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Earthshine Project Document: Atmospheric extinction corrections

Hans Gleisner and Peter Thejll

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Authors:
Hans Gleisner and Peter Thejll

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0.1 Dansk resumé

For at kunne bruge fremtidige jordskinsmålinger til klimaforskning er det nødvendigt at kende til de eventuelle bias'er og unøjagtigheder der kan være i de af jordskinsmålingerne afledte albedo data. Derfor undersøger vi her hvor godt vi kan fjerne kendte trends og cyklus'er i simulerede observationer af en punktkilde. Dette giver indblik i hvor godt vi kan analysere ægte data den dag vores jordskinsteleskop producerer data. Det viser sig at lineære trends i både instrumentets følsomhed, og i luftens ekstinktion kan fjernes uden problemer af standardmetoden, men at en årlig variation i ekstinktionen kan medføre små bias i bestemmelsen af driften i følsomhed og ekstinktion - dette bør studeres nærmere når rigtige data er ved hånden.

0.2 Abstract

In order to be able to use future earthshine data for climate studies we must know to which degree there might be bias and scatter in derived albedo data. We therefore investigate how well standard atmospheric extinction reduction methods detect and remove trends in instrument sensitivity and atmospheric extinction, and how sensitive they are to cycles in the extinction. It turns out that trends in both sensitivity and extinction can be found and removed by the method, but that the addition of a cycle in the extinction can lead to a small bias in the determination of trends in sensitivity and extinction - this should be further investigated when real data are at hand.

1. Introduction

The Earthshine project - which is a collaboration between DMI and Lund Observatory in Sweden - seeks to develop a system capable of measuring terrestrial albedo by using observations of the earthshine on the Moon. A network of autonomous telescopes will be built and distributed at observatories around the world so that the Moon can be kept under constant observation. When the Moon is not too close to New or Full, observations can be performed that can be reduced to semi-hemispherical averages of the terrestrial albedo. Albedo can be used in climate studies and in calibrations of earth observing platforms in space. See DMI Technical report 04-18 for more details on the project.

One of the data-reduction steps required in our system is the reduction of photometric data for the effects of atmospheric extinction and instrumental sensitivity drift. As the observations of extinction from the La Palma observatory show (see Figure 2.1) there are annual events that induce large extinction (sand and dust storms from Sahara) as well as volcanic eruptions (1991, Mt Pinatubo). The changes in extinction are eliminated by the observing technique we use, which is based on simultaneous relative photometry - but it is a science goal for our project to also determine atmospheric extinction for use in long-term studies of the so-called 'global dimming' problem, and for building global datasets of the aerosol load, which cannot be sufficiently observed from space when the extinction is small. The classical astronomical technique we use can very accurately measure small amounts of aerosol extinction and thereby fill in the picture of the global aerosol load partially provided by satellites.

In this report we investigate how well the standard astronomical technique of determining nightly extinction copes with realistic problems such as drifts in instrumental sensitivity and in extinction. We also wish to insert cyclical changes in the extinction as this is clearly a feature of the real data. The analysis is based on simulated observations of standard stars.

The classical extinction correction method applies a nightly correction based on some (usually linear) function of *airmass* (Z). As the night passes a given source (a star, say) will be observed through changing amounts of atmosphere. If the extinction properties of the atmosphere are unchanged there will be a simple proportionality between the observed magnitude and the airmass for the individual observations. The airmass is calculated for each observation and is approximately equal to $\frac{1}{cos(\theta)}$ where θ is the zenith distance (more elaborate expressions exist). Plotting observed magnitude against airmass will thus give a linear relationship each night and we can find the intercept and slope of this relation. The intercept (i.e. ordinate value at zero abscissa) should be the magnitude of the source outside the atmosphere, while the slope of the line is the extinction coefficient (i.e. absorption per unit airmass). If the extinction changes from night to night but is constant through the night the slope of the relation will change while the intercept remains unchanged - as long as the source is constant. Changes in extinction can therefore be studied over long times by analyzing the nightly extinction coefficient.

