Validation Study for standard atmospheric products

Short description	Validation for standard aerosol products
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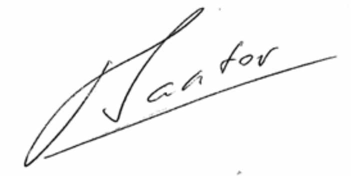
Author(s) and affiliation(s)	Richard SANTER 
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Definitions, Acronyms, Abbreviations

AAI	Absorbing Aerosol Index
AERONET	Aerosol RObotic NETwork (http://**aeronet**.**gsfc**.**nasa**.gov/)
AOT	Aerosol optical thickness
ATBD	Algorithm Theoritical Basis Document
ARM	
CalVal	Calibration Validation
CEOS WGCV	Committee on Earth Observation Satellites Working Group Calibration Validation
COP	Cloud Optical Thickness
CTP	Cloud Top Pressure
ECMWF	European Centre for Medium range Weather Forecasting
ENVISAT	Environmental Satellite
EO	Earth Observation
ESA	European Space Agency
GPS	Global Positioning System
IASI	Infrared Atmospheric Sounding Interferometer
IRIS	Infrared Interferometer Spectrometer
MERIS	Medium Resolution Imaging Spectrometer (ESA Envisat)
MODIS	Moderate-Resolution Imaging Spectro radiometer (NASA EOS)
NIR	Near InfraRed
POLDER	Polarization and Directionality of the Earth's Reflectances (CNES, ADEOS)
PM10	Particulate Matter (10: less than 10 µm diameter)
RTC	Radiative Transfer Code
TOA	Top Of the Atmosphere
TOMS	Total Ozone Monitoring Sensor
UV	Ultra Violet
VOS	Visible Optical Sensor

1. Introduction

We will restrict this study to passive VOS looking the Earth (no limb measurements) and we will exclude the spectrometer sensors (Such as Sciamachy). The VOS we will consider have as priority mission the observation of the ocean and of the land. The cloud mission exists as an additional opportunity. The additional spectral bands, which allow generating the atmospheric products we considered here, are required in the ocean and land processes, mainly to perform the classification and the atmospheric correction. As side products to the atmospheric correction, we have:

(i) The land surface pressure as a candidate for the Rayleigh correction

(ii) The aerosols

(iii) The water vapour

This link to the atmospheric correction is a clear limitation to the quality of the atmospheric product. It is a limitation in amplitude of the retrieval domain: for the atmospheric correction over the ocean, it is not necessary to search for an aerosol model where the atmospheric turbidity is high (poor performance of the atmospheric correction algorithm) while conversely it is important for aerosol studies to catch these circumstances. The same limitations occur with the geometrical conditions: large grazing angles are not favourable to AC while they offer better conditions for aerosol remote sensing. It is also a limitation in quality: the objective of the aerosol remote sensing is more to predict they optical properties rather than to describe they micro physical properties.

2 The atmospheric products

2.1 The aerosols

Principle of the algorithms

The principle both for land and ocean is simple:

(i) Identify the spectral bands for which the surface is black or dark.

(ii) Extract the aerosol reflectance from the TOA signal.

(iii) Select an aerosol model from the spectral dependence of the aerosol reflectance.

(iv) Convert the aerosol reflectance into an aerosol optical thickness.

Step (ii) requires the knowledge of the surface contribution, which is easier over the ocean because the ocean body is black in the NIR [R. 1] and more challenging over the land where the darkness surfaces are dense vegetation, which is dark in the blue and in the red [R. 2].

Step (iii) relies on a library of aerosol models, which is a potential problem because each mission uses it own set of aerosol models.

[R. 1] Gordon H. R., and M. Wang, "Retrieval of water-leaving radiances and aerosol optical thickness over the oceans with SeaWiFS : a preliminary algorithm", *Appl. Opt*., Vol. 33, No. 3, 443-452, 1994

[R. 2] Kaufman Y.J., Tanré D., Remer L., Vermote E.F., Chu A., Holben B.N., (1997) Operational Remote Sensing of Tropospheric Aerosol Over the Land from EOS-MODIS. *Journal of Geophysical Research*, Vol.102, D14, 17,051-17,068.

The optical product

The aerosol optical thickness in a reference band is the first. Because the ocean is dark at 865 nm, 865 nm is the reference band for ocean colour missions. Because the vegetation is the darkest at 440 nm, this band is the reference band over land.

The second product is the Angstroem coefficient α. Two spectral bands are used to produce it. It is a so-called dynamic Angstroem coefficient α. Because the spectral ranges to remote sense the aerosol over land and over the ocean, their respective α are not directly comparable.

The geophysical product

The above optical products are side products from the atmospheric correction and as such informs on what has been used to perform these atmospheric corrections. In some missions, there is a specific algorithm branch for the aerosols. Therefore, the aerosol product may be more informative on the geophysical aspect. It is the case for POLDER[R. 3] which makes the distinction between the accumulation mode and the coarse mode.

Monitoring the air quality is required by law (or regulation). The aerosols play an important role in the air quality, regulation brings on the density of particles of diameter less than 10 µm. The AOTs can be converted into PM10 [R. 4].

[R. 3] Herman, M., J.-L. Deuzé, A. Marchand, B. Roger, and P. Lallart (2005), Aerosol remote sensing from POLDER/ADEOS over the ocean: Improved retrieval using a nonspherical particle model, *J. Geophys. Res.*, *110*.

[R. 4] Vidot J., Santer R., Ramon D., **(**2007). Atmospheric particulate matter (PM) estimation from SeaWiFS imagery, Remote Sensing of Environment, vol