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Imaging spectrometer stray spectral response: In-flight characterization, correction, and validation

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ABSTRACT

We present a new method for more accurate in-flight calibration and correction of imaging spectrometer spectral response functions. Non-Gaussian tails of spectral response functions can be difficult to characterize in the laboratory, and calibration can shift during deployment. Consequently, in-flight techniques are useful for validating and updating laboratory measurements. Our approach exploits predictable changes in the shape of the oxygen A band across varying surface elevation, with diverse scene content providing numerical leverage to characterize spectral response tails 3–4 orders of magnitude below the peak. We present a correction to recover the nominal response function, and show case studies based on NASA's Next Generation Airborne Visible Infrared Imaging Spectrometer (AVIRIS-NG). Corrected radiances are better conditioned for downstream analysis by sensitive atmospheric codes. We evaluate accuracy using multiple independent standards: simulation studies; consistency with laboratory measurements; elimination of a surface pressure retrieval bias; better alignment of retrieved reflectance with ground reference data; and statistics of over 250 flightlines from a campaign across the Indian Subcontinent showing consistent improvements in atmospheric correction.

1. Introduction

Imaging spectrometers in the Visible/ShortWave InfraRed (VSWIR) range capture the majority of solar-reflected energy, enabling diverse Earth science studies including: terrestrial ecosystem processes and diversity (Ustin et al., 2004), mineralogy (Clark et al., 2003), greenhouse gas sources (Frankenberg et al., 2016), aquatic and benthic environments (Nair et al., 2008), and more. These analyses typically begin by translating raw Digital Numbers (DNs) to calibrated radiance measurements. Next they estimate atmospheric properties, either as ends in themselves or to invert atmospheric interference to determine the surface reflectance (Fig. 1). An accurate initial radiance calibration is critical since instrument uncertainties propagate to all subsequent products. The most compelling science questions of any era lie at the frontiers of measurement accuracy.

Key calibration parameters include detector elements' radiometric responses, and their sensitivities to different wavelengths as represented by the Spectral Response Function (SRF) (Mouroulis, 1999). Laboratory calibration procedures have been refined for decades (Chrien et al., 1990; Schaepman et al., 2015), but campaigns often augment them with flight data (D'Odorico et al., 2011). This helps determine parameters that are difficult to measure in the laboratory, such as stray light or UV radiometric response (Helmlinger et al., 2016). Focal Plane Array (FPA) electrical effects may be sensitive to illumination over the entire field, making estimates from realistic flight data more effective. Additionally, calibration can shift during deployment due to changes in thermal, mechanical, and electronic state, or changes in system pressure that shift the refractive index (Hueni et al., 2014). Moreover, in-scene analyses are always desirable to validate spectral response functions obtained through other means (Dell'Endice et al., 2007). These considerations motivate in-flight calibration using onboard calibrators (D'Odorico et al., 2011), specially defined ground reference targets (Green et al., 1990; Brook and Ben Dor, 2011), and atmospheric or solar features (Kuhlmann et al., 2016). In-flight calibration will be particularly important for planned and future orbital spectrometers such as HISUI (Iwasaki et al., 2011), HyspIRI (Hochberg et al., 2015), and EnMAP (Guanter et al., 2015).

Here we focus on in-flight calibration and validation of the instrument Spectral Response Function (SRF). For pushbroom spectrometers, the response function varies along spatial and spectral axes. Here we treat spatial and spectral response independently, focusing on the spectral dimension. Spectral response is particularly important since

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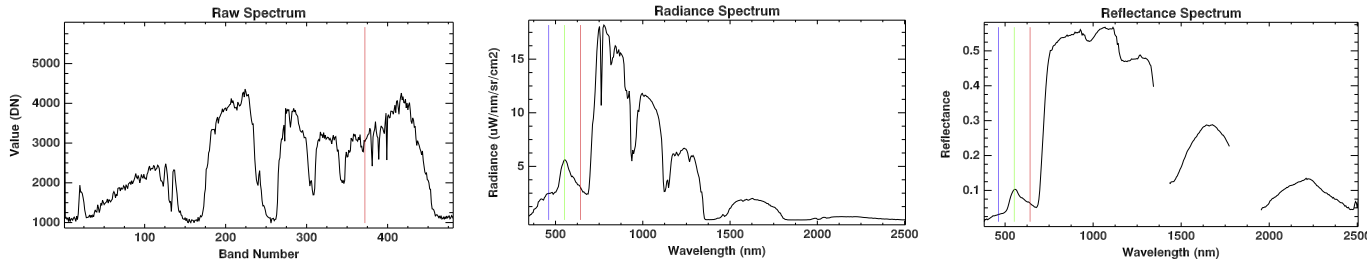

Fig. 1. Typical spectrum analysis progressing from raw Digital Numbers (DNs, left) to radiance (middle) and reflectance (right).

minor SRF deviations can significantly affect estimates of sharp features such as atmospheric phenomena (Green, 1998). Investigators typically use nominal Gaussian line shapes parameterized by center wavelength and Full Width at Half Maximum (FWHM). Prior studies fit these parameters using flight measurements of atmospheric oxygen features (Gao et al., 2004), water absorption features (Thompson et al., 2015b), solar lines (Kuhlmann et al., 2016), and the surface reflectance (Guanter et al., 2006, 2009). This is even possible for instruments with smile effects (Richter et al., 2011; Kuhlmann et al., 2016).

