Instrument noise model for the Sentinel 5 SWIR bands

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Summary

This Technote describes the instrument noise model which has been employed to simulate signal-to-noise reference spectra for the Sentinel 5 SWIR-1, -2, and -3 spectral bands.

Distribution

- SRON
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This Technote describes the instrument noise model which is employed to simulate signal-to-noise (SNR) spectra of the SWIR-1, -2, and -3 reference spectra. The model is based on fundamental instrument characteristics and assumes one common performance for the three bands. Temperature drifts in the detector and the instrument background, and non-linearity of the detector and the read-out circuit are not considered.

The Sentinel 5 SWIR spectrometer measures the Earth radiance spectrum $L(\lambda)$ as a function of wavelength λ. The corresponding photosignal $S_{\mathrm{ph}}(\lambda)$, the number of electrons measured by the instrument, is

$$S_{\mathrm{ph}} = c_{\mathrm{ph}}\, L\,, \tag{1}$$

with a calibration constant c_{ph}. Here we consider a spatial co-adding of the photosignal, i.e. S_{ph} represents the photosignal of b co-added spatial measurements.

The instrument noise model assumes two major contributions to the measurement noise: the shot noise contribution $\sqrt{S_{\mathrm{ph}}}$ and the instrument noise N_{i}, which is the sum of all other instrument related noise sources. Thus, we obtain the signal-to-noise ratio

$$\mathrm{SNR} = \frac{S_{\mathrm{ph}}}{\sqrt{S_{\mathrm{ph}} + N_{\mathrm{i}}^2}}\,. \tag{2}$$

The calibration constant c_{ph} in Eq. **??** can be derived from the instrument characteristics given in Tab. 1, viz.

$$c_{\mathrm{ph}} = b\,\frac{d_{\mathrm{swath}}\, d_{\mathrm{track}}}{H^2}\, a_{\mathrm{t}}\, t_{\mathrm{int}}\, \frac{\Delta_\lambda}{n_{\mathrm{s}}}\, \eta\, f_{\mathrm{det}}\, \tau\,, \tag{3}$$

where $d_{\mathrm{swath}}\, d_{\mathrm{track}}$ is the area of the (unbinned) instantaneous field of view given by the nadir ground-pixel sizes d_{swath} and d_{track} in swath and flight-track direction, respectively. H is the orbit height of the satellite, a_{t} is the aperture of the telescope, and t_{int} is the measurement integration time. The spectral sampling interval $\frac{\Delta_\lambda}{n_{\mathrm{s}}}$ accounts for the spectral integration of the signal, where Δ_λ is the spectral resolution and n_{s} is the spectral sampling ratio. Furthermore, τ represent the transmittance of the instrument optics, f_{det} is the detector filling factor, and η is the quantum efficiency for the photon-to-electron conversion of the detector.

In the following we distinguish two contributions $N_{1,\mathrm{i}}$ and $N_{2,\mathrm{i}}$ to the instrument noise, $N_{\mathrm{i}} = \sqrt{N_{1,\mathrm{i}}^2 + N_{2,\mathrm{i}}^2}$, where $N_{1,\mathrm{i}}^2$ scales linearly with integration time t_{int} and $N_{2,\mathrm{i}}^2$ scales linearly with the number of the temporal co-adding of measurements. $N_{1,\mathrm{i}}$ comprises thermal background current I_{bgr}, dark current I_{d}, and 'Johnson current' I_{J}, the last of which includes any noise sources that have no corresponding radiance signal. Hence,

$$N_{1,\mathrm{i}} = \sqrt{b\,(I_{\mathrm{d}} + I_{\mathrm{J}} + I_{\mathrm{bgr}})\, t_{\mathrm{int}}/q}\,, \tag{4}$$

with electron charge q. The thermal background current can be estimated from the Planck radiation of the optical bench with a temperature T_{bgr}, viz.

$$I_{\mathrm{bgr}} = a_{\mathrm{p}} q \eta \overline{\Omega} \int_{\lambda_{\mathrm{bgr},0}}^{\lambda_{\mathrm{bgr},1}} \frac{\lambda}{hc}\, \frac{c_1/(\pi\lambda^5)}{\exp\left(\frac{c_2}{\lambda T_{\mathrm{bgr}}}\right) - 1}\, \mathrm{d}\lambda\,, \tag{5}$$

with constants $c_1 = 2\pi hc^2$ and $c_2 = hc/k$. h is the Planck constant, c is the speed of light, and k is the Boltzmann constant. The factor $a_{\mathrm{p}} q \eta \overline{\Omega}$ converts the radiance signal to a current, where a_{p} is the detector pixel area , η is the detector quantum efficiency, and $\overline{\Omega}$ characterizes the cosine-weighted solid angle of the thermal background seen by the detector pixels. In Tab. 1 the values of dark current I_{d} and Johnson current I_{J} represent the expected performance of the Sentinel-5 Precursor TROPOMI SWIR-3 detector.

