

IMPLEMENTATION OF ALGORITHMIC CORRECTION OF STRAY LIGHT IN A PUSHBROOM HYPERSPECTRAL SENSOR

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ABSTRACT:

The effects of spectral stray light on the radiometric calibration of the pushbroom imaging spectrometer ROSIS (Reflective Optics System Imaging Spectrometer) are discussed. Due to construction, spectral stray light can span the entire detector array, e.g. the channels in the blue part of the spectrum detect red and infrared light. This leads to significant errors in measurements and calibration. In order to develop a correction algorithm, the effect of stray light has been characterised and quantified with the help of laboratory measurements. Different approaches for the measurements are presented. As hardware modifications of ROSIS are not feasible, the correction of this effect will be done in software.

1. INTRODUCTION

The radiometric accuracy of hyperspectral sensors depends on a calibration of the instrument with as few systematic errors as possible.

As any imaging device, hyperspectral pushbroom sensors are, depending on design and construction, more or less subject to stray light effects: incoming light leads to signals in the wrong channels or pixels. In this paper, spectral stray light is studied and corrected for the imaging spectrometer ROSIS (Kunkel et al. 1991).

Spectral stray light has implications in the calibration of sensors, as the incandescent lamps used in many calibration laboratories for radiometric calibration have radiance spectra that are usually very different from the in-flight spectra. This leads to systematic, wavelength-dependent errors in the response function of the instrument, as the incandescent lamps emit only a very small fraction of the total emitted light in the blue part of the spectrum (< 500 nm) and the quantum efficiency of Si detectors is very low at these wavelengths.

The measurements described here were carried out in the Calibration Home Base in Oberpfaffenhofen, Germany (Gege et al. 2009)

2. SPECTRAL STRAY LIGHT

In order to be able to perform a correction of the stray light on a hyperspectral image, the relation between incoming light and stray light has to be determined. This relation is given by the Line Spread Function, which is also called Spectral Response Function (SRF) in the case of spectral channels.

Usually, the SRF is measured by illuminating the instrument with a bandwidth significantly smaller than the bandwidth of a channel of the instrument. As it was already observed beforehand, the spectral stray light in ROSIS can span almost the entire spectral range of the instrument. Due to the finite radiometric resolution of ROSIS (14 bit, noise ~30 DN),

standard measurements of the SRF are not sensitive enough to measure this effect.

Instead, we performed two different kinds of measurements, both with much higher irradiances, which enabled us to quantify the "long range" stray light.

2.1 Using optical band-pass filters

The first set of SRF measurements was performed by illuminating our instrument with an integrating sphere, and a set of optical band-pass filters (fig. 1) that covers the spectral range of ROSIS.

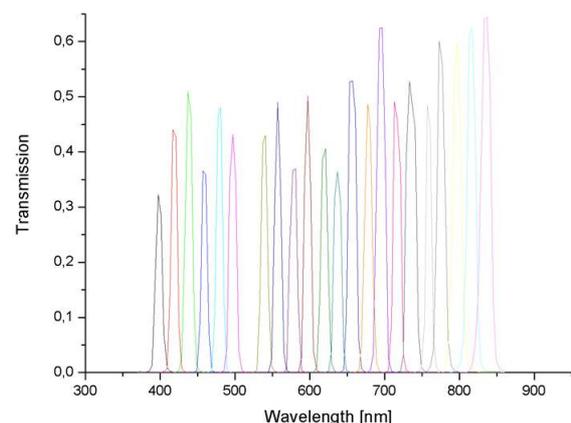


Figure 1 Transmission curves of the band pass filters.

The stray light contribution in these measurements was then determined as follows:

- Computing the expected signal by multiplying the known transmission coefficients of the band-pass filters with the signal measured at the unobscured broad-band integrating sphere.
- Dividing the spectral channels that have been measured using band-pass filters into two groups: spectral channels that are considered to detect light

(also called in-band channels), and channels that are considered to detect only stray light (out-of-band channels). This is done by setting appropriate thresholds: the stray light, or out-of-band channels are defined by transmission values of the band-pass filters that are so low that not enough light to generate 1 DN on a detector element is transmitted, and the in-band channels are defined by transmission values of the filters that are so high that transmitted light can generate at least 1 DN of stray light.

- The stray light contribution is the difference between the estimated signal and the actual measurement.
- The sum of the signals of the in-band channels is used for normalisation.
- The correction algorithm described in sec. 3 was applied preliminarily in order to correct the estimations for stray light. This leads to a more accurate stray light correction afterwards. In this case, one iteration was sufficient.

