# Filter Design for Measuring Atmospheric Extinction Fluctuations at the SNfactory

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This memo describes the filter design and method for determining changes in the atmospheric extinction across the optical band from below 3200 Å up to 10000 Å. A major goal of the SNfactory is to study a few hundred SN, and for each one to record full spectroscopic information many times over several months. However, to accurately measure spectral changes in the SN light output, spectral changes from day-to-day fluctuations in the atmospheric extinction must be independently determined.

An ideal spectral monitor would be to measure spectra for stars in the same field of view as the SN under study, but there are two problems with this: (i) the extra measurement time significantly reduces the number of SN that can be studied, and (ii) measuring SN and stellar spectra at different times within the same night does not guarantee that both measurements have the same atmospheric extinction. To get around this problem, a technique has been proposed[1] to measure changes in the atmospheric extinction using a few dozen star fluxes measured through optical filters. Very simple simulations are presented here to evaluate this method, and to determine the appropriate filter geometry and bandpasses.

The basic idea is that during the measurement of each SN spectrum, a set of band-pass filters is used to simultaneously measure the flux of several dozen stars in the same $9' \times 4.7'$ field as the SN. For a given star, the same filter is always used. The transmission through the atmosphere can be written

$$T_{\rm atm}(\lambda) = e^{-kX} \qquad (1)$$

where $k = \sum_i A_i k_i(\lambda)$ and $X$ is the airmass. $k_i(\lambda)$ are the wavelength-dependent "extinction" functions, and $A_i$ are coefficients near unity. The time dependence is not shown, but is implicit in $T_{\rm atm}(\lambda)$ and the $A_i$. The index $i$ refers to different extinction processes, which are shown in top of Fig. 1 and are listed below:

1. Rayleigh scattering: $k_1 = A_1\lambda^{-4+x}$, where $x \sim 0.04$ .

[1] G.Aldering, "*SNfactory Spectrophotometry Requirements*", Dec 4, 2000

2. Aerosols: $k_2(\lambda) = A_2\lambda^\gamma$. $\gamma$ varies roughly between 1 and 2, and is fixed to 1.5 in this study.

3. Water vapor and ice, $H_2O$: $k_3(\lambda)$ = template.

4. Oxygen: $k_4(\lambda)$.

5. Ozone: $k_5(\lambda)$ = template.

The $O_2$ and $H_2O$ templates are provided by G.Aldering; the Ozone template is from the libRadtran code, version 0.15. The key assumption used here is that the extinction functions $k_i(\lambda)$ are known *a priori*, so that we need only determine the $A_i$. We also assume that the $O_2$ change ($A_4$), which has two very sharp peaks, is determined independently from the SN spectra and therefore is not covered by any filter. A fit is used to extract the $A_i$ (except $A_4$), and is based on a $\chi^2$ minimization using MINUIT. The function to minimize within one field is

$$\chi^2 = \sum_s \frac{\left[I_s - \int d\lambda \mathcal{F}_s(\lambda) T_{f,s}(\lambda) T_{\rm atm}(\lambda)\right]^2}{\sigma_{I_s}^2} \tag{2}$$

where $I_s$ is the obserbed flux of star "$s$" through its filter, $\mathcal{F}_s(\lambda)$ is the flux vs. wavelength of the star as would be observed from above the atmosphere, $T_{f,s}(\lambda)$ is the response of filter "$f$" through which star $s$ is measured, $T_{\rm atm}(\lambda)$ is the atmosphere transmission (Eq. 1) which contains the $A_i$ parameters that we want to extract, and $\sigma_{I_s}$ is the uncertainty in the flux measurement.

The stellar spectra $\mathcal{F}_s(\lambda)$ are the only unknowns besides the $A_i$. To get the approximate spectrum for each star, I assume that on one arbitrary night, the field-of-view is moved to a few different orientations so that each star is recorded in a few different filter bands. Since high accuracy is not required, the scheduling program might use nights of relatively poor seeing to measure the star spectra. With initial estimates of $T_{\rm atm}(\lambda)$, we can extract crude $\mathcal{F}_s(\lambda)$.

A suggested set of five filter bandpasses are shown at the bottom of Fig. 1. The first filter measures the Rayleigh component and the second filter gives information about the Ozone. As will be shown later, the third filter is not really needed in this model, but may be needed if the extinction model becomes more complicated. The last two filters give information on the water vapor. The filter geometry is shown in Fig. 2. The UV filter (3500-4500Å) is larger to account for the reduced light per star compared to the other filters. The shaded regions indicate the useful part of the field. The unshaded regions indicate the frame and shadowed regions that cannot be used. Initial estimates had 7.5 mm (1.16 arcmin) gaps between the filters, and this 7.5 mm gap is used in the simulations presented here. There are good prospects for reducing these gaps down to about 2 mm, which would increase the number of calibration stars by 45%.

