A Verification of the Ozone Monitoring Instrument Calibration Using Antarctic Radiances

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Abstract. A technique for evaluating the radiometric calibration of satellite-born radiometers has been developed utilizing the stable reflectance of the Antarctic land mass. Previously, the scene radiances measured over the Antarctic and Greenland land masses were used to monitor time evolution of sensor radiometric sensitivity and to compare instruments with similar spectral responses. Through the use of radiative transfer modeling, we can now evaluate the albedo calibration (Earth radiance sensitivity divided by solar irradiance sensitivity) of any nadir-viewing, polar orbiting sensor measuring in the 300-800 nm range. Our evaluation of the Ozone Monitoring Instrument on the NASA Aura spacecraft confirms a 2% calibration uncertainty.

The Ozone Monitoring Instrument

The Ozone Monitoring Instrument (OMI) launched aboard the Earth Observing System (EOS) Aura satellite on 15 July 2004 is intended as the successor to the Total Ozone Mapping Spectrometer (TOMS) operated by NASA over the past 25 years. With improved horizontal resolution and an expanded wavelength range (270-500 nm), the OMI capabilities extend well beyond those of TOMS. Traditional TOMS products (column ozone, surface reflectance, aerosol index, UV surface flux) depend upon knowledge of absolute albedo calibration and the relative albedo calibration between wavelengths. Establishing an accurate OMI calibration and maintaining calibration consistency with the TOMS instruments are of equal importance.

Furthermore, future data products will likely utilize OMI-measured radiances combined with radiances and products from other sensors, on Aura as well as on spacecraft in similar orbits. Given that no attempt was made to inter-calibrate OMI with other sensors prior to launch, a relative adjustment based upon in-flight data may be required to improve these products.

The ice radiance technique

Our approach to verifying a UV/VIS/NIR sensor's albedo calibration is to compare measured and computed radiances for Earth scenes with known backscatter properties. We have chosen the surface and atmosphere of Antarctica for their highly predictable behavior over a broad range of wavelengths and viewing conditions (Jaross et al.). The spatial extent of the continent provides good sample statistics for sensors with very large footprints, a characteristic that provides for verification of older data sets. The stable nature of the Antarctic radiances arises from the high surface reflectivity (> 90%), the regenerative nature of the pure snow coverage, and the relatively low aerosol concentrations.

The reflective properties of the Antarctic surface have been measured by numerous groups, most thoroughly and convincingly by Warren et al. They have published total hemispheric reflectance (Grenfell et al.) and a parameterization of reflectance anisotropy (Warren et al.) based on a variety of ground locations and viewing conditions. Their results compare well with model predictions for deep snow-covered surfaces. One important conclusion is that reflectance varies little between 300 nm and 650 nm, a range of primary interest for many Earth backscatter-measuring sensors.

Reflectance anisotropy is an important characteristic to include in radiative transfer models of snow surfaces. The top-of-the-atmosphere (TOA) radiance difference between a Lambertian and a forward scattering snow surface with the same reflectance grows from 2% at 350 nm to 7% at 600 nm. We have derived a mean bidirectional reflectance distribution function (BRDF) for the Antarctic surface using the Warren et al. anisotropy. We employed combinations of reciprocity and interpolation to generate a model covering 2π steradians in reflected angles and solar incidence angles down to 0°. Though the continent never receives direct illumination at less than 45° incidence, the radiative transfer model must account for diffuse scattered light that can arrive at any incident angle. Jaross et al. estimated that BRDF knowledge represents the largest error component in the TOA radiance predictions, approximately 2% at moderate solar zenith angles (SolZA).

In order to compare measured and calculated TOA radiances we created a look-up table of radiances using a Gauss-Seidel atmospheric modeling code (Herman et al.). This table has nodes covering all possible satellite viewing conditions, sensor wavelengths, surface pressures, and column ozone amounts. It does not include minor absorption species, aerosols, clouds, or a correction for rotational Raman scattering in the atmosphere. Monochromatic calculations were used to represent measurements with finite bandwidths, which are 0.4-0.7 nm in the case of OMI. A difference is computed between every valid Antarctic radiance measurement and a corresponding interpolated value from the table.

OMI results

In order to obtain the widest possible range of solar zenith angles, we chose OMI radiances measured during a 4 week period centered on December 21, 2004. The irradiance-normalized radiance differences at each wavelength were binned in solar and satellite zenith angles and the average computed for each bin.

