



Hyperspectral Remote Sensing: Ground-based calibration/validation for air quality and atmospheric composition satellite mission

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Introduction

Air quality issues are gaining more attention due to increased human health impacts from wildfire smoke, ozone, fossil fuels, and COVID related atmospheric changes¹. Current instruments such as TROPOMI aboard the Sentinel-5P satellite have been monitoring these pollutants from a Low Earth Orbit (LEO), providing daily observations globally. With the recent launch of the TEMPO UV-VIS hyperspectral spectrometer, it can provide hourly observations from a Geostationary Earth Orbit (GEO) over North America. The future GeoXO ACX² instrument will support geostationary observations after TEMPO. Calibration/validation (cal/val) will be needed to make sure that the data collected is correct and can be made into products to be used for air quality monitoring and forecasts. Therefore, ensuring the measurement consistency from GEO, LEO, and ground is very important. My project at NOAA NESDIS STAR during the 2023 Lapenta program was about understanding how cal/val is done using ground and LEO observations.

Objectives

- To learn about cal/val of satellite measurements using ground observations.
- To learn about radiance, irradiance, reflectance and transmittance, what curves of each measurement should look like when accounting for solar radiation interaction with the atmosphere.
- Get hands-on experience with a hyperspectral spectrometer, from calibration to taking radiance and irradiance ground measurements.
- Validate data by plotting and comparing ground-ground and ground-satellite observations and understanding the differences of each from errors and uncertainties.
- Present findings as a poster at conference(s) and as presentation at the end of the internship.

Methodology

We took measurements on days that the Sentinel-5P satellite passed over NCWCP in College Park, MD, using both a portable low-cost spectrometer (Ocean Insight Ocean SR Miniature³, 190 nm – 1050 nm) with OceanView software, and a MicroTOPS II Sunphotometer. The spectrometer was calibrated using a Halogen light source in the lab, and then radiance measurements were taken outdoor using a solar diffuser with a 2-inch diameter made of Spectralon at an approximately 45-degree angle. A Lambertian reflection of the Spectralon is assumed. By adding a cosine corrector to the top of the fiber cable, solar irradiance can also be measured.

The effective spectral range of the spectrometer was 350 nm – 1050 nm due to the limited spectral range of the optical fiber cable. The sunphotometer has five channels at 440 nm, 500 nm, 675 nm, 870 nm and 1020 nm. Spectrometer observations were done at 10AM, 12PM and 2PM EST on July 17th and compared to the sunphotometer measurements. The spectrometer and sunphotometer measurements in the parking lot in front of the NCWCP and ESSIC buildings on July 17th, a clear sky day with TROPOMI overpass, were then compared to TROPOMI⁴ Bands 1–6 radiance and irradiance observations.

Methodology

The governing equations for the ground-based spectrometer measurements are as follows:

$$L = r * E_{sun_{ground}} * \cos(SZA) / (\pi * D^2) \quad (1)$$

Where: L is the reflected solar spectral radiance (uW/cm²-sr-nm) from the Spectralon solar diffuser, measured by the spectrometer; r is the Spectralon solar diffuser reflectance, assumed to be a constant (~0.98) across the spectral range of measurements. E_{sun_{ground}} here is the in-situ incident solar irradiance (uW/cm²-nm). D is the normalized sun-earth distance (assumed to be 1 AU in this case). SZA is the solar zenith angle (degrees) at the time of the measurement. π = 3.14159 and represents the projected hemisphere solid angle (unit: Steradian).

Here E_{sun_{ground}} can be either derived from L or measured directly by adding a cosine corrector in front of the bare fiber. However, that requires additional calibration in the laboratory with additional equipment's such as an integrating sphere. Instead, as a first step, we derived the E_{sun_{ground}} from Equation (1) based on reflected solar spectral radiance L, with the spectrometer calibrated with the Halogen light source in the laboratory. Then the atmospheric transmittance can be calculated using:

$$T = E_{sun_{ground}} / E_{sun_{TOA}} \quad (2)$$

Where: T= transmittance of the atmosphere; E_{sun_{ground}} = solar irradiance on the ground; E_{sun_{TOA}}= Top of atmosphere solar irradiance (such as from TSIS).

