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AirMSPI radiometric/polarimetric uncertainties

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Signal-to-noise ratio

Both the radiometric and polarimetric uncertainty calculations require determining the signal-to-noise ratio (SNR). This is given by:

$$SNR = \frac{S(lmn)^{1/2}}{(1.25S + r^2 f)^{1/2}} \tag{1}$$

where

S = signal in electrons

l = the number of rows read out from the AirMSPI detector array in a given channel. Since the rows are co-registered in ground data processing, this has no effect on spatial resolution. The instrument is currently configured such that l = 1 in all channels.

m = number of cross-track pixels to be averaged during image analysis

n = number of along-track pixels to be averaged during image analysis

r = read noise = 9 electrons

f = number of subframes in each image frame = 23

Signal S is calculated from the following formula:

$$S = \frac{1.408\text{x}10^{18}\xi\eta\rho\Delta\lambda}{\lambda^4 \exp\left[\frac{2489.7}{\lambda} - 1\right]} \text{ electrons} \tag{2}$$

where

ξ = optical throughput (dimensionless)

η = detector quantum efficiency (electrons/photon)

ρ = top-of-atmosphere equivalent reflectance, equal to $\mu_0 R$, where R is the bidirectional reflectance factor (BRF) and μ_0 is cosine of the solar zenith angle (dimensionless)

λ = band center wavelength in nm

$\Delta\lambda$ is bandpass in nm

Radiometric uncertainty

The uncertainty in top-of-atmosphere equivalent reflectance is the result of radiometric calibration uncertainty and random noise. Letting C be the radiometric calibration uncertainty, expressed as a fraction of total signal, then the fractional uncertainty is

$$\frac{\Delta\rho}{\rho} = \left(C^2 + SNR^{-2}\right)^{1/2} \tag{3}$$

SNR is calculated from Eq. (1) and C is currently estimated at 5%. With further refinement, it is expected to improve to ~3%. Using the band-by-band parameters in Table 1, and setting m = n = 1 in Eq. (1) (i.e., full resolution) the results are plotted in Figure 1.

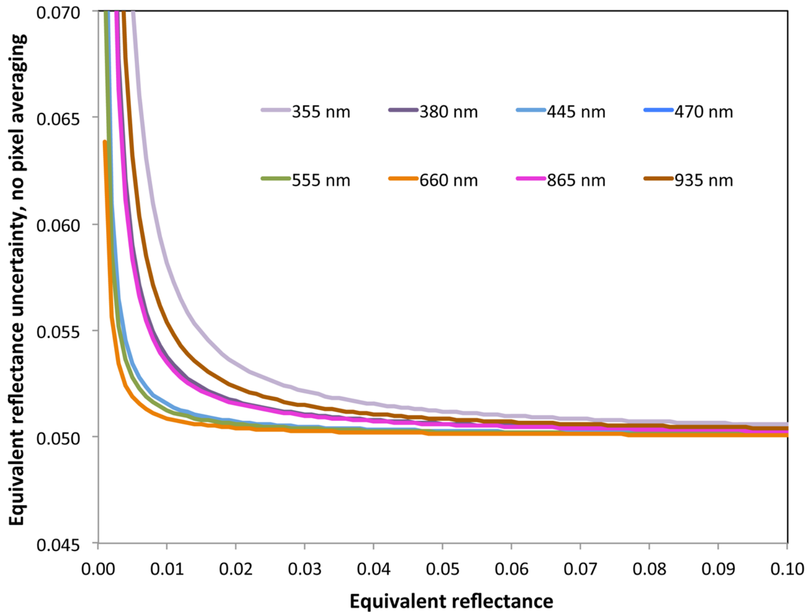

Fig. 1. $\Delta\rho / \rho$ vs. equivalent reflectance at full resolution.

DOLP uncertainty

To meet the ACE DOLP uncertainty requirement it is necessary to average pixels in the L1B2 product. Averaging pixels results in a proportionate decrease in spatial resolution. The uncertainty in DOLP is given by:

$$\Delta DOLP = s / SNR \tag{4}$$

where s is the noise sensitivity factor resulting from the PEM demodulation approach. The values of s in the AirMSPI polarization bands are given in Table 1. The results of Eq. (4) for 8 x 8 pixel averaging (m = n = 8) are plotted in Figure 2.