A simple simulation is used to generate stellar spectra for one field of view. The Bahcall-Soneira Galaxy model is used to generate star counts at a given B and L, and the Pickles library is used to associate a spectrum for each star. The software integration of the Bahcall-Soneira model and the Pickles library was provided by E.Pecontal. Using this model for B=50 and L=0, a random sampling of stars is overlaid on the filter geometry in Fig. 2. A magnitude cutoff at 22 is used to speed up generation. The distribution of star magnitudes, the CCD efficiency and the telescope efficiency are shown in Fig. 3. The integration time is taken to be 500 seconds.

The number of stars per filter is shown in Fig. 4 for different B,L. Based on these plots, and without doing any detailed calculations, we might expect to have an empty filter (i.e., no stars in a filter) for up to 10% of the fields. Reducing the gap between the filters would help reduce this problem.

For each galactic coordinate in Fig. 4, the field-of-view is simulated 50 times, and each time the $A_i$ are randomly picked from a Gaussian centered at 1.0 with 10% width. The random $A_i$ simulate the different atmospheric extinction for each measurement. For the first measurement, all of the $A_i$ are set to 1.0, so that the goal is to find the relative changes in the $A_i$. The airmass $X$ is always set to 1.

Using the numbers of stars in Fig. 4, the result of the fit at each B,L is given in Fig 5. By comparing the reconstructed atmosphere transmission with the generated transmission, the RMS of the 50 fields is shown as a function of wavelength. The precision is well below the overall 1% error budget, except for the case in which one filter has no stars (L=90,B=70).

The effect of sky noise is shown in Fig. 6. The top plot shows the sky noise vs. $\lambda$ in different percentiles. For each star, these noise levels are integrated over the filter bandpass and over 3.08 arcsec$^2$. The sky noise in each band was obtained from the table in

`http://www.gemini.edu/sciops/ObsProcess/obsConstraints/ocSkyBackground.html`

and then a simple fit was used to interpolate. The I-band value for dark sky was provided by G.Aldering. Note that the interpolation above 7000 Å is not physical because the 20 and 50 percentile noise curves are above the 80-percentile curve; however, since the noise at lower wavelengths is more important, I have not fixed the problem above 7000 Å. The bottom plot in Fig. 6 shows the precision in the atmosphere transmission for the different levels of sky noise. The brightest nights result in a degradation to 3% precision at 3500 Å. For 80% of the nights, the precision is better than 1.2% at all wavelengths.

Figure 7 shows the RMS precision using four of the five filters; i.e., with one filter removed. Figure 8 shows the same plots on a magnified scale. From this exercise we see that (i) filters 1,2 and 5 are essential, (ii) filter 4 helps a little below 3200 Å and above 7000 Å, and (iii) filter 3 helps only a little below 3200 Å.

Finally, to verify the method for measuring changes in the atmospheric extinction, a few percent of the SN statistics should be sacrificed in order to follow several "ordinary" stars in exactly the same way as the SN.

