Heritage and summary of VIIRS Deep Blue and SOAR aerosol property retrieval algorithms

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https://deepblue.gsfc.nasa.gov/

Overview

Since 2004, the Deep Blue algorithm (https://deepblue.gsfc.nasa.gov) has been successfully applied to determine aerosol properties over land from a variety of satellite instruments (to date SeaWiFS, AVHRR, MODIS, and VIIRS). Since 2012, the Satellite Ocean Aerosol Retrieval (SOAR) algorithm has joined it as a companion to provide aerosol data coverage over ocean for SeaWiFS, AVHRR, and VIIRS. These algorithms are mature, with a physical basis that is well-understood, and have been validated on both a global and regional basis by the Deep Blue team and others, using standard reference networks (AERONET and the Maritime Aerosol Network, cf. https://aeronet.gsfc.nasa.gov).

The Deep Blue and SOAR algorithms, their validation, and scientific application have been documented in a number of peer-reviewed papers in international journals. A selection of key references can be found at https://deepblue.gsfc.nasa.gov/publications. With reference to VIIRS, the key papers at present are as follows:

- Hsu, N. C., M.-J. Jeong, C. Bettenhausen, A. M. Sayer, R. Hansell, C. S. Seftor, J. Huang, and S.-C. Tsay (2013), Enhanced Deep Blue aerosol retrieval algorithm: The second generation, J. Geophys. Res. Atmos., 118, 9296–9315, doi:10.1002/jgrd.50712.
- Sayer, A. M., N. C. Hsu, C. Bettenhausen, R. E. Holz, J. Lee, G. Quinn, and P. Veglio (2017), Cross-calibration of S-NPP VIIRS moderate-resolution reflective solar bands against MODIS Aqua over dark water scenes, Atmos. Meas. Tech., 10, 1425-1444, doi:10.5194/amt-10-1425-2017.
- Sayer, A. M., N. C. Hsu, C. Bettenhausen, J. Lee, W. V. Kim, and A. Smirnov (2018), Satellite Ocean Aerosol Retrieval (SOAR) Algorithm Extension to S-NPP VIIRS as Part of the "Deep Blue" Aerosol Project, J. Geophys. Res. Atmos., 123, doi:10.1002/2017JD027412.

A new paper titled VIIRS Deep Blue aerosol products over land: extending EOS long-term aerosol data records by Hsu et al. is in preparation, and is due for submission to a peer-reviewed publication shortly.

Deep Blue history

First applications

The Deep Blue algorithm was initially developed to fill gaps in remotely sensed aerosol optical depth (AOD) data sets over some bright land surfaces such as deserts and urban areas, where existing 'dark target' (DT) approaches based on dense dark vegetation (DDV) assumptions fail (e.g., Kaufman et al., 1997). The initial demonstration applications were used to SeaWiFS and MODIS over arid parts

of Africa (Hsu *et al.*, 2004) and eastern Asia (Hsu *et al.*, 2006), where DT persistently lacked coverage.

Deep Blue utilises blue wavelength (412-490 nm) measurements from instruments such as SeaWiFS and MODIS to infer the properties of aerosols. This spectral range is useful because the surface reflectance over land in the blue part of the spectrum is much lower than for longer visible wavelengths. This allows better separation of the atmospheric contribution from the surface signal, and thus renders easier aerosol retrieval.

In order to estimate the surface reflectance required to retrieve AOD, this version of the Deep Blue algorithm used a surface reflectance database, derived using a variant of the minimum reflectance technique composited from clear scenes across the satellite mission. The retrieval algorithm was then performed by finding the AOD and Ångström exponent (AE), using this assumed surface reflectance, required to match the top of atmosphere (TOA) reflectance observed by the satellite. The Deep Blue algorithm primarily uses the two blue MODIS channels (412 and 470 nm). The red band (650 nm for MODIS) is used only when the aerosol plumes are optically thick, to mitigate the larger surface contribution at this channel compared to the blue bands. Using this approach, the Deep Blue product allows scientists to quantitatively determine, for the first time, aerosol properties over desert and semi-arid regions at a higher spatial resolution available from SeaWiFS- and MODIS-like instruments.

