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Earthshine Project Document: Earthshine data reduction error budget

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0.1 Dansk resumé

For at kunne forbedre fremtidige optiske systemer til måling af jordskinnet - til bestemmelse af Jordens albedo - har vi kigget på den kæde af data-behandlingstrin der ligger mellem optagelsen af månebillederne ved teleskopet til stadiet lige før det spredte lys skal fjernes. Vi finder at der er sampling-errors der kan formindskes ved at have flere billeder ved hånden. Vi finder at brugen af de flat-fields vi har for øjeblikket ikke kan anbefales da en større fejl introduceres ved at bruge dem end ved at lade være. Vi ser også at alignment af billeder medfører en lille fejl der i princip kan formindskes hvis konservative billed-interpolationsmetoder bruges. Disse resultater kan bruges til at forbedre det nuværende data-processeringssystem, samt til at sikre at bedre systemer fremover kan designes og bygges.

0.2 Abstract

The error budget of the data-reduction pipeline for earthshine data is reviewed and analysed. Considering the part of the reduction chain before scattered light is removed, we look at methods to align images; at estimates of sampling error; at image interpolation issues; and at the effect of choice of flat fields. We conclude that at present the sampling error is the biggest source of scatter - by acquiring more images we can reduce the error. The use of flat fields is at present not recommended - there is simply less error in not using the FFs. We also see that image interpolation is a source of error - use of 'conservative interpolation schemes' are in order. We also see that the VE2, VE1 and to some degree the IRCUT red filters all suffer from large errors - up to several percent. These findings can be used to improve the present earthshine telescope and data-reduction system, as well as ensure better future system designs.

1. Data reductions prior to removal of scattered light

1.1 Introduction

We document in this report the various data reduction steps of the pipeline starting with raw observed images and ending with clean images from which measurements can be obtained without further processing and used for calculation of actual terrestrial albedo.

These pipeline steps include

1. Bias subtraction
2. Flat field removal
3. Alignment and co-addition of images in stacks

Throughout this report we shall mainly evaluate the following statistic:

$$R = \frac{median(DS)}{T} \tag{1.1}$$

where DS is a region on the dark side of the lunar disk, and T is the total flux of the image DS+BS+sky.

1.2 Bias subtraction

For each stack of 100 images we obtain one dark exposure before and after the stack, taken with the same exposure time as each image in the stack. The average of these two dark frames will, when subtracted from science frames, effectively remove the bias as well as - an average representation of - any dark current signal accumulated. As the dark current of the Andor BV-897 is extremely low we mainly remove the bias in this way. Further details of properties of dark frames and the dark current are given in Schwarz (2012). The bias level is known to about ± 0.1 count, and the standard deviation of single pixels in the bias frame is about 3 counts. Importantly, during system characterization stage, early in the project, a periodicity in the bias level (about 20 minutes) was found. It is eliminated by the use of average bias frames obtained just before and after the science exposure. The actual average bias frame is not the one used for subtraction, but a 'superbias' frame, developed as the average of a huge number of bias frames, is scaled to the level of the observed average bias level, and then this is used to do the bias-removal, thus reducing the amount of noise added to the reduction pipeline.

The bias field has considerable curvature, so it is not an option to not remove the bias level.

1.3 Flat fields

Flat-fields (FFs) were obtained at MLO using the inside of the dome as well as the dusk sky, for each of our filters. We did not obtain FFs for every night and evaluate two aspects of this: What is the effect on R if no FF removal at all is performed, and what is the likely effect of not having FFs for every observing night?

1.3.1 No FF removal at all

We investigate what happens to R for a number of images if no FF is removed. We used means of available FFs, for each filter, as the reference. Results are in Table 1.3.

1.3.2 Using out of date FFs

We investigate the effect of having FFs that are not obtained on the same night as the science frame, by using the multiple FFs we have, and reporting the maximum difference. Table 1.2 shows results.

1.4 Alignment and co-addition of images

1.4.1 Effect of alignment method

We have to align the images in each image-stack because of telescope drift and atmospheric motion, as well as change in refraction during the duration of the multi-image stack.

We perform alignment iteratively, starting the procedure by constructing a reference image by either median or mean of the stack of selected images. Each subimage is aligned against the current reference image using the sub-pixel alignment method of Chae (2004); Gleisner and Thejll (2008). When all the subimages have been aligned, a new reference image is obtained by either median or mean of the current partially aligned image stack. This procedure is then repeated 10 times. This produces in the end two images, and R is extracted from each. Then the difference between the two R-values is calculated. Table 1.4 gives details.

Non-conservative sub-pixel interpolation

The alignment method we use is based on identifying the best shift between two images while allowing for sub-pixel shifts, which implies image interpolation. The method is based on use of the **INTERPOLATE** function in **IDL** with keyword **CUBIC** set to -0.5 as recommended, and is in turn based on optimal interpolation theory (Park and Schowengerdt, 1983). What is the effect of this, since the method may not be 100% flux-conserving?