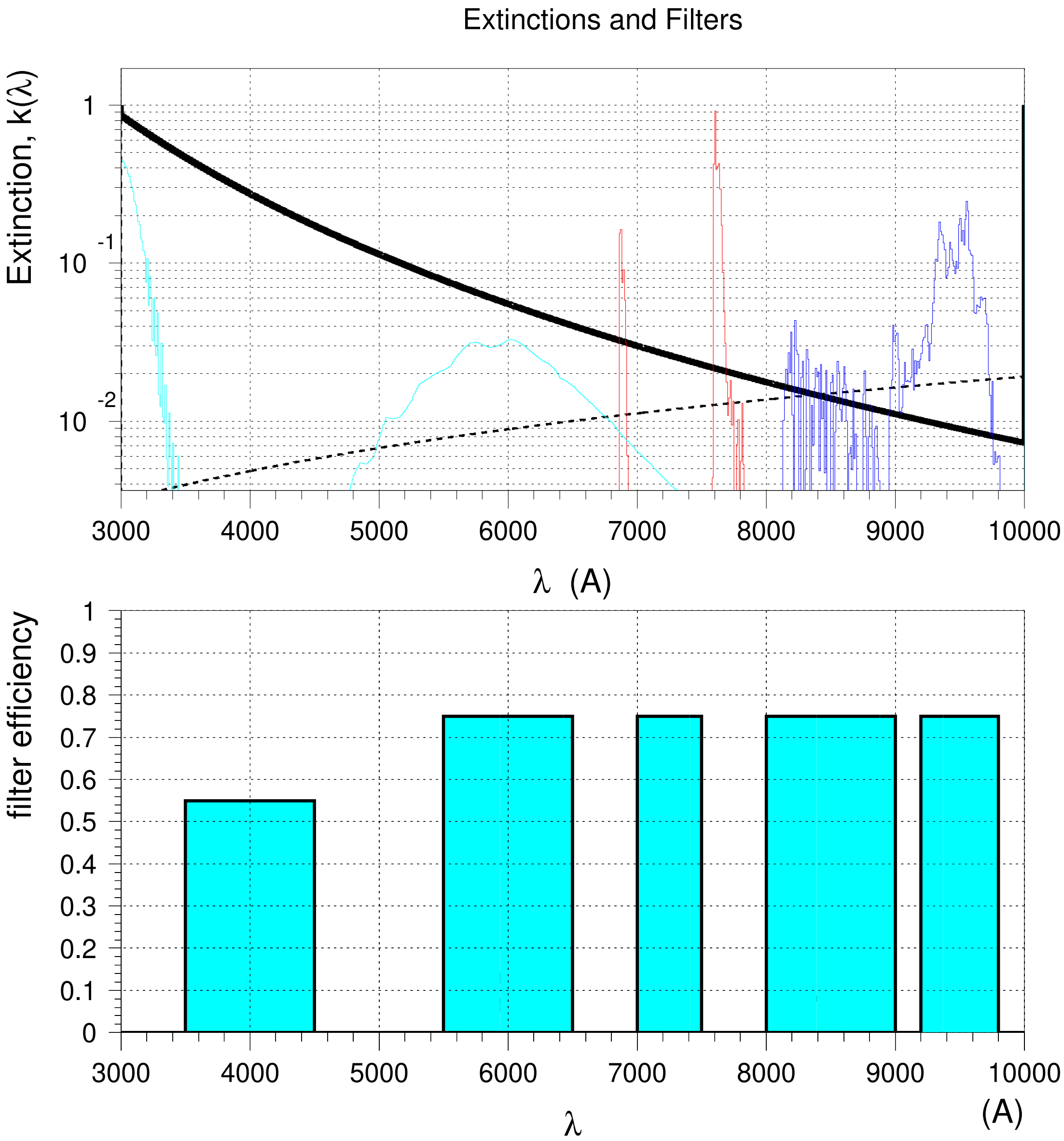


Figure 1: Top shows the extinction functions $k_i(\lambda)$ for: Rayleigh (thick), aerosols (dashed), water (0.8-1.0 Å), $O_2$ (narrow peaks at 0.69 and 0.75 Å) and $O_3$ (broad peaks at 0.3 and 0.6 Å). The bottom plot shows the efficiency and bandpass for each filter used in this study.

