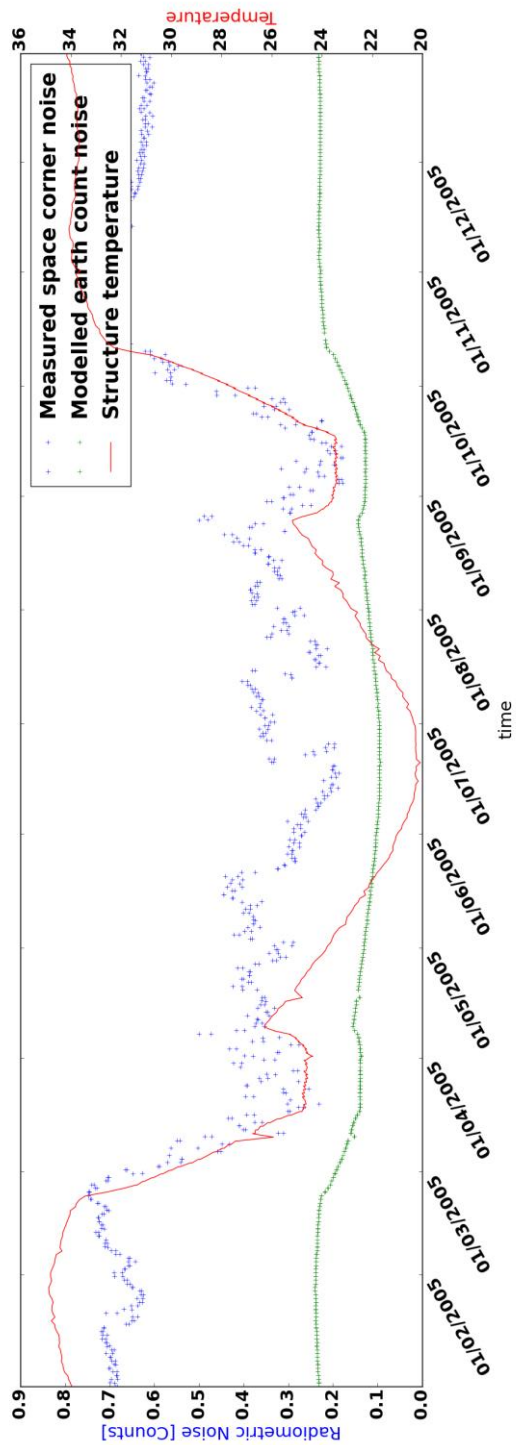


Figure 10: Measured noise of the dark signal (blue) compared to the structure temperature (red) and the modelled electronics noise. Note, that the difference between modelled (expected) electronics noise and measured noise is due to the temperature dependent behaviour of the A/D converter count-switches.