From the atmospheric transmittance T, we can see absorptions from various gases at different wavelengths and can be compared to satellite observations. One caveat is that the observations from TROPOMI is reflected radiance from the earth (with diverse background such as landcover) and atmosphere, which does not have identical path to the measurements on the ground, although the gas absorption features should match relatively well spectrally.

Preliminary Results

It is noted that not many opportunities exists for exact nadir overpass for the NCWCP site with clear sky conditions especially during summer months. Nevertheless, we were able to take measurements on a few days. Figure 1 shows the measurements on 7/17/2023 which had a good TROPOMI overpass around 2PM local time (blue) as well as measurements made at 10AM and 12PM.

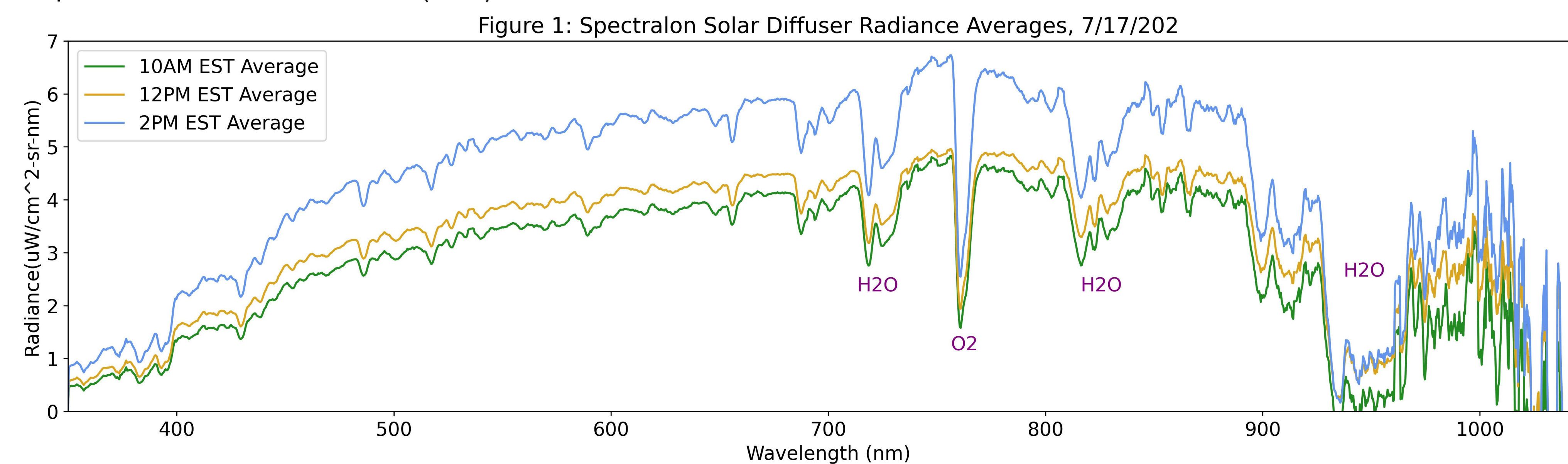


Figure 1 shows that O₂ and H₂O can be clearly detected from the Ocean Insight spectrometer with the laboratory calibration. Also, the O₃ absorption and Rayleigh scattering contributed to the overall decrease in the radiance towards the shorter wavelength 350nm to the left, although the decreasing responsivity of the detector (presumably Silicon) may have contributed to it as well. Similarly, towards the 1000 nm, the measurement becomes noisier, which is likely caused by the low responsivity (quantum efficiency) of the detector, reaching the upper limit of the detector response. Aerosol and NO₂ effects should be embedded in the below 530 nm spectral region, although these cannot be easily observed in this plot. Other features could be due to artifacts from the measurement setup such as extraneous sources from the surround.