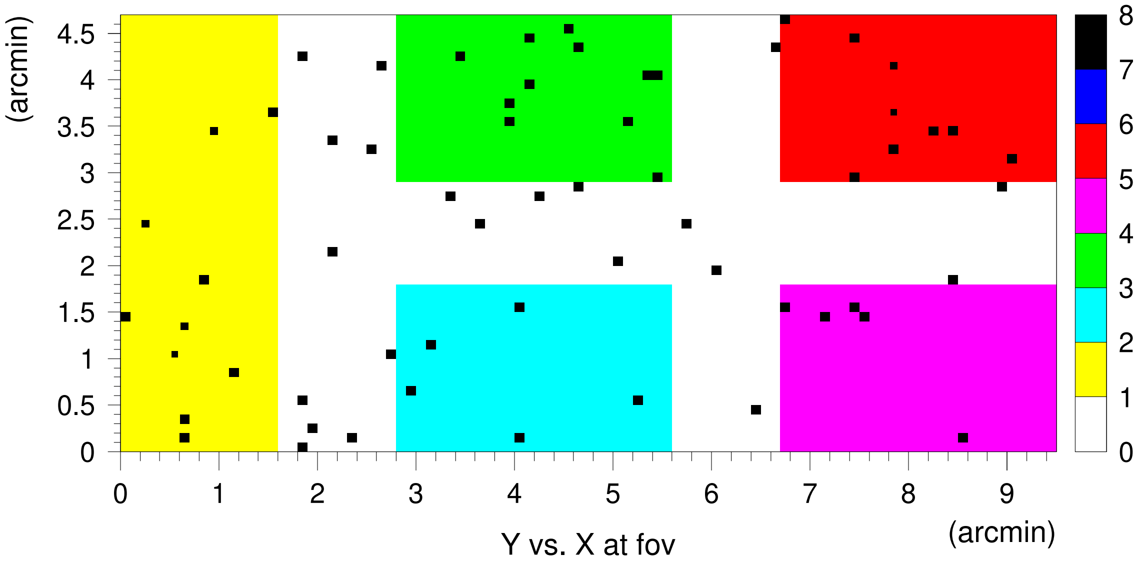


Figure 2: Geometry of five filters. The largest filter (left) covers the UV region (filter 1). The white regions indicate the filter frame and shadow in which stars cannot be used. The black squares represent a random illumination of stars (B=50,L=0) that give at least $10^4$ photons within the filter bandpass.

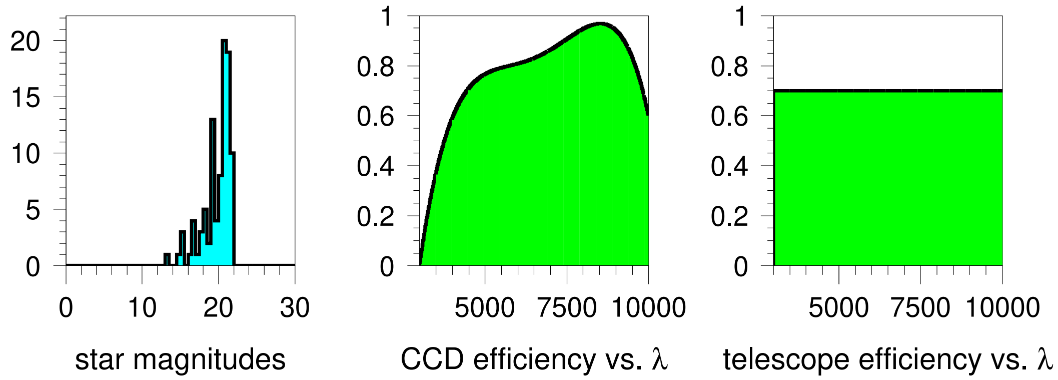


Figure 3: Distribution of star magnitudes used in the simulation (left). The next two plots show the CCD and telescope efficiencies used in the simulation.