In practice, actual SRFs do not perfectly match a nominal Gaussian distribution; they can diverge in the tails due to stray light scattered through interactions with the grating and optical system (Wilson et al., 2003; Zong et al., 2006), or to effects of order-sorting filters and electrical crosstalk. This could cause measurable response outside the nominal function. Stray light in the spatial direction can reduce spatial contrast and cause halos around bright high-contrast objects (Mouroulis et al., 2016). Similarly, spectral stray light can reduce contrast in sharp atmospheric features and distort surface reflectances. Other subtler effects are possible downstream. For example, we hypothesize that surface pressure retrieval biases observed in prior studies (Thompson et al., 2015b) may be related to lost spectral contrast of oxygen features. This in turn can influence atmospheric models of Rayleigh scattering or aerosols, producing more significant distortions in surface reflectances. Similarly, observed errors in reproducing the fine structure of UV irradiance (Thompson et al., 2015c) are consistent with stray spectral response "filling in" solar absorption features. This study aims to correct the stray portion, recovering the measurement that would have been acquired under the nominal instrument specification. The result is still limited by the nominal spectral resolution of the instrument. However, correcting stray response improves the measured radiances' agreement with downstream models of sharply-contrasting features. To enable this we decompose the SRF into Nominal and Stray components (the NSRF and SSRF respectively, portrayed in Fig. 2).

Contemporary in-flight SRF calibration typically presumes the nominal response profile, recording the NSRF parameters but leaving the SSRF uncorrected. There has been limited effort to characterize the SSRF outside the laboratory. Even laboratory measurements can be challenging, since they often rely on high-contrast illumination with cutoff filters or monochromatic sources near "dark" channels on the active focal plane. Excess DNs in dark channels are attributed to the SSRF (Zong et al., 2006). This approach can be effective, but the unnatural illumination could create different electronic regimes of fixed pattern noise or pedestal shifts that would affect the signal at levels comparable to SRF tails. Moreover, the SSRF signal is measured at low illumination exposing it to any nonlinear properties of the detector signal response. SSRF effects can significantly affect sensitive applications at magnitudes which are 0.1–0.001% of the peak, similar to the relative uncertainty in the radiometric calibration. Consequently, it is desirable to augment laboratory estimates with in-flight alternatives. This could close the SSRF calibration with high signal levels, realistic illumination patterns, and the ability to update parameters during deployment. In previous work we demonstrated a procedure to implicitly recover precise spectral sampling of solar irradiance using flight data (Thompson et al., 2015c). The resulting correction improved residuals around Fraunhofer line features, but could not disambiguate changes in sampling from natural variability in UV solar irradiance. Consequently, it was not a general solution to SSRF characterization. To our knowledge, no prior study has demonstrated a method that successfully isolated the tail regions of the SSRF using flight data.

This study presents a new approach to recover SSRF parameters using the shape of the oxygen A band at 760 nm. Our approach performs a sequential estimation of NSRF and SSRF parameters. We exploit predictable changes in the shape of the A band across varying surface elevation, with diverse scene content providing numerical leverage to characterize spectral response tails 3–4 orders of magnitude below the peak. We present a correction to recover the nominal response function and case studies based on NASA's Next Generation Airborne Visible Infrared Imaging Spectrometer (AVIRIS-NG) (Bender et al., 2010; Hamlin et al., 2011). We evaluate accuracy using multiple independent standards: simulation studies; consistency with laboratory measurements; elimination of a surface pressure retrieval bias; better alignment of retrieved reflectance with ground reference data; and statistics of over 250 flightlines from a campaign across the Indian Subcontinent showing consistent improvements in atmospheric correction.

2. Method

NASA's Next Generation Airborne Visible Infrared Imaging Spectrometer (AVIRIS-NG) was developed at the Jet Propulsion Laboratory as a successor to the "classic" Airborne Visible Infrared

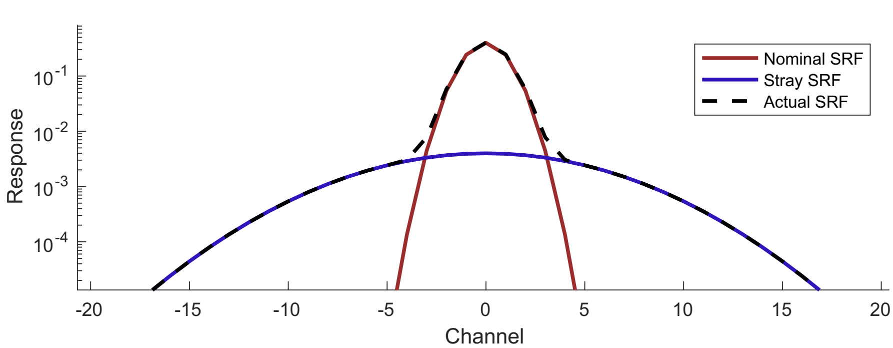

Fig. 2. Contributions of Nominal and Stray Spectral Response Functions to the measured response. The response function is normalized to have unit area.