Figure 1 contains the nadir-view results as a function of SolZA for several wavelengths. If OMI were perfectly calibrated and our model calculations were exact representations of the mean Antarctic surface and

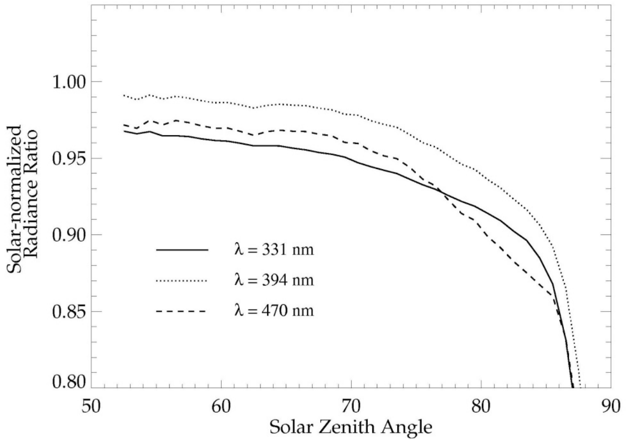

Figure 1. The ratio of solar-normalized radiances measured by OMI over Antarctica to those derived from a radiative transfer model. Shown for a selection of OMI wavelengths.

atmosphere, we would expect the result at each wavelength to be 1. The large radiance differences at high SolZA are primarily a result of poor surface characterization in our model. We have no reason to suspect a significant change in OMI sensitivity with angle. Large reflectance anisotropies, small measurement signals, and surface effects such as shadowing all contribute to model problems. The larger relative errors observed for long wavelengths are expected because of the greater contribution to TOA radiances from surface reflection compared to that from atmospheric Rayleigh scattering.

Results at low SolZA should be most accurate due to decreased sensitivity to modeling errors. Radiance ratios plotted in Figure 2 have been further averaged between 62° and 68° SolZA. These OMI results suggest a radiometric bias of 2.5% between 330 nm and 500 nm. The wavelength-independent albedo calibration uncertainty (1σ) for OMI in the nadir view is 2% (Dobber et al.). We anticipate substantially better relative calibration between wavelengths, something that is born out by these results. The residual structure observed between wavelengths is most likely the result of ignoring Raman scattering in our model, and the dip at 477 nm results from the O_2-O_2 collisional complex. The decrease at wavelengths less than 330 nm could be a result of ozone cross section errors caused by our monochromatic calculations.

MODIS comparisons

As a validation of our OMI results, we directly compared MODIS and OMI radiances. We chose MODIS data from the EOS Aqua spacecraft due the similarity of the Aura and Aqua orbits. Since we compared only nadir views, this restriction was not critical. The measured radiances for MODIS bands 3, 8, 9, and 10 were binned and aggregated in a manner identical to that described above for OMI. For the comparison, we averaged multiple OMI measurements over each MODIS spectral band width. The lack of any significant SolZA dependence in the radiance ratio confirms that the behavior seen in Figure 1 is caused by our model rather than instrumental effects.

After accounting for small differences in the solar flux measured by OMI compared to MODIS, we computed the albedo calibration difference of the two as a ratio of OMI to MODIS for each of the bands. These 5-6% differences are seen in Figure 2. We note that Band 10 data are available at only the highest solar angles over the continent, so we expect larger errors.

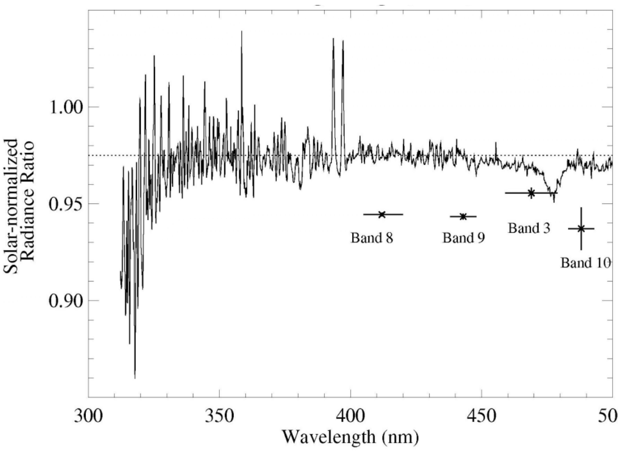

Figure 2. The ratio of measured and modeled Antarctic radiances are shown over part of the OMI spectral range. The ratio of OMI and MODIS /Aqua radiances are also shown for 4 of the MODIS reflective bands (1σ error bars shown).

Conclusions

The OMI solar-normalized radiances measured over the Antarctic continent compare well with our modeled radiances. Given the 2% radiometric calibration uncertainty of OMI and our 2% estimated fractional uncertainty for the ice radiance technique, we are pleased with the observed 2.5% difference. We believe there are good explanations for the spectral structure seen in the difference. Differences with MODIS are larger than can be explained by OMI calibration errors alone. The implication of Figure 2 is that MODIS differs from model results by approximately 3%. This is troubling because the published radiometric uncertainties for these MODIS bands are less than 2% (Esposito, et al.). It is our hope that a direct comparison between MODIS and our model will yield better agreement.

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