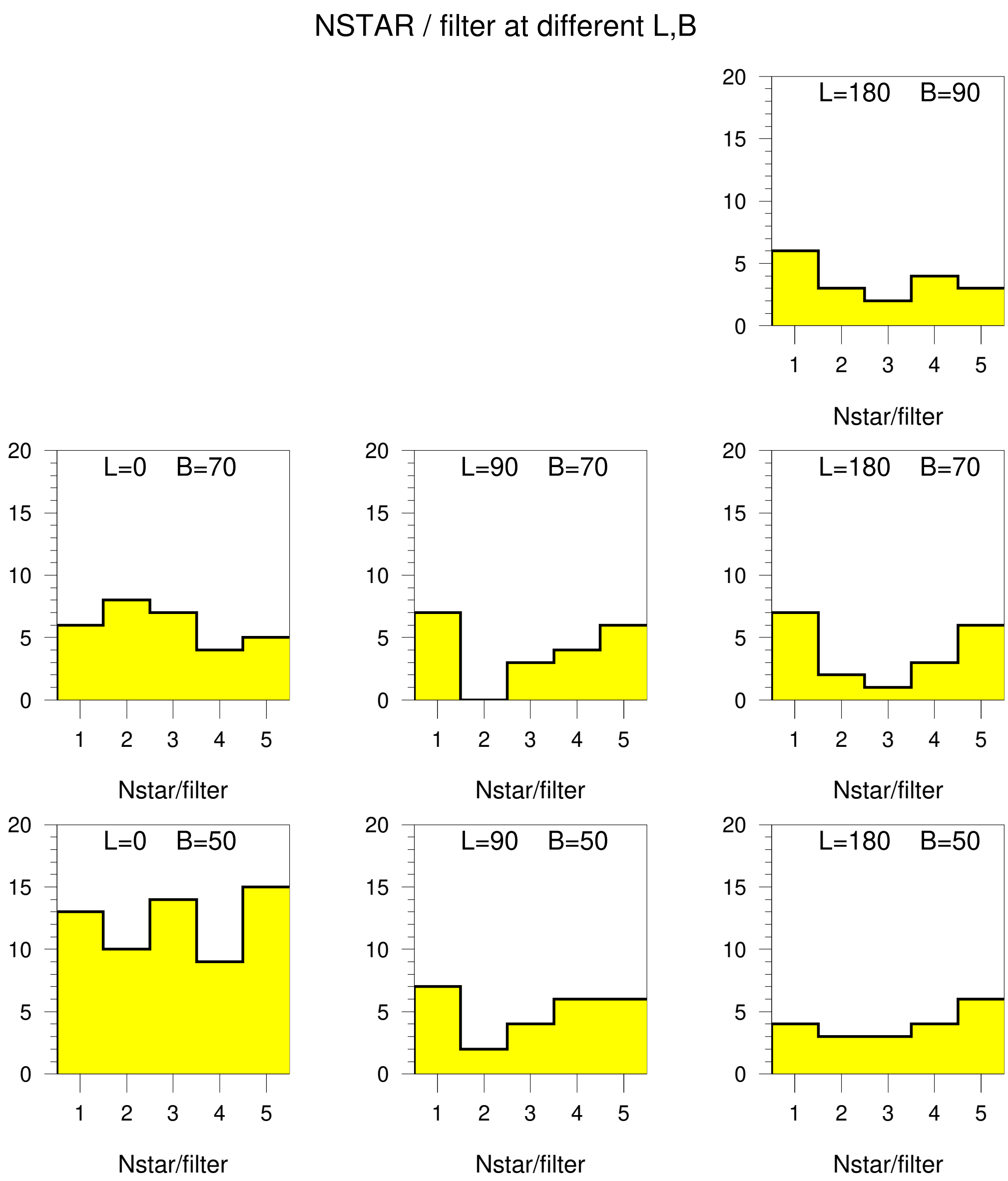


Figure 4: Number of stars per filter at different B,L (degrees), using the Bahcall-Soneira Galaxy model. The fluctuations reflect Poisson statistics of the MC generation.

