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Earthshine Project Document: Effect of light scattering on photometric errors

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0.1 Dansk resumé

Målinger af styrken af jordlyset der falder på Månens nat-side kan bruges til at udregne Jordens reflektivitet, eller 'albedo'. Albedoen bestemmer hvor meget sollys der kommer ind i klimasystemet og er derfor en vigtig klimaparameter at kunne observere. Albedoen kan observeres fra satelitter i rummet ved at disse tager billeder af Jordens reflekterende skyformation osv, men sådanne datasæt lider under unøjagtigheder der gør dem kun lidt brugbare i undersøgelser af klimaændringer på lang sigt. Vi er ved at udarbejde planer til et bedre observationssystem for albedoen, der er baseret på at observere styrken af jordskinnet på Månen. Dette kan gøres med teleskoper på Jorden eller fra satelitter i rummet der kigger på Månen i stedet for på Jorden. For at udnytte billeder af Månen skal vi forstå hvordan lys spredes i teleskopernes optik og i jordens atmosfære. Denne rapport viser nogle overvejelser vi har gjort omkring spredning af lys i typiske Månebilleder og værktøjet skal bruges ved udarbejdelse af planer om nye typer observationsudstyr. Rapporten konkluderer at betydelige fordele kan opnås ved at observere jordskinnet på Månen udenfor Jordens atmosfære.

0.2 Abstract

In order to be able to use future earthshine data for climate studies we must know to which degree light-scattering in optics and the atmosphere causes scatter and bias in derived albedo. This report studies the problem by use of synthetic lunar images that are convolved with progressively realistic scattering functions, and the scattered light in the images is evaluated quantitatively. The results can be used in formulating plans for better observing equipment. The Report concludes that considerable advantages are available for photometric accuracy if observations could be performed in the absence of the Earth's atmosphere.

0.3 Introduction

Earth's reflectivity, or albedo, governs the net energy pouring into the climate system from the Sun. The albedo is given at each moment by the reflective properties of the atmosphere and the surface, and is expected to change as the climate system warms up. Climate models currently do not constrain the evolution of cloud-cover under climate warming sufficiently. Good measurements of albedo are needed to empirically describe the actual Earth, and thus help constrain climate models.

A unique technique to measure the albedo of the Earth is to indirectly observe the Earth by measuring the intensity of its light falling on the portion of the Moon not illuminated by the Sun, so-called 'earthshine'. Observing the whole lunar disk and essentially measuring the ratio of the earthshine illumination on the shadow side to that on the solar-illuminated side gives a measure of Earth's hemispheric-average albedo at the observing moment. The use of such a relative measurement ensures common-mode rejection in the instrumentation compared to standard absolute photometry of the Earth.

Earthshine observations with this technique were first started about 80 years ago. While there have been significant technological advances over the past eight decades to better measure the earthshine from EarthâĂŹs surface, our work shows that interference from the scattered light in the atmosphere alone can reach up to 30% of the earthshine, and be 6 times stronger than diffraction effects alone.

Modern earthshine observing technology relies on observations from the ground with either two separate or a single exposure obtained with a refractor using secondary optics to provide a collimated beam for filters or occulters, and 16-bit dynamic range linear CCDs. After image acquisition, data-reductions relying on assumptions about the distribution of scattered light in the image, as well as the nature of the bidirectional reflectance function for the Earth and the Moon, are performed to calculate the almost-hemispherical mean terrestrial albedo. Two systems are in operation: The first started, in modern times, is that of the group around the BBSO (Goode et al., 2001) - this system consists of a small refractor with secondary optics; a positionable occulter can cover the sunlit bright side (BS) of the lunar disc image allowing less scattered light to fall across the earth-lit dark side (DS). In separate exposures the BS is imaged directly, or through a neutral density filter; the DS is observed in a long exposure made possible by the absence of the BS in the image plane. Photometric filters can be inserted in the collimated beam. The other system - the DMI/Lund Observatory telescope (Thejll et al., 2014), is based along the same lines as the optics of the BBSO system, but obtains its science data in repeated single exposures of the full un-occulted lunar disc. Co-addition of aligned images allows recovering high SNR data which is impossible in shorter exposures required to avoid saturation of the BS part of the image. Both methods are dependent on detector linearity.

Relative photometry of the lunar night-side referenced to the bright, sunlit, side is thus the basis of observing terrestrial earthshine and calculating the terrestrial albedo. It becomes essential that the bright light scattering from the BS onto the DS is minimized.

