**Determination of Aerosol Optical Properties for Retrieval of Water-Leaving Radiance at Roodeplaat Dam relating to Calval of Sentinel 2 and 3**

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**Abstract**

Remote sensing of inland water quality is a particularly challenging satellite earth observation (EO) application. This arises because inland water bodies are small and optically complex targets that are generally dark compared to surrounding land. Signal reaching the satellite is usually dominated by light scattered in the atmosphere. Aerosols, which are a strongly variable atmospheric constituent, play a major role in generating this unwanted signal which must quantified and removed before any conclusions about water state can be reached. A field campaign has been executed at Roodeplaat dam near Pretoria relating to calibration and validation (calval) of the recently launched Sentinel 2 and Sentinel 3 satellites. Radiative transfer modelling for the atmosphere is required for satellite retrievals of surface radiant quantities. Aerosol models for radiative transfer have been evaluated and refined to improve retrieval accuracy of water-leaving radiance at Roodeplaat.

**Keywords**: Satellite sensor calibration and validation; aerosols; remote sensing; water quality

**1. Introduction**

Satellite systems are an important and growing source of measurements for Earth Observation (EO). Recent launch of the European Space Agency’s (ESA) Sentinel 2 and Sentinel 3 satellites [Donlon 2012] has created a requirement for quality assessment of the resulting data products. Calibration and data product validation (calval) is a lifecycle process addressing product quality. A campaign has been executed at Roodeplaat dam near Pretoria relating to calval of Sentinel 2 & 3 in the water quality application.

The atmosphere has a very significant effect on satellite EO of the surface. Aerosols and water vapour are the most variable atmospheric constituents and these have optical effects which must be understood in order to utilise satellite observations of the surface in an accurate, quantitative mode.

Measurements of aerosol optical depth and other optical properties are presented for the Roodeplaat campaign, together with analysis of the effects on satellite retrieval of water-leaving radiance.

**2. Instrumentation**

The aerosol optical thickness/depth (AOT/AOD) is an important determinant of the amount of sunlight reaching the surface and then reflected back up to the satellite. AOT was measured at wavelengths of 440 nm, 500 nm, 675 nm and 870 nm using a MicroTOPS II handheld sunphotometer. The instrument also estimates the total water vapour column using an additional optical thickness measurement at 936 nm. Two MicroTOPS units were used at Roodeplaat on 5, 6 and 24 June 2016 to measure AOT at the times of Sentinel overpasses. An ASD Fieldspec 3 spectroradiometer with a remote cosine receptor was used to measure global and diffuse downwelling spectral irradiance. A BWTek SpectraRad-1050 spectroradiometer calibrated for irradiance was also used to perform the same measurement. A second ASD Fieldspec 3 was used in radiance mode to measure the remote-sensing reflectance of the dam itself.

In addition, the Cimel CE318 robotic sunphotometer at the CSIR Pretoria campus was used as a reference instrument. This instrument is a node in the AERONET [Holben 1998] network.

**3. Theory and Methods**

Many of South Africa’s inland water bodies are in danger of eutrophication [van Ginkel 2011, Harding 2015] due to the growing influx of pollutants. Eutrophication can be monitored across many water bodies using carefully applied satellite observations [Matthews 2011]. The relative amount and spectrum of light emerging from the water surface under specific conditions is called the water-leaving radiance . This is the quantity which must be retrieved from satellite observations. is generally small so that light scattering and absorption in the atmosphere is a major source of spurious signal reaching the satellite at top-of-atmosphere (TOA). The relationship between the downwelling irradiance at the water surface (at bottom-of-atmosphere, BOA) and is

( 1)

where is the spectral remote sensing reflectance of the water body. is measured at the dam using an ASD spectroradiometer together with a white reference reflectance standard according to a specific measurement protocol [Mobley 1999, Lee 2010] executed from a boat at several points on the water.

While depends on water state, depends on a number of factors including solar zenith angle (which depends on date and time), atmospheric composition, notably aerosol optical properties/thickness and water vapour column. Through scattering in the atmosphere, also depends on the spectral reflectance of the land area surrounding the water body. The latter influence is known as the “adjacency effect” at BOA.

The atmospheric radiative transfer code, MODTRAN® 5 [Berk 2005], was used to model on the basis of measured AOT and aerosol spectral single-scattering albedo (SSA) as well as adjacent land spectral reflectance. The SSA expresses the probability that a photon will be scattered rather than absorbed when interacting with an aerosol particle.

While MODTRAN offers several canned aerosol types, including “urban”, “rural”, “maritime”, “tropospheric” and “desert”, none of these options were found to be appropriate in this case, probably due to the fact that the aerosols for this location and season are dominated by biomass burning. Biomass burning aerosols tend to have smaller particles and higher carbon content causing lower SSA than other aerosol classes.

**3.1 Computation of Total Radiance at TOA**

The total spectral radiant signal (spectral radiance) reaching the satellite sensor is computed using MODTRAN with the following procedure.

1. The atmospheric model is compiled in MODTRAN using available MicroTOPS and Aeronet data.
2. The mean area-averaged land/water surface spectral reflectance is retrieved from the Sentinel 2/3 image and input to MODTRAN.
3. The total downwelling spectral irradiance at BOA is computed using MODTRAN.
4. The water leaving radiance is computed from the in-situ measurement of using Equation (1).
5. MODTRAN is used to calculate the radiance of the sky seen by reflection from the water surface.
6. The water surface reflectance is computed from tables by Mobley [Mobley 2015] and the reflected sky radiance is added to the water-leaving radiance to obtain the total upwelling radiance above water at BOA.
7. The total upwelling radiance at BOA is propagated to TOA by multiplying by the atmospheric path transmittance provided by MODTRAN.
8. The atmospheric path radiance (due to light scattering in the atmosphere) is added to radiance from the previous step to obtain the total spectral radiance seen by the satellite at TOA.
9. The channel radiances for the satellite in question are computed by weighting with the spectral response functions (SRF) of the satellite sensor. These can be compared to the values actually provided by the satellite data product.