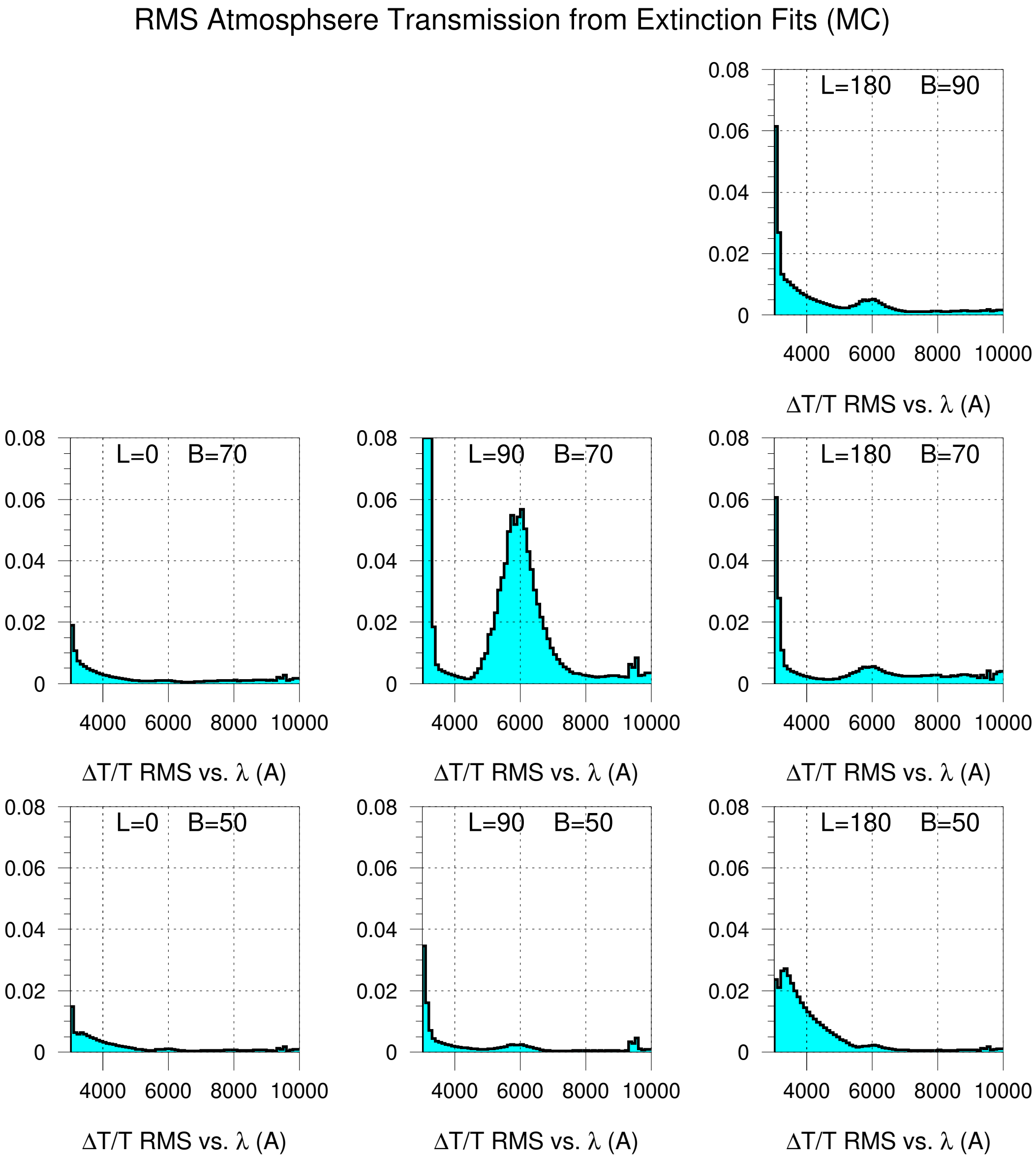


Figure 5: RMS precision of measuring atmosphere transmission change at different B,L (degrees). For the middle plot (L=90,B=70), there are no stars in filter 2.