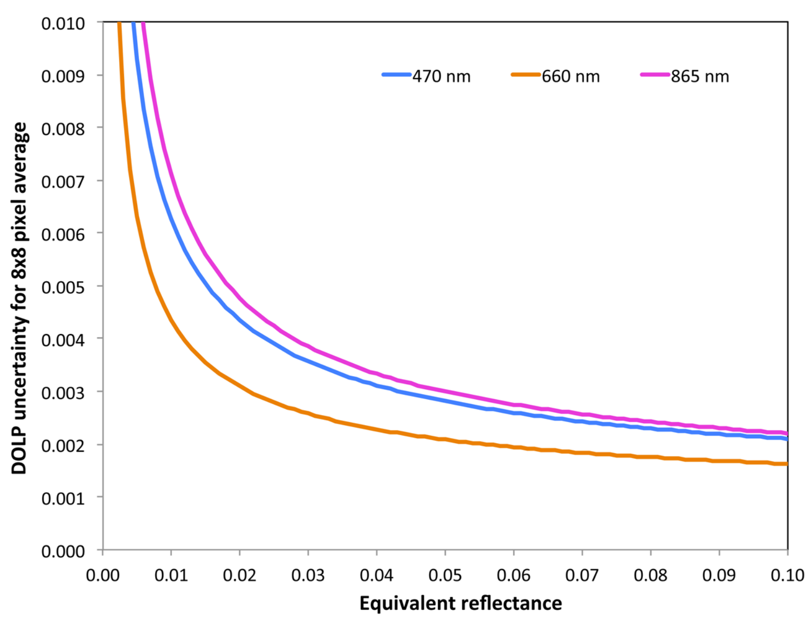

Fig. 2. DOLP vs. equivalent reflectance assuming 8x8 pixel averaging.

Table 1: Values for the camera parameters (Diner et al., 2013):

λ	355	380	445	470	555	660	865	935
$\Delta\lambda$	30	32	36	37	31	42	39	48
ξ	0.806	0.710	0.551	0.516	0.641	0.605	0.602	0.607
η	0.12	0.19	0.35	0.40	0.43	0.35	0.13	0.08
s				4.37		3.61	2.96	

Appendix

This Appendix describes how the SNR formula is derived.

The solar spectral irradiance at 1 AU is given by Planck's law for spectral radiance multiplied by the solid angle of the Sun as seen from Earth, Ω_{sun}.

$$B_\lambda(T_{sun}) = \frac{2hc^2}{\lambda^5}\left[\exp(\frac{hc}{\lambda k T_{sun}}) - 1\right]^{-1} \Omega_{sun} \quad \text{W m}^{-2}\text{ m}^{-1} \qquad \text{(A.1)}$$

where

λ is the wavelength in m

T_{sun} = 5783 K; h = 6.626068 x 10^{-34} m^2 kg s^{-1}

c = 3 x 10^8 m s^{-1}; k = 1.38065 x 10^{-23} m^2 kg s^{-2} K^{-1}

$\Omega_{sun} = \pi R_{sun}^2 / d^2$, where R_{sun} = 6.96 x 10^5 km, and d = 1.5 x 10^8 km

The units in Eq. (A.1) are written as such to indicate that the irradiance is per unit area and unit wavelength interval. Making use of the energy per photon = hc/λ, then from Eq. (A.1) the solar irradiance is

$$E_{sun} = \frac{4.058\text{x}10^{19}}{\lambda^4 \exp\left[\frac{2489.7}{\lambda} - 1\right]} \quad \text{photons s}^{-1}\ \mu\text{m}^{-2}\text{ nm}^{-1} \qquad \text{(A.2)}$$

where the units have been transformed such that λ is now in nm, detector area is in μm^2, and spectral bandpass is in nm. The radiance incident on the instrument is given by:

$$L = \frac{\rho E}{\pi} \quad \text{photons s}^{-1}\ \mu\text{m}^{-2}\text{ nm}^{-1}\text{ sr}^{-1} \qquad \text{(A.3)}$$

where ρ is the top-of-atmosphere equivalent reflectance. The AirMSPI pixels are 10 μm x 10 μm in area, and the detector solid angle is $\pi / 4F^2$, where F = 5.6 is the camera *F/#*. For a given bandpass $\Delta\lambda$ and frame integration time of 43.5 ms, optical throughput ξ, and detector quantum efficiency η (electrons/photon), the detected signal in a single pixel is given by Eq. (2). The various noise sources are as follows (Diner et al., 2013):

Shot noise: Given by the square root of the number of electrons calculated in Eq. (2)

Quantization noise: Nonlinear on-chip analog-to-digital conversion keeps quantization noise at or below 0.5 x shot noise

Read noise: Each frame is sampled in f = 23 subframes, so there are 23 reads per frame. The read noise r is 9 e-/subframe.

Dark current is negligible.

Hence, noise in one pixel in one integration frame is given by $(1.25S + r^2 f)^{1/2}$.

Note that the signal calculation does not incorporate the loss of 50% of light due to the focal plane polarizer. This is because in Diner et al. (2007) we express uncertainties in terms of the SNR for an equivalent intensity measurement in the absence of a polarizer.

References

Diner, D.J., A. Davis, B. Hancock, G. Gutt, R.A. Chipman, and B. Cairns (2007). Dual-photoelastic-modulator-based polarimetric imaging concept for aerosol remote sensing. *Appl. Opt*. **46**, 8428-8445.

Diner, D.J., F. Xu, M.J. Garay, J.V. Martonchik, B.E. Rheingans, S. Geier, A. Davis, B.R. Hancock, V.M. Jovanovic, M.A. Bull, K. Capraro, R.A. Chipman, and S.C. McClain (2013). The Airborne Multiangle SpectroPolarimetric Imager (AirMSPI): a new tool for aerosol and cloud remote sensing": *AMT* **6**, 2007-2025.