This report quantitatively investigates the effect of point spread functions (PSFs) of various widths on the scattering. We do this by generating ideal images of the Moon for a range of lunar phases, and then convolve each image with a set of PSFs that range from the PSF expected from diffraction-limited optics to diffraction plus scattering in the atmosphere. The effect of the PSF is then quantified in terms of the ratio of the light added by the PSF to the actual DS light, at a point near the edge of the DS disk.

0.4 Methods

The ideal lunar images are generated with our synthesis code (Thejll and Glesiner, 2016) held at the online Astrophysics Source Code Library.

The PSF is generated from a base-PSF that was empirically devised from large numbers of co-added images of point sources using our earthshine telescope, as well as investigations of the asymptotic profile of the halo observed around extended objects such as Jupiter or the Moon. The PSF is based on a look-up table for the central part of the PSF and for larger radii a certain radial dependence is smoothly added on. This PSF is then varied for use in generating realistic images under varying observing conditions by raising it to an exponent. This method effectively mimics the observed asymptotic halo profiles in our data. The expected shape for a diffraction-limited aperture's PSF is $\sim \frac{1}{r^3}$ and we find that on the very best nights available at the NOAA Mauna Loa observatory we approach radial exponents of 2.8 or 2.9 in the empirical PSF.

We allow asymptotic exponents for the PSF from 3 and downwards in convolving the set of ideal images.

0.5 Results

We generated ideal lunar images at 9-hour intervals from New Moon to Full. We convolved each image with PSFs with asymptotic exponents from 3.0 down to 2.76. We measured the image intensity at a point on the photo-equator of the lunar disc, near the DS edge. An example of the effect of convolution of an ideal image near -100 degrees phase is shown in Figure 1.

In Figure 2 we show the photometric error in a small patch near the DS edge due to un-corrected scattering of light from the DS. As an example, at lunar phase -110 degrees (about quarter Moon, a very realistic value for Earth-based observations), we see how the error depends on the width of the PSF. For an ideal situation with PSF due to diffraction only we have about 1% of error in the photometry, while this rises towards 5% for values of α that corresponds to realistic levels of atmospheric scattering on a good night at Mauna Loa. Thus, at this phase, the contribution from the atmosphere to light-scattering is more than 4 times greater than that contributed by diffraction alone.

Notice in lower panel of Figure 2 that the ratio of the realistic-level scattering (α=2.76) to that of diffraction α=3) reaches a peak of more than 4 at Half Moon and is everywhere above 2. Towards New Moon (at phase -180 degrees) the difference is almost independent of the strength of scattering, which makes good sense as there is only so little BS light to scatter then. Such lunar phase angles are very close to New Moon and implies that the Sun is very nearby in the sky, which makes for difficult terrestrial observing conditions – the Moon has to be captured right before sunrise or after sunset. In space, the sky, or the part of the image field near the Sun, would be very dark and observations could be continued to phases nearer -180 degrees, providing more effective observing access to the Moon. From Earth the practical limit is near $\pm$ 45 degrees away from New Moon.

0.6 Discussion

We have in the Results section seen the effects of light scattered by diffraction and the atmosphere and compared them. We see that realistic amounts of atmospheric scattering can be many times greater than the diffraction, suggesting that the accuracy of lunar disc photometry could be improved by the absence of the atmosphere.

In actual use, images of earthshine are not left uncorrected for the halo of scattered light. Instead, in