To answer this we test the loss or gain of flux by shifting an image four times, in a square, bringing the last image back to the starting position.

Generating the random floating-point shifts needed to move in a square we repeated the test 1000 times. Note that this gives the accumulated, possibly random, error over 4 shifts, suggesting that one shift may be half of that.

1.4.2 Sampling error

We explore the magnitude of sampling error by bootstrapping, with replacement, on the images available in a given stack. Table 1.4 shows the details.

1.5 Summary

In Table 1.1 the results from above are summarized in one place. Looking at these we see clearly that some sources of error can be ignored while others are important. We also see a difference between the filters - VE2 tends to be in the worst shape, followed by VE1, while B,V and IRCUT are less affected.

Table 1.1: Summary table of all results in Part 2. Columns are: (1) Julian day of observation for identification purposes, (2) The type of filter for that observed stack of images, (3) Flat-field standard deviation in counts, (4) is the max-min effect of taking an arbitrary flat-field for the given filter, (5) gives the effect of not using a FF at all, (6) sampling error on stack subimage selection, (7) Effect of suing median or means in generating the aligned images. Columns 4-7 give the relative percentage effect of the trial on R - i.e. $\Delta R/R$. 100 bootstraps were performed for the results in column 6, on each filter.

JD (1) JD	Filter (2)	FF S.D. (3) (counts)	max ΔR FF (4) %	No FF at all (5) %	Sampl. err. (6) %	Median or Mean (7) %
2456046.7515686	B	0.7	0.19	-0.17	0.13	-0.003
2456046.7433535	V	0.4	0.16	0.09	0.36	0.01
2456046.7492295	IRCUT	0.4	0.11	-0.01	0.21	-0.01
2456046.7560803	VE1	0.4	0.31	0.05	0.16	0.006
2456046.7473049	VE2	1.7	4.0	1.8	0.06	0.002

Specifically:

1. we can ignore the effect of using either means or medians in generating the iterated aligned image stack.
2. The error due to not using a FF correction is smaller than using an arbitrary FF, for the appropriate filter.
3. Sampling error is the largest of the contributions considered, except mainly for the VE2 filter.
4. the act of aligning the images brings about a cost in terms of non-conservation of flux. The magnitude may be near 0.15%.

From item 2 above we conclude that the flat fields we developed contained too much noise to be worth using, which should be used as a guideline for future procedures to obtain FFs.

From item 3 we conclude that more images should be averaged. At present our system is limited to 100 images per stack - another stack can be obtained afterwards with almost identical camera and sky properties, but we did not do that, cycling instead over the filters. In future, with this system, we should try getting longer sequences of same-filter stacks. In another system it might be possible to obtain more images for each stack at present 512x512 resolution. In the present system binning to, say, 256x256 pixels would be possible, potentially raising the number of frames that can be stored in one file prior to mandatory download, but this procedure has not been tested and the consequences for later data-analysis stages are as yet unknown.

If the sampling error is beaten down, the remaining largest issue would be the effects of image-interpolation, followed by FF issues.

Table 1.2: Influence of changing flat field. For each filter the available flat fields were all used, and the maximum difference in R was calculated as a percentage of median R.

Filter	max Δ R
B	0.19 %
V	0.16 %
IRCUT	0.11%
VE1	0.31%
VE2	4.0%

Table 1.3: Effect, on R in selected DS patch, of applying flat field or not, in percent of the R median (column 3). Column 1 gives the filter name, and column 2 gives the standard deviation of the flat field itself – the flat field median value is 1.0 for all filters. The data in column 3 are based on single image-stacks - see code **test_yesnoflat.pro** for details.

Filter	SD	Δ R
B	0.7	-0.17
V	0.4	0.09
IRCUT	0.4	-0.01
VE1	0.4	0.05
VE2	1.7	1.8

Table 1.4: Results of aligning stacks of images under bootstrapping with replacement of stack subimages. In column 1 is the identifying image date (JD), column 2 shows the filter used for that set of exposures, and column 3 shows the standard deviation of R-values relative to the median of R, in percent. Column 4 shows number of bootstraps performed. Column 5 shows the difference between using median or mean in image alignments (see text for details), in % of the DS/Total ratio.

JD	Filter	Bootstrapping	N	Median/Mean
2456046.7515686	B	0.13%	100	-0.003 %
2456046.7433535	V	0.36%	131	0.01 %
2456046.7492295	IRCUT	0.21%	100	-0.01 %
2456046.7560803	VE1	0.16%	100	0.006 %
2456046.7473049	VE2	0.06%	131	0.002 %

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1.6 Previous reports

Previous reports from the Danish Meteorological Institute can be found on:
`http://research.dmi.dk/publications/other-publications/reports/`