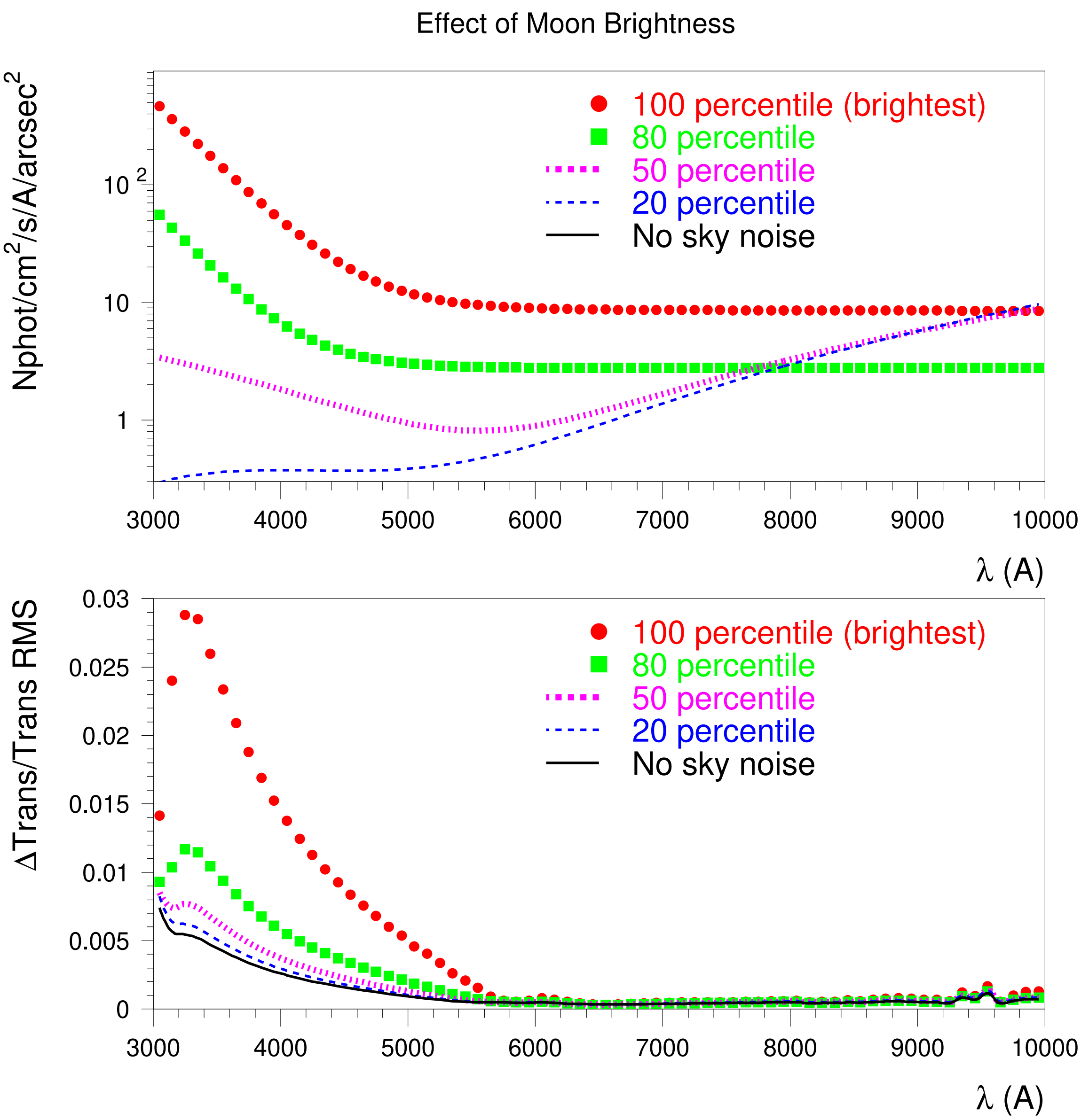


Figure 6: Sky noise in different percentiles (top) and the RMS precision in measuring changes in the atmosphere transmission (bottom).

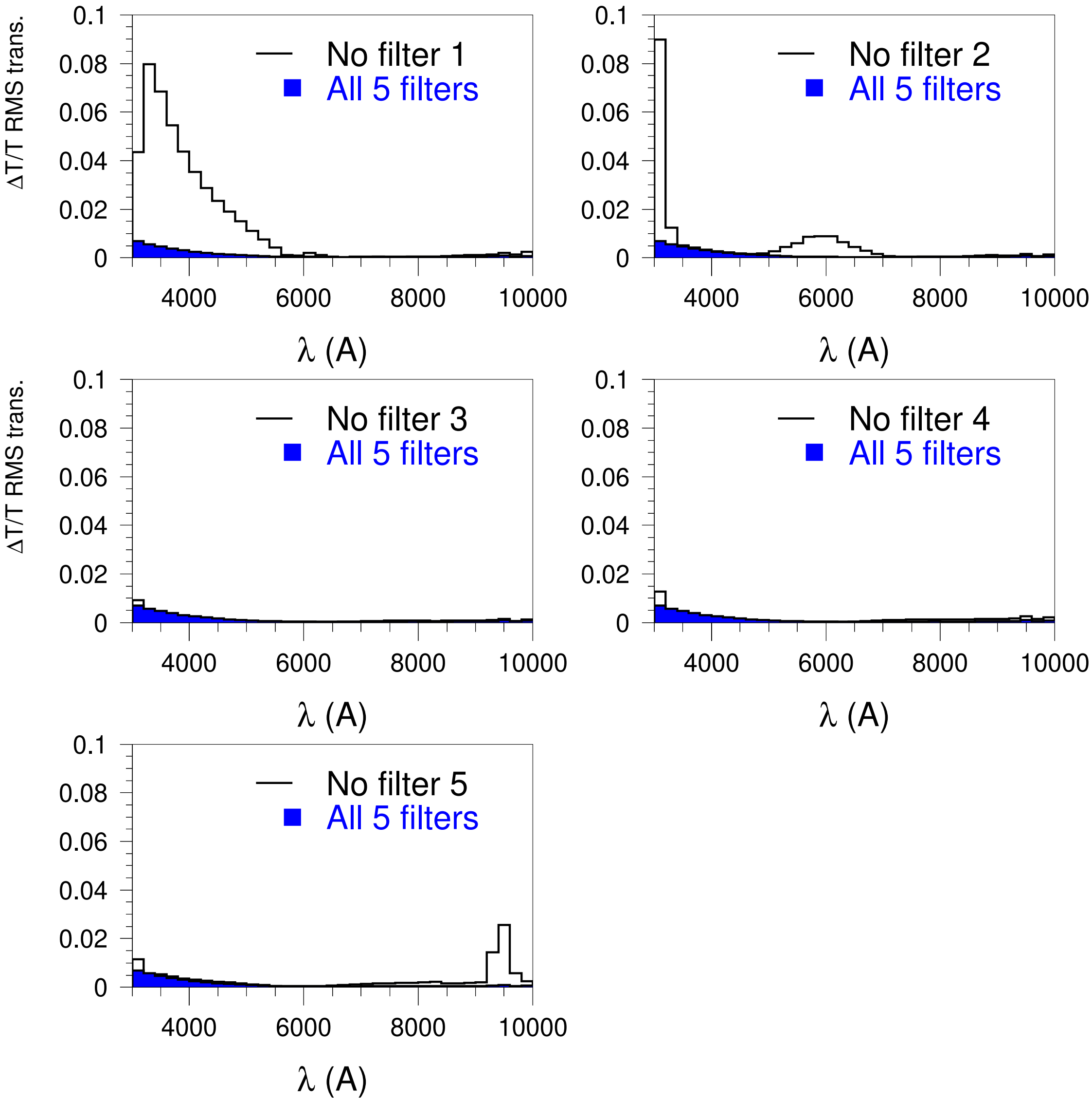


Figure 7: RMS precision with each filter removed (max scale=10%).