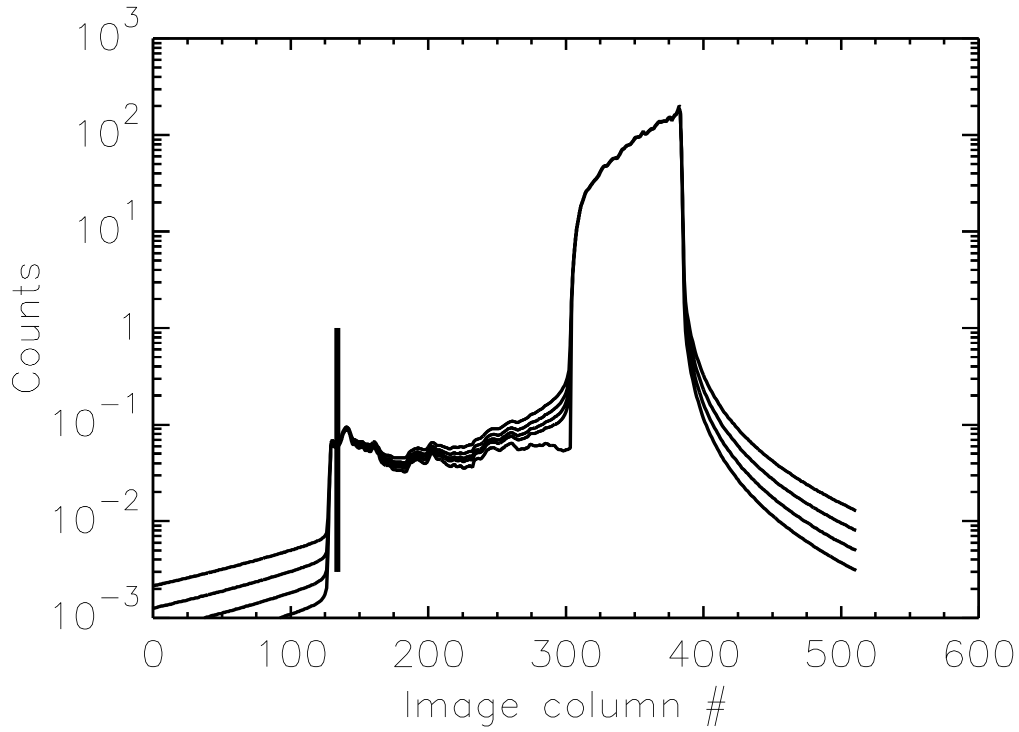

Figure 1: A slice through ideal images of the Moon near phase -100 degrees, showing effect of convolution by realistic PSFs. The BS is to the right and the DS is the level area to the left of the BS. Increased widths of the applied PSFs results in the growing halo around the BS shown by the sloped profile-wings. α evolved from 2.75 to 3.0. The photometric error at the vertical line near the DS edge rose from 2% ($\alpha = 3$, i.e. diffraction alone) to 11% at α=2.75 (diffraction as well as good Mauna Loa seeing conditions).

the BBSO method the image containing the DS-only image is corrected by the subtraction of a linear extrapolation of the halo profile outside the lunar disc onto the lunar disc, while in the DMI/LU method, the halo of scattered light is modelled using a forward-modeling approach based on convolving ideal images with realistic trial PSFs until a best fit is found, and the fitted model albedo is then used.

As we can see in this analysis the majority of the halo of scattered light can be due to the atmosphere, in which case the halo is present as the 'object' when light enters the optics and the BBSO occulting device does not reduce the strength of the halo. Some of the light is scattered and diffracted by the internal optics of the system and this light, provided it is generated before the occulter is reached along the optical path, can be blocked by covering the BS at the primary focus - the light blocked by the occulter should then be gone, but of course, as it is very bright it will have to be captured inside the telescope to not scatter further.

In other words, the BBSO system cannot remove the strong contribution of scattering from the atmosphere, but can hinder the strong light from entering the rest of the system, and also hinder it from saturating the CCD. Saturation can cause bleeding along rows or columns of the CCD and is undesirable.

In the DMI/LU system, all light is allowed to fall on the imaging device – the full halo is there; that due to diffraction as well as the majority due to the scattering by the atmosphere. As the CCD does not absorb 100% of the BS light some is reflected and scatters on the inside of the system.

The BBSO and DMI/LU systems thus differ in terms of how much damage the light from the BS might cause to image quality and the BBSO system is able to remove the minority part of the scattered light due to diffraction and prime objective scattering, but the large contribution from the atmosphere is present in both systems' images.

The BBSO system acquires its data in two steps - one for the DS and one for the BS. The DS image can have a long exposure time thanks to the occulting device and thus has a high SNR. The BS exposure is either short, in which case you need to know the shutter's performance well, or is made long by insertion of a neutral density filter, in which case you need to know the density of this filter quite well in order to combine the information in the two images with accuracy. The DMI/LU system acquires full-disc images of the DS and BS together, and is thus independent of shutter performance. Many images must be gathered to reassemble the higher SNR needed.

0.7 Conclusions

Since the BBSO occulter does not remove the whole halo – it only can remove a minority part due to objective diffraction – there is no huge advantage in having the occulter. Both systems end up with images where compensation for the scattered light is required. The DMI/LU system is mechanically simpler but has to acquire 100s of images each time, while the BBSO system only needs two images but does not benefit from the common mode rejection principle that the DMI/LU system has.

In terms of the analysis in this report, both systems could thus clearly benefit by observing from outside the Earth's atmosphere.