For each read-out of the signal the analog-to-digital (AD) signal conversion and the electronic read-out of the detector contribute to the instrument noise with N_{AD} and N_{r}, respectively. The analog-to-digital conversion error is given by

$$N_{\mathrm{AD}} = Q\sqrt{\frac{1}{12} + N_{\mathrm{ADC}}^2}\,. \tag{6}$$

The first term of the right hand side is the quantization error, where we consider an equidistant quantization with a quantization interval Q and an equally distributed error between $-Q/2$ and $Q/2$. N_{ADC} describes an additional error term of the AD converter. For a n_{ADC} bit analog-to-digital conversion and a fraction f_{ADC} of the digitizer full range available for the full well capacity n_{well}, the quantization interval is

$$Q = \frac{n_{\mathrm{well}}}{2^{n_{\mathrm{ADC}}} f_{\mathrm{ADC}}} \,. \tag{7}$$

Hence, for a given co-adding factor n_{coad}

$$N_{2,i} = \sqrt{n_{\mathrm{coad}} \left\{ \left(\frac{n_{\mathrm{well}}}{2^{n_{\mathrm{ADC}}} f_{\mathrm{ADC}}} \right)^2 \left(\tfrac{1}{12} + N_{\mathrm{ADC}}^2 \right) + N_{\mathrm{r}}^2 \right\}} \,. \tag{8}$$

describes the noise contribution which depends on the number of co-added measurements. Here, the co-adding factor n_{coad} has to be determined such that a saturation of the detectors for a spectral radiance L_{max} is avoided, viz.

$$n_{\mathrm{coad}} = \left\lceil \frac{\left(I_{\mathrm{d}} + I_{\mathrm{bgr}}\right) t_{\mathrm{int}}/q + c_{\mathrm{ph}} L_{\mathrm{max}}/b}{n_{\mathrm{well}} f_{\mathrm{well}}} \right\rceil , \tag{9}$$

where $\lceil x \rceil$ is the rounded-up integer of x. Thus n_{coad} may differ for the different SWIR bands. However, to simplify matters, we use one common co-adding factor, which is derived for the SWIR-3 spectral band. Thus summarizing the different contributions the instrument noise is described by

$$N_{\mathrm{i}} = \sqrt{b \left\{ \left(I_{\mathrm{d}} + I_{\mathrm{j}} + I_{\mathrm{bgr}}\right) t_{\mathrm{int}}/q + n_{\mathrm{coad}} \left[\left(\frac{n_{\mathrm{well}}}{2^{n_{\mathrm{ADC}}} f_{\mathrm{ADC}}} \right)^2 \left(\tfrac{1}{12} + N_{\mathrm{ADC}}^2 \right) + N_{\mathrm{r}}^2 \right] \right\}} \,. \tag{10}$$

To formulate requirements on the noise performance of the SWIR spectrometer, it is not possible to derive requirements on all the instrument parameters given in Tab. 1. Although several parameters are constrained by other requirement of the Sentinel 4 and 5 MRD, the number of free parameters is too large and so the problem is underdetermined. For the TROPOMI mission, the degree of freedom of the instrument model is reduced by fixing all parameters in Tab. 1 except for the transmittance of the optical system τ and the co-adding factor n_{coad}. Thus, using Eq. (2) the noise model can be written as

$$\mathrm{SNR}(\tau, n_{\mathrm{coad}}, L) = \frac{c_{\mathrm{ph}}(\tau) L}{\sqrt{c_{\mathrm{ph}}(\tau) L + N_{\mathrm{i}}(n_{\mathrm{coad}}, c_{\mathrm{ph}})^2}} \,. \tag{11}$$

Next, two scenarios were considered. For a bright scene with a surface albedo of 0.65 and a solar zenith angle of 10° with a maximum radiance $L_{\mathrm{max}} = 1.67 \times 10^{13}$ photons/(s sr nm cm^2) in SWIR-3, the co-adding factor (see Eq. 9) is determined for a given throughput of the instrument. Subsequently, for a dark scene with a surface albedo of 0.05 and a solar zenith angle of 70° with a maximum SWIR-3 radiance $L_0 = 4.44 \times 10^{11}$ photons/(s sr nm cm^2) in combination with a CO and CH_4 retrieval performance analysis we determine the required optical transmission of the instrument for the co-adding factor derived in the previous step. Due to the coupling of both steps, the problem is solved iteratively and convergence is achieved for an optical transmittance of $\tau = 0.30$ and a co-adding factor $n_{\mathrm{coad}} = 4$. Alternatively, the instrument parameters are uniquely defined by two SNR values for two different signals. This approach is chosen for TROPOMI requirements with a required SNR of 120 and 1200 for the dark scene with radiance L_0 and the bright scene with radiance L_{max}, respectively.

Table 1: Instrument noise model parameters derived for the SWIR-3 spectral band 2305–2385 nm.

category	parameter	symbol	value
throughput	transmittance of optical system	τ	0.301073
	nadir pixel size along track	d_{track}	3.4 km
	nadir pixel size across track	d_{swath}	7.2 km
	satellite altitude	H	820 km
	telescope aperture area	a_{t}	11.8652 mm^2
	detector filling factor	f_{det}	1
	detector quantum efficiency	η	0.8
spectrum	spectral resolution	Δ_λ	0.25 nm
	spectral sampling ratio	n_{s}	2.5
digital signal	number of ADC bits	n_{ADC}	14
	ADC signal fraction	f_{ADC}	0.92
	full well capacity	n_{well}	523000 electron
	well capacity used fraction	f_{well}	0.85
on-board adding	spatial binning along swath	b	1 pixel
	integration time	t_{int}	1 s
	co-adding factor	n_{coad}	4
dark current and noise	dark current (per pixel)	I_{d}	0.7 fA
	‘Johnson current’	I_{J}	0.2 fA
	detector read noise	N_{r}	150 electron
	ADC noise	N_{ADC}	1 bit
thermal background	temperature of optical bench	T_{bgr}	200 K
	background wavelength range	$[\lambda_{\mathrm{bgr},0}, \lambda_{\mathrm{bgr},1}]$	[2000, 2500] nm
	background weighted solid angle	$\overline{\Omega}$	π sr
	detector pixel area	a_{p}	900 µm^2