If the instrument suffers a change in sensitivity this will correspond to shifts in the intercept - think of it as observing the star outside the atmosphere with a detector that has a changing sensitivity: As the sensitivity drifts you will interpret this as the star changing its brightness. Inside the atmosphere the effect will one be of nightly offsets of the intercept in the extinction reduction.

A combination of extinction drift and sensitivity drift are therefore separable by the evaluation of the extinction coefficient and the intercept, respectively. This is the basic idea for our concept - if the separation is clear enough we do not need separate instrument calibration facilities. However, reality may not be that clean and simple - there may be a limit to numerical methods' abilities to separate the drift in the intercept from the drift in the slope, and we need to study this!

2. Experiments

We simulate photometric standard star observations by picking nightly observation times randomly and specify a realistic number of observing nights during 5 years. Each observing night consists of a number of observations at different simulated zenith distances. Each individual data point is generated by first calculating a simulated magnitude for the star, in the absence of camera sensitivity variations, using the equation:

$$m_{sim} = m_0 + k(t) \times Z + n \times N, \tag{2.1}$$

where m_0 is the magnitude of the star in the absence of extinction - assumed constant - Z is the airmass calculated from the zenith distance as[1] $Z = \frac{1}{cos(\theta)}$. The zenith distance for the assumed standard star is calculated from its assumed right ascension and declination and information about the date and time of day, and place of observation. N is noise drawn from a normal distribution with unit standard deviation and zero mean; n was set to 0.003 magnitudes. $k(t)$ is the atmospheric extinction coefficient at time t.

The observed magnitude of the star depends on the camera sensitivity and is modelled by:

$$m_{obs} = -2.5 \times log[S(t) \times 10^{(-m_{sim}/2.5)}], \tag{2.2}$$

where log is the base-10 logarithm. In the equation, m_{sim} is first converted to flux so that $S(t)$ can act multiplicatively on the flux, and then the observed flux is converted back into a magnitude. $S(t)$ and $k(t)$ were modeled in various ways. $k(t)$ was given a trend and annual cycle. $S(t)$ was given a linear trend. m_{obs} is a general equation of t and Z; with linear evolutions in time for $k(t)$ and $S(t)$, of the type $k(t) = a * (1 + \frac{b}{a}t)$, and $S(t) = A * (1 + \frac{B}{A}t)$, m_{obs} becomes nonlinear in t and Z. [2]

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[1] The Buie IDL library contains an `airmass.pro` function. This is an advanced formula for calculating the airmass - closer to reality than the simple formula $Z = \frac{1}{cos(\theta)}$. In these experiments we do not use the Buie function, but it may lend an advantage to do so when reducing real data.

[2] Inserting 2.1 into 2.2 and expanding in a Taylor series to first order we get

$$a\,Z - \frac{5\,B\,t}{2\,\ln 10\,A} - \frac{5\,\ln\left(\frac{A}{10^{\frac{2\,m_0}{5}}}\right)}{2\,\ln 10} = const + k_1 t + k_2 Z. \tag{2.3}$$

Expanding to second order we get

$$b\,t\,Z + a\,Z + \frac{5\,B^2\,t^2}{4\,\ln 10\,A^2} - \frac{5\,B\,t}{2\,\ln 10\,A} - \frac{5\,\ln\left(\frac{A}{10^{\frac{2\,m_0}{5}}}\right)}{2\,\ln 10} = const + k_1 t + k_2 Z + k_3 tZ + k_4 t^2 \tag{2.4}$$

We experimented with trend models with slope coefficients that were small: $\frac{b}{a} \approx \frac{B}{A} = 10^{-2}$. Evaluating the coefficients above we see that the linear terms, and the cross term have the same order of magnitude, while the t^2 term is two orders of magnitude smaller. The expansion to first order, in equation 2.3 therefore probably omits a necessary term - the cross term.