In order to retrieve the water-leaving radiance at BOA, the same process as above is used, neglecting the (supposed unknown) water-leaving radiance, but including all other radiance components. The shortfall in channel radiance at TOA compared to the satellite measurement is then assumed to be residual water-leaving radiance at TOA, which is then back-propagated to BOA by dividing by the (channel averaged) path transmittance.

**3.3 Aerosol Optical Properties**

The optical properties of aerosol particles and dispersed aerosols can be computed and specified in various ways. The aerosol model input options for MODTRAN 5 include the canned models mentioned above, where the aerosol loading (total amount) is specified with an optical visibility range or a vertical aerosol optical depth at 550 nm. Other alternatives include Ångstrom law manipulations, spectral SSA inputs, direct inputs of spectral absorption and scattering coefficients as well as spectral phase function inputs. In this case, Ångstrom law manipulations and spectral SSA inputs were provided to MODTRAN on the basis of MicroTOPS measurements at the dam combined with AERONET measurements at CSIR.

Aerosol optical property inputs to MODTRAN were fine-tuned to best match the MicroTOPS measurements, AERONET measurements and also the diffuse/global spectral irradiance ratio at Roodeplaat obtained with the ASD and BWTek spectroradiometers.

**3.3 Sunphotometer Intercomparison**

Both of the MicroTOPS instruments belonging to CSIR had expired calibrations. Hence there was a need to compare the instruments to one another and also to the AERONET Cimel CE318, which is calibrated annually at NASA.

Table 1 shows the co-located comparisons between the two MicroTOPS instruments and with AERONET, including the dates and times of comparison.

**4. Results and Discussion**

It was found that absolute measurements of spectral irradiance with the ASD and the BWTek instruments were not in good agreement, leading one to suspect a calibration problem with one or both instruments. However, the diffuse to global irradiance ratios were in good agreement (see Figure 2) and therefore it was decided to use only the diffuse/global irradiance measurements to fine-tune the aerosol optical model in MODTRAN.

Figure 1 shows the AOT measurements performed with the MicroTOPS instrument at Roodeplaat at the time of the Sentinel 3 overpass, together with AOT for the “rural” and “urban” canned MODTRAN aerosol models. Figure 1 also shows the result of tuning the aerosol optical model in MODTRAN to best match AOT at all measurement wavelengths using Ångstrom law adjustment and spectral SSA from AERONET measured at the same time. We assume that spectral SSA measurements at the CSIR AERONET site are representative also of the aerosols at Roodeplaat some 15 km away.

Figure 2 shows the diffuse/global spectral irradiance ratio, measured using the ASD and BWTek instruments, together with the MODTRAN canned urban aerosol result.

Figure 3 shows the same data as in Figure 2, but expressed as a percentage error (difference divided by the mean) between the MODTRAN urban aerosol result and the ASD, respectively the BWTek measured diffuse/global ratio.

Figure 4 shows how the relative error for the MODTRAN urban aerosol result can be reduced relative to Figure 3 by tuning the MODTRAN aerosol optical model using the in-situ measurements.



Figure 1 : Comparison of MODTRAN urban and rural aerosol spectral AOD models with user-defined model tuned using in-situ measurements



Figure 2 : Diffuse/Global ratio for Roodeplaat on 2016-06-05 computed using MODTRAN canned urban aerosol model together with diffuse/global ratio measured in-situ with ASD and BWTek radiometers.



Figure 3 : Relative percentage error between global/diffuse ratio computed with MODTRAN using the urban aerosol model with respect to the ASD and BWTek diffuse/global ratio in-situ measurements.



Figure 4 : Relative percentage error between global/diffuse ratio computed with MODTRAN using the tuned aerosol model with respect to the ASD and BWTek diffuse/global ratio in-situ measurements.

Figure 5 shows the Sentinel 3 retrieved water-leaving radiance at Roodeplaat on 2016-06-06 versus that measured via . The errors are particularly large in the blue spectrum due to the poorly matched MODTRAN urban aerosol model.



Figure 5 : Water-leaving radiance at Roodeplaat retrieved from Sentinel 3 using MODTRAN urban aerosol model, compared to the in-situ water-leaving radiance measured via remote-sensing reflectance.

Figure 6 shows the improvement in the accuracy of the retrieved water-leaving radiance if the MODTRAN aerosol model is tuned to match in-situ measurements of SSA and diffuse/global irradiance.



Figure 6 : Water-leaving radiance at Roodeplaat retrieved from Sentinel 3 using MODTRAN user-tuned aerosol model, compared to water-leaving radiance measured via remote-sensing reflectance.

**5. Conclusion**

The atmosphere has a very important influence on satellite remote sensing views of the Earth surface. Particularly for dark and small targets such as inland water bodies, it is necessary to perform atmospheric correction/compensation of raw satellite EO data. The effect is increasingly pronounced with increasing off-nadir view angles.

Aerosols are the most dynamic atmospheric component in cloud-free views and knowledge of aerosol loading and optical properties is required for accurate retrievals of BOA radiant variables. In this application, this knowledge can only be obtained through integration of satellite and in-situ measurements such as those offered by AERONET.

Measurement of the spectral diffuse/global irradiance ratio at BOA provides a more robust way of tuning the aerosol optical model than measurement and use of absolute spectral irradiance.

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