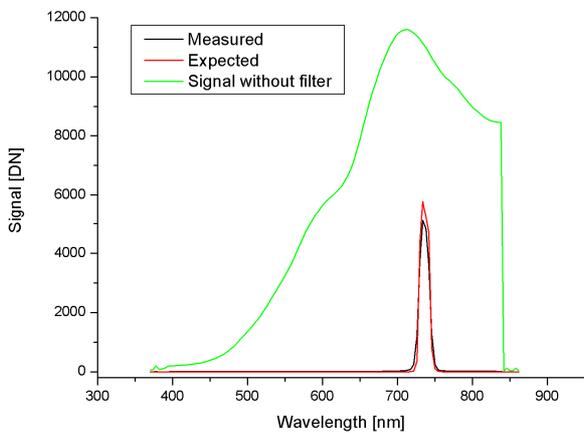


Figure 2 Exemplary measurement for the characterisation described in sec. 2.1. The signal without filter is a spectrum measured by a single geometric pixel of ROSIS of an integrating sphere.

An exemplary measurement is shown in fig. 2. The differences between the expected and the measured curve indicate the presence of spectral stray light (Damm 2007).

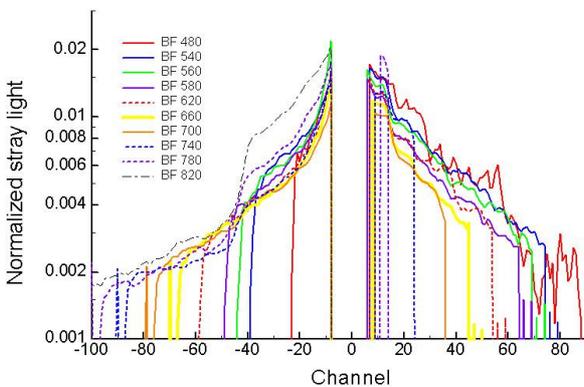


Figure 3 Results of the band-pass filter measurements. For comparative purposes, the central wavelengths of all filters have been set to channel 0.

The results of the spectral stray light characterisation measurements (Damm 2007) are illustrated in fig. 3. It can be seen that the spectral stray light can span 60 or more channels. The gap around channel 0 is due to the fact that only the out-of-band channels are shown (Damm 2007).

While this method quantifies the stray light over “long ranges”, it is not suited for the channels in the vicinity of the originating channel. These are characterised by a different method described in sec. 2.2.

2.2 Using a monochromator

The measurements to quantify the stray light in the neighbourhood of the originating channel were performed using a monochromator providing a spectral bandwidth of 1.3 nm. While this is a higher bandwidth than used for standard measurements of the SRF, it was chosen to obtain a higher radiance on the detector elements. This set-up illuminates only a single channel, hence signals in other channels are due to spectral stray light. To enhance the signal-to-noise ratio of these out-of-band signals, a very high radiance level was chosen which saturated the illuminated detector element. It followed a measurement at lower signal level to determine quantitatively the ratio of stray light to signal. For this, a neutral density filter of known transmission was inserted in the optical path.

To quantify the stray light, the non-saturated measurement is scaled with the inverse transmission coefficient of the neutral density filter to calculate the actual signal level of the saturated measurement, so that the normalisation factor for the saturated SRF measurement is known. This way, a SRF is obtained for the detector in the vicinity of the illuminated pixel (fig. 4), as opposed to the band-pass filter measurements that yield the SRF for larger distances.

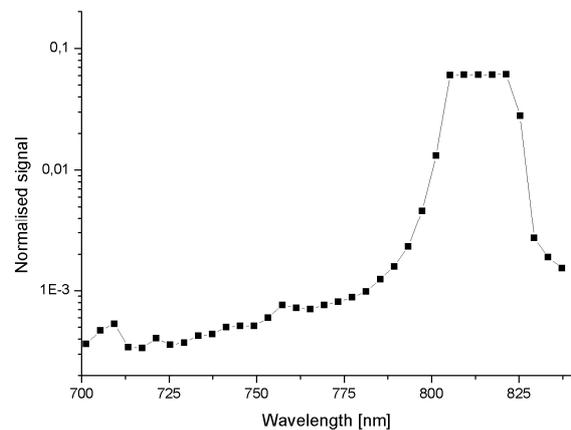


Figure 4 Results of the stray light measurement with saturation of the detector. Next to the five saturated channels, stray light is visible.

These measurements have yet to be carried out in a systematic way, also to exclude the presence of electronic effects such as blooming. The results could then be easily incorporated in the spectral correction matrix described in the next section.

3. SPECTRAL CORRECTION

The correction algorithm used here was taken from (Zong 2006) and will be described briefly in this section. The basic assumption for this correction algorithm is that stray light in one detector element originates is proportional to the signal of surrounding detector elements. The knowledge obtained through the above mentioned measurements is therefore suited to be applied for such corrections.