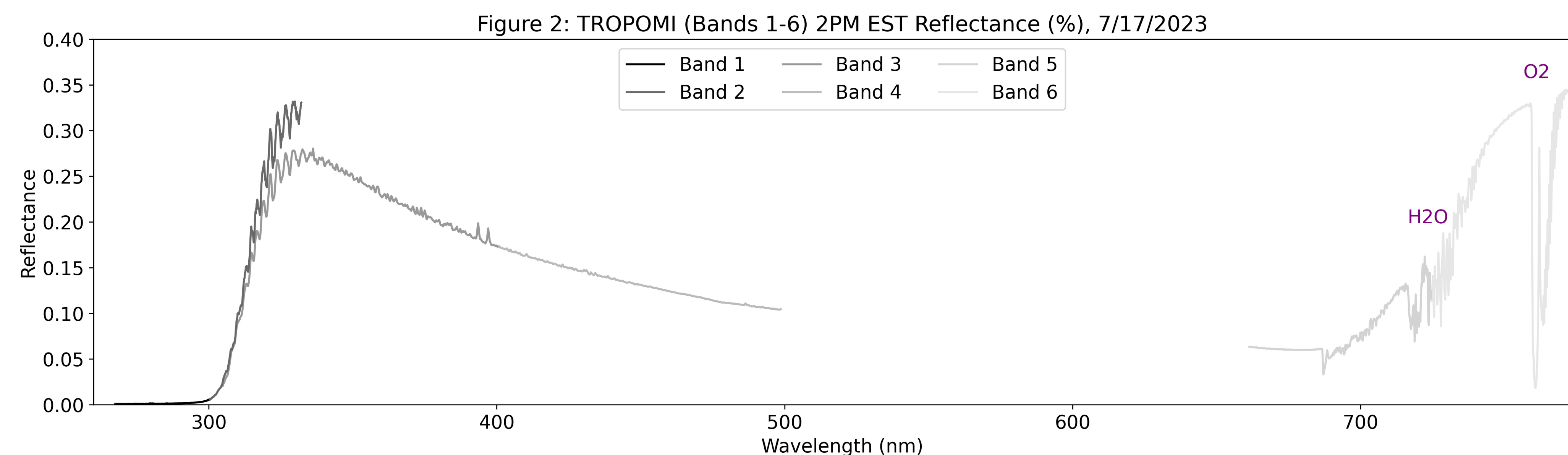


Figure 2 shows the coincidental TROPOMI observations over the NCWCP/ESSIC area at the same time of ground measurements. Like the ground measurements, the O₂ and H₂O absorption peaks can be clearly identified, although other gas absorption features can not be easily identified which requires more sophisticated retrieval algorithms.

Discussion

The preliminary results are encouraging in developing ground-based cal/val capabilities to support atmospheric composition satellite missions. We found that the instrument calibration based on high quality laboratory light sources and understanding of the spectrometer characteristics are critical for obtaining good quality measurements. However, although the major gas absorption features such as O₂ and H₂O can be readily detected with a basic laboratory calibration, more stringent calibration is required to make reliable quantitative measurements that can be compared between ground and satellite, as well as detect trace gases. Therefore, going forward, we plan to enhance the ground-based spectrometer calibration in several areas:

1. Compare the sunphotometer measurements with those from the ground-based spectrometer.
2. Compare measurements with RTM simulations to zoom in on gas absorption features.
3. Improve spectrometer laboratory calibration. Re-establish the industry standard ASD FieldSpec spectroradiometer calibration for NIST traceability and perform rigorous performance comparisons with the miniature Ocean Insight spectrometer under different operating conditions.
4. Develop a standard procedure for comparing ground-based spectrometer measurements with those from satellites, taking into account of the homogeneity of land cover vs. over ocean.
5. Augmenting the ground validation capability by looking into multi-axial differential optical absorption spectroscopy (MAX-DOAS) methodology.

References

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