1 Error budget analysis (PRELIMINARY)

We must understand the sources of error on the earthshine data we can obtain with our new hardware and software system. Not only do the design choices we make for optics and observing strategy determine our ability to measure terrestrial albedo - so do the choices we will make in data analysis. We will here try to break down the various factors that determine the level of error on the end-result.

The uncertainty-levels we can reach depend on how well we measure the desired quantity as well as the natural level of variability. Terrestrial albedo is quite variable, as we shall see, so we shall have to average over space and time in order to get numbers for the albedo which are so accurate that they can be compared to e.g. climate model albedo values (which themselves also will have to be heavily averaged), or simply for statistical analysis, such as looking for trends in multiannual data. What then are the natural levels of albedo variability?

1.1 Natural albedo variability

Albedo depends on the nature of the surface and the amount of clouds in the atmosphere. Surfaces can be dark (e.g. the ocean, or forests) or light (deserts or snow landscapes) and variable on various time scales (seasonal and multi-annual in the case of de- or re-forestation, and desertification issues). Clouds cover about half the Earth almost randomly. Some latitudes have more clouds than others. Due to the seasonal changes there are large hemispheric seasonal cycles in albedo, while the global mean albedo varies less seasonally. Inspection of monthly-smoothed albedo data shown in Bender et al. (ref here) shows that the seasonal cycle in albedo in global mean, is on the order of .022 (or about 7%) while year-to-year variations amount to 0.004 (or 1.3%). The volcanic eruption in 1991 at Mt. Pinatubo apparently changed global mean albedo by 0.005 (or 1.6%) according to an ensemble of climate models (there are neither ERBE nor CERES observations for 1991). Measurements of terrestrial albedo, based on one year of daily satellite photography, gives a standard deviation on the daily global mean albedo of between 0.3 and 0.4%.

We see that the daily variation in albedo is less than the smoothed monthly albedo variation. This is probably because we have only a short data set with daily values and a longer with monthly-smoothed values. The longer but smoothed data set probably sets a more realistic lower limit to the actual daily variability in global mean albedo. We therefore take the conservative approach and estimate daily albedo variation to be no less than 1.5% when inspected over many years (we are talking about seasonally adjusted values, of course).

In one year of observations we may, with a globe-spanning network of telescopes, be able to get albedo observations for something like 150 nights a year - taking into account the loss of nights where the Moon has a phase that is too large or small. The standard deviation of an average of 150 values, each with a 1.5% error level, will be 0.12% approximately.

Can we use data with such a level of uncertainty to detect interesting climate change? Even a climate without a drift (as our current climate probably is undergoing due to changes in greenhouse gasses) will have annual and multi-annual variations that are considerable compared to the 0.12% uncertainty level here developed empirically. We would be well equipped to detect Mt. Pinatubo-type events, by a factor of 13. As there may be a link between albedo and global mean temperature we can estimate the magnitude of the link by using simple energy balance models. The exercise results in estimates saying that 0.1 to 0.2 degrees K increases in global mean temperature should result from 0.5% decreases in albedo. Our estimated annual precision in averaged albedo data is therefore well under what is needed to follow climate changes at the 0.1 degree level. The CERES data shows a drift in shortwave flux of 2 W/m2 over 4 years - this is equal to about 0.5% per year.

We summarize this development of estimates of natural albedo variation: it seems that we would be well equipped to follow interesting climate changes using annual mean albedo data.

Now, how well do we imagine we can measure albedo?

1.2 Estimating observational precision

Our observations of the Moon will yield lunar flux levels, not terrestrial albedo values. In order to obtain albedo values we must combine the observations of the dark side and the bright side and use other information to model lunar-surface reflectivity, which depends on various angles (which we derive from the position on the Moon we are observing and ephemerid information), knowledge about the lunar albedo and the reflectance of the lunar surface soil. These factors all have some uncertainty, and we must now try to quantify each of them.

We start simply, and merely consider photometric precision, as if all other factors were well known.

1.2.1 Photometric precision

The ratio of Moonshine to Earthshine is always large. In the case where both sides are observed at the same time we would have observed flux levels that differed by factors of a thousand and more and this would determine the level of the pure Poisson noise in each pixel. For a pair of pixels, one on the bright side and one on the dark side, we would expect the noise-to-signal ratio of the fraction $r = \frac{D}{B}$ to be,

$$\frac{\Delta r}{r} = \sqrt{\frac{1}{D} + \frac{1}{B}}, \tag{1}$$

since $\Delta X = \sqrt{X}$ for Poisson statistics; and we have assumed errors are independent and applied common error propagation, adding the squares of the partial derivatives.

For a 16-bit detector, with low dark current, it is not unreasonable to have $B = 45000$ and $D = 45$, just after the new Moon phase. This gives $\frac{\Delta r}{r}$ of approximately 0.15, or 15% relative error. Averaging over n pixel-pair ratios should lower the relative error to $\frac{1}{\sqrt{n}}$ times the above. To reach 0.1% error we should have to have $n \approx 10.000$ pairs. This is not unrealistic since it is merely a patch of 100x100 pixels on a frame that may be 1kx1k.

This estimate is very idealized - we have not taken into account the need to remove scattered light in the image. It is also unrealistic in that for larger lunar phases the 'direct imaging' technique will not be useful; instead observational provisions must be made to obtain the two lunar halves using different optics, exposure times and/or absorbing filters that eliminate some uncertainties that arise when very fast exposure times are needed for the bright side.