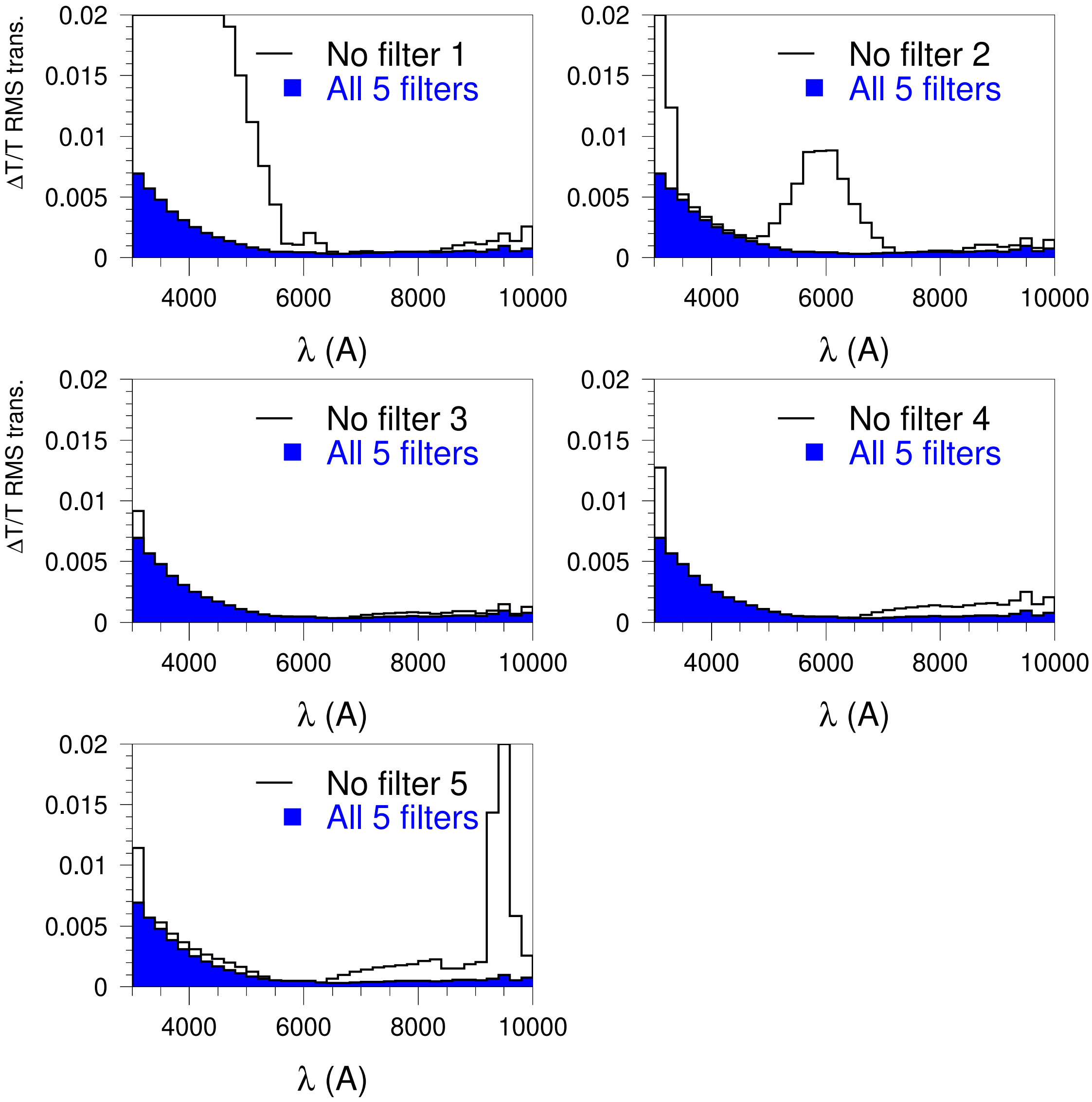


Figure 8: RMS precision with each filter removed (max scale=2%).