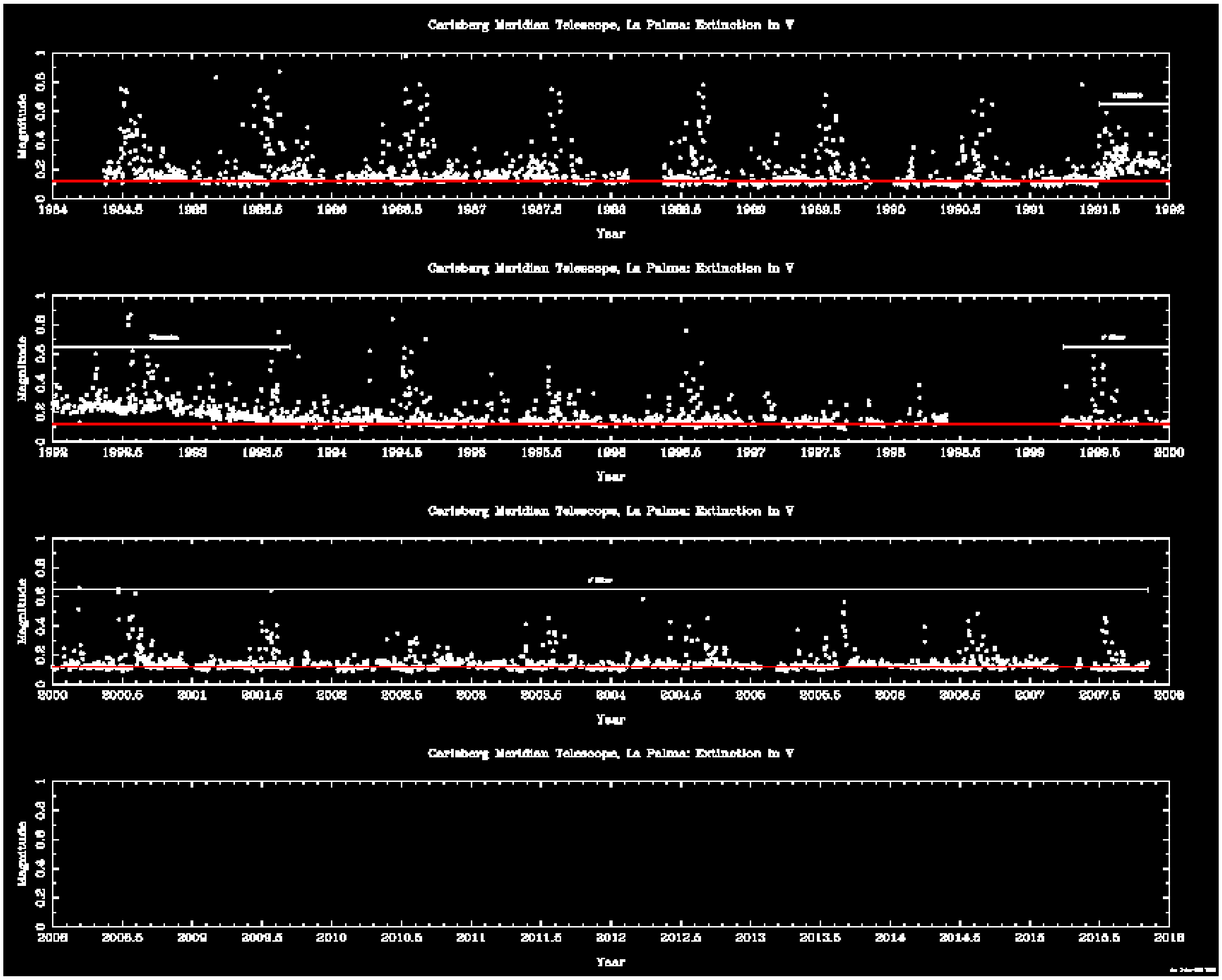

Figure 2.1: Atmospheric extinction observed from the meridian telescope on La Palma since 1984. The Mt. Pinatubo eruption in mid-1991 is visible.