This version of Deep Blue was incorporated into the MODIS operational aerosol product for both the Terra (MOD04) and Aqua (MYD04) satellites beginning with Collection 5.1, released around 2007, and it has been part of the routine MODIS Atmospheres data processing stream since, covering 2000 onwards for Terra and 2002 onwards for Aqua, which are available from the NASA LAADS.

Second generation

Later, a second-generation approach was developed (Hsu *et al.*, 2013) which extended Deep Blue's coverage to darker surfaces. This uses a variant of the DDV technique: essentially, it relates surface reflectance at visible and nIR/swIR wavelengths based on known spectral features for a given type of vegetated surface (e.g., trees, croplands). By combining with the existing bright surface retrieval approach, from this point onwards, Deep Blue now provided coverage, in principle, for all snow-free, cloud-free land surfaces. Additional miscellaneous improvements were included for this version. They included better cloud masking, aerosol optical models, quality assurance, and augmenting the surface database by including factors such as directional dependence and making use of AERONET-derived bidirectional reflectance distribution functions at some locations.

This second-generation algorithm was applied to the whole SeaWiFS data record (covering 1997-2010), and also applied beginning in MODIS Collection 6. In MODIS from this point onwards, a combined Deep Blue/Dark Target data set has also been available (Sayer *et al.*, 2014).

Recent advances

Subsequently, this second-generation approach was adapted to process data from the AVHRR sensors (Hsu *et al.*, 2017). The AVHRRs are somewhat less capable than SeaWiFS or MODIS, with no on-board calibration, and most having only two solar bands (centred near 630 and 850 nm). This required adapting the algorithm to make the best use of these available bands while retaining as far as possible Deep Blue's principles. Despite these limitations, a reasonable data quality has been obtained (Sayer *et al.*, 2017), which opens up, for the first time, the nearly 40-year AVHRR record as

an AOD data source over land. While some over-land algorithms had been developed for the AVHRRs previously, they were typically regional in scope rather than global, and/or required ancillary satellite information from e.g., MODIS which prohibited their consistent extension back in time to the 1980s.

In parallel to the AVHRR effort, refinement of Deep Blue continued to provide the version used in the latest MODIS Collection 6.1 and VIIRS. This continues the second generation approach (Hsu *et al.*, 2013) found in MODIS Collection 6, but with additional refinements to parameterisations to reflect developer and data user experience over the past years. Some additional modifications are necessary for VIIRS to account for differences in spatial and spectral coverage compared to MODIS, but the cores of the algorithms remain the same.

SOAR history

SOAR, like many other over-ocean AOD retrieval algorithms for passive sensors, performs a multispectral inversion of TOA reflectance from visible to swIR wavelengths to simultaneously and self-consistently retrieve AOD, aerosol fine-mode fraction, and aerosol type (from a selection of candidate aerosol optical models). Note that although the term 'ocean' is typically used by SOAR and other algorithms, the algorithm is in fact applied over all pixels identified as water-covered by satellite land/sea masks, to include e.g., large lakes.

Ocean surface reflectance is modelled as a function of chlorophyll concentration, wind speed, and geometry, which reproduces the main variations in color and brightness such as Sun glint features. Aerosol optical models are based on aggregates of AERONET inversions. In general, aerosol remote sensing is easier over ocean than land because the ocean surface is (outside of glint) darker and generally more predictable, meaning that there is a longer heritage of over-ocean aerosol property retrieval algorithms from passive imaging radiometers than over land, and they all tend to converge on the approach of a weighted multispectral fit.

The first iteration of SOAR (Sayer *et al.*, 2012) was developed to accompany the SeaWiFS Deep Blue data set, using TOA reflectances at 510, 670, and 865 nm measured by this sensor. Subsequent application to the AVHRR (Hsu *et al.*, 2017) and VIIRS (Sayer *et al.*, 2017, 2018) sensors has retained this principle, although parametrisations related to the surface reflectance model and aerosol optical models have been updated, and additional modifications have been necessary to account for the different spectral and spatial features of each sensor.

Note at present, SOAR has not been applied to MODIS measurements, as the MODIS aerosol products already contain an over-water data set implemented by the Dark Target team.