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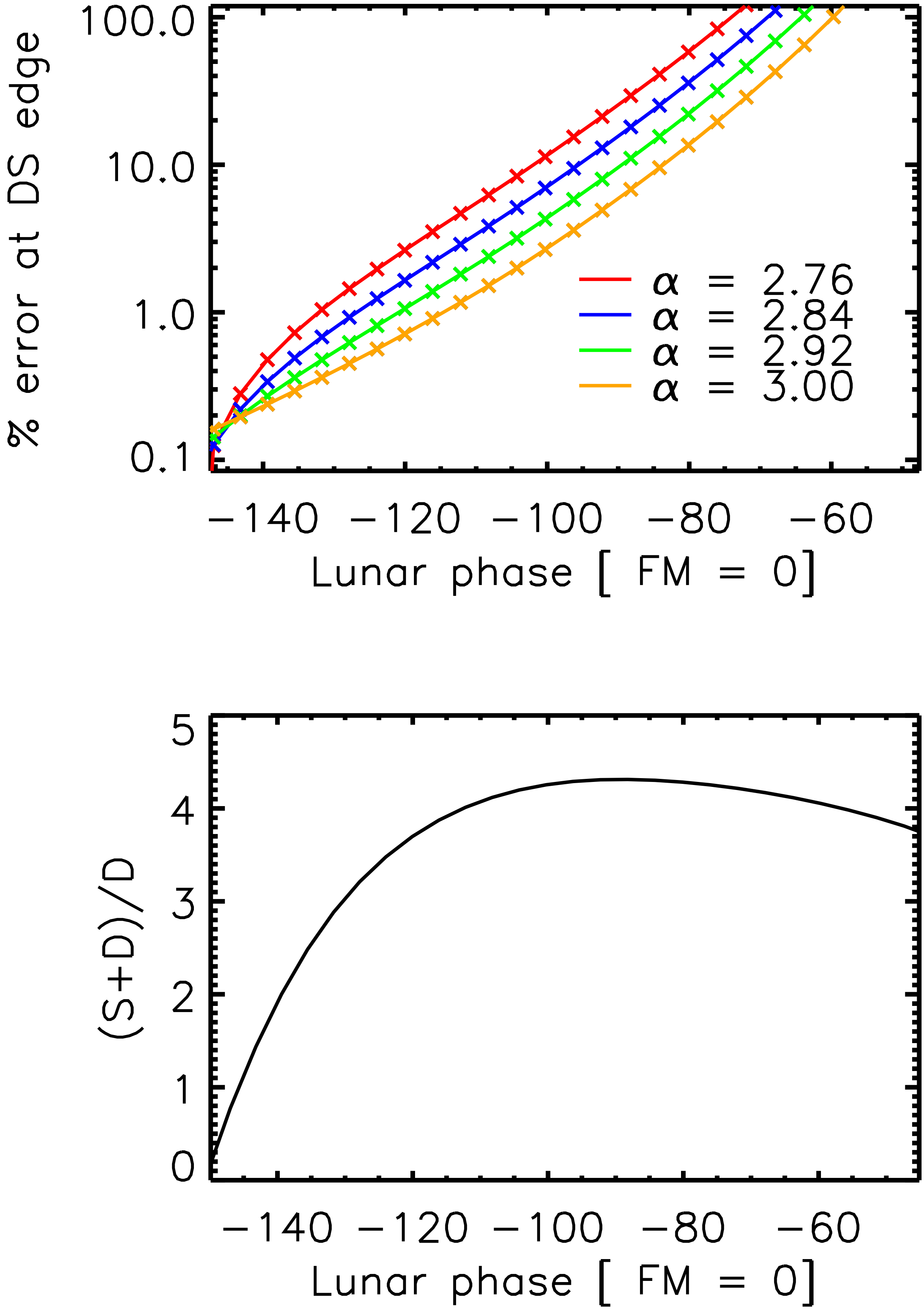

Figure 2: **Top:** Photometric error in % at the edge of the DS, due to increasing levels of scattered light from the BS onto the rest of the image. For the four indicated values of α the corresponding PSFs were convolved on the ideal image, as seen in Figure 1. α=3 corresponds to a PSF given by the diffraction of a circular objective opening, while values for α near 2.8 correspond to realistic levels of atmospheric scattering on a good night at Mauna Loa. The vertical line at phase -110 degrees shows that for α=3 we have about 1% error in photometry, while this rises to more than 4% for realistic values of scattering due to the atmosphere.
Bottom: The ratio of light intensity due to scattering plus diffraction to that due to diffraction alone, at the same point near the edge of the DS edge as in top panel.