For each night, observations with airmass under 2 and with a span in airmass of at least 0.5, were used. At least 19 observations for each night, which is not an unrealistic number, were required. We simulated a star at a certain right ascension and declination, and assumed a modest linear trend in sensitivity as well as extinction. A straight line was fitted to each nights simulated observations, with airmass as the regressor and observed magnitude as the regressand, and the extinction coefficient k and the intercept m_0 were determined, as well as their uncertainties, for each night during the 5 simulated years. See Figure 2.2 for an example.

When all nights have been reduced a linear fit is made to the nightly values of m_0 against time to get the rate of change so it can be compared to the imposed sensitivity drift in the experiments. Likewise, the nightly extinction coefficients are regressed against time to find the linear trends in order to compare to the imposed drifts.

We performed experiments of various nature. We varied the presence of trends in extinction and sensitivity and used set right ascensions (which cause an annual cycle to appear in the airmass) or randomly distributed right ascensions, and we optionally added an annual cycle to the extinction, and so on. In all 8 experiments were performed, and the results summarized in Table 2.1. Some experiments were repeated to show the extent of variability in the results.

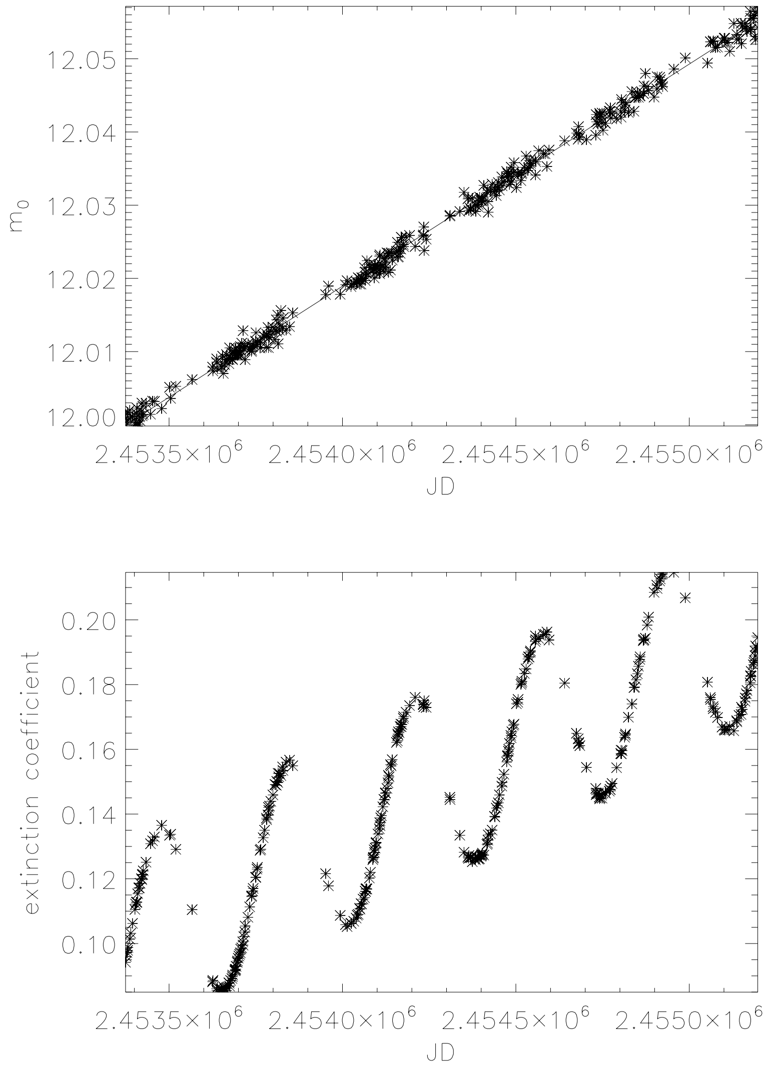

Figure 2.2: Example of modeling atmospheric extinction. A linear trend of -1% in the CCD sensitivity was modeled, as well as an annual cycle and a drift of 0.02 mags/year in the extinction. Plotted are nightly reduced values of the extinction corrected magnitude for a model 12th magnitude star (upper panel), and (lower panel) the nightly determined extinction coefficient. .