The information about the spectral stray light can be summarised into a single matrix, D . Each column of D contains the out-of-band contribution to the SRF of one spectral channel. For instance, if the vector S_{measured} consists of all spectral channels of one geometric pixel, the operation

$$S_{\text{measured}} = D_{\text{spec}} \cdot S_{\text{in}} + I \cdot S_{\text{in}} = (D_{\text{spec}} + I) \cdot S_{\text{in}} = C \cdot S_{\text{in}} \quad (1)$$

with $C = D_{\text{spec}} + I$ and I being the unity matrix, relates the incoming signal S_{in} to the actually measured signal. By inverting C and solving for S_{in} , the incoming signal becomes accessible from S_{measured} .

$$S_{\text{in}} = C^{-1} \cdot S_{\text{measured}} \quad (2)$$

For the case of spectral correction, this assumes that the SRFs may vary over the spectral channels, but remain constant over the geometric pixels.

The results shown in fig. 3 were used to construct the correction matrix for ROSIS. As the SRF could not be measured for each channel, each channel was assigned the SRF to which it was an in-band channel during the measurement. In the cases where a SRF could not be assigned this way, it was linearly interpolated from the adjacent channels. This requires the assumption that the SRFs do not change rapidly over the detector array, which is supported by fig. 3.

An example of a correction is shown in fig. 5. The black curve shows a dark-current corrected measurement of our integrating sphere, and the red curve is additionally corrected for spectral stray light.

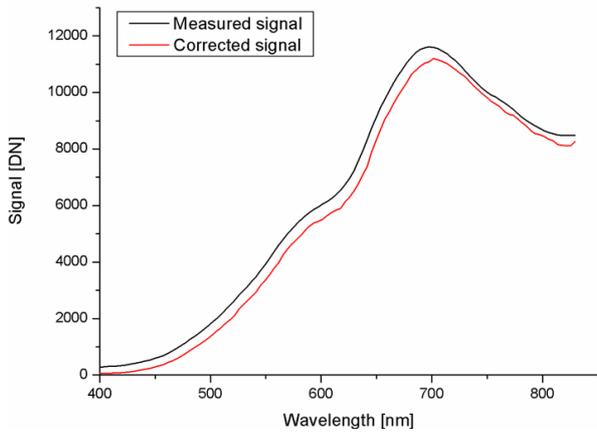


Figure 5 Exemplary spectral correction. The red curve is corrected, the black curve uncorrected.

One can see that in the lower channel numbers, which are supposed to measure the blue part of the spectrum, most of the signal is generated by stray light (fig.6).

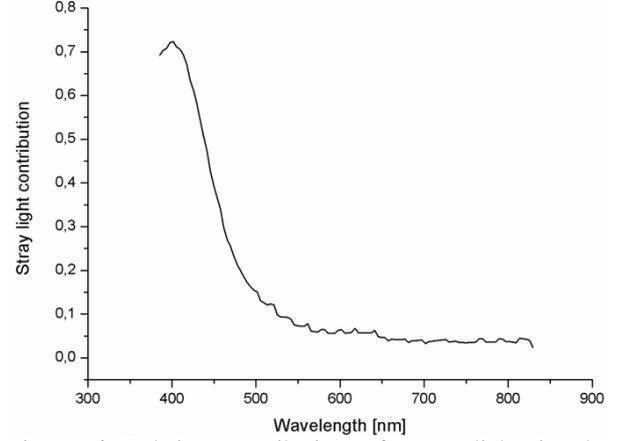


Figure 6 Relative contribution of stray light in the measurements of fig. 5

This behaviour is expected, as a long-pass filter built into ROSIS blocks incoming light below a wavelength of 430 nm. On the other hand, this means that the curve in fig. 6 should peak at 1. The deviation can be explained by the fact that the measurements that were taken into account for the correction characterise only a fraction of the entire stray light.

4. CONCLUSIONS

While not included in this paper, geometric stray light can also cause additional radiometric errors. Spectral and geometric stray light corrections should be applied simultaneously, as both effects have the same origin. Unfortunately, this would require with ROSIS (114 spectral channels and 512 geometric pixels) and the described algorithm a four-dimensional tensor with $(\# \text{ of channels})^2 \cdot (\# \text{ of pixels})^2 \approx 5 \cdot 10^9$ elements, which requires a high computational effort.

As a next step, we will try to implement the spectral correction in our processing chain, as we estimate that it is of higher importance for an imaging spectrograph. Especially, it has to be verified that the SRF is reasonably uniform over the whole detector array.

Also note that after the implementation of any kind of correction algorithm, the reprocessing of old ROSIS data will lead to different results!

5. SUMMARY

Stray light can introduce significant errors in calibration. In this paper, we have presented measurement procedures to quantify the amount of stray light within a pushbroom hyperspectral sensor, and estimates to the errors made by ignoring stray light effects within our instrument, ROSIS. We conclude that it is absolutely necessary to consider stray light effects during calibration and measurement in order to minimise systematic radiometric errors.

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