3. Discussion of Results

Inspection of Table 2.1 shows that the addition of an annual cycle in the extinction can cause the estimation of trend in extinction and sensitivity to become biased. However, it should be noted that the bias in general is on the order of the uncertainty in the estimates and thus at the 10^{-4} level, which is about 1/10 of the error we have as design goal for the earthshine system.

We must be aware that the removal of a cycle was achieved by including an explicit cyclical term in the regression. This will not be easy to do with real data - most astronomical sites have some sort of seasonal cycle in the extinction and this will have to be parameterized to be used in the regression - either we must wait a few years to build up an average model for the cyclical term, or we must rely

Table 2.1: Determining trends in sensitivity and extinction. Experiment numbers refer to sections in the test. Sensitivity trends are in units of flux-changes/year, while extinction trends are in units of magnitudes/year. Z is the absolute value of the error (i.e. the difference between determined slope and imposed slope) in units of the standard deviation. Cycles in extinction were modeled as sinusoids with amplitude 0.03 magnitudes. All regressions used time and airmass and an annual sinusoid as regressors. Experiment 8 was repeated 3 times to show the variability to be expected in the simulation results.

Exp. No.	Imposed sens. trend Imposed ext. trend	Detected sens. trend Detected ext. trend	Z	Notes
1	0.0 0.0	0.000019 +/- 0.000123 -0.000019 +/- 0.000083	0.16 0.23	No trends. Fixed RA. Secant.
2	0.0 0.0	-0.000021 +/- 0.000080 -0.000001 +/- 0.000055	0.27 0.03	No trends. Random RA. Secant.
3	-0.01 0.0	-0.010190 +/- 0.000121 0.000050 +/- 0.000085	1.57 0.59	Sensitivity drift. Set RA. Secant.
4	0.0 0.02	0.000039 +/- 0.000119 0.020028 +/- 0.000083	0.33 0.34	Extinction drift. Set RA. Secant.
5	-0.01 0.02	-0.010214 +/- 0.000128 0.020053 +/- 0.000089	1.67 0.59	Sens. and Ext. drift. Set RA. Secant.
6	0.0 0.0	-0.000119 +/- 0.000114 -0.000273 +/- 0.000108	1.05 2.52	No trends. Ann. cycle in Ext. Set RA. Secant.
7	-0.01 0.0	-0.010440 +/- 0.000114 -0.000333 +/- 0.000106	3.86 3.15	Sens. trend. Set RA. Secant. Ann. cycle in Ext.
8a	-0.01 0.02	-0.010093 +/- 0.000124 0.020125 +/- 0.000119	0.75 1.05	Trends in both. Set RA. Secant. Ann. cycle in Ext.
8b	-0.01 0.02	-0.010342 +/- 0.000135 0.019867 +/- 0.000115	2.54 1.16	Trends in both. Set RA. Secant. Ann. cycle in Ext.
8c	-0.01 0.02	-0.010340 +/- 0.000117 0.019863 +/- 0.000104	2.91 1.32	Trends in both. Set RA. Secant. Ann. cycle in Ext.

on local determinations of the cycle.

4. Conclusions

We conclude that the standard extinction correction method, consisting of nightly extinction corrections, is able to separate a drift in instrumental sensitivity from a drift in extinction in the presence of annual cycles in the extinction to a level that is acceptable as far as results based on idealized simulations go. The question of the level of bias using real data must be reexamined when such become available.

References

Thejll, P.A., *An Automatic Earthshine Telescope,* DMI, Technical Report 04-18, 2004.

4.1 Previous reports

Previous reports from the Danish Meteorological Institute can be found on:
`http://www.dmi.dk/dmi/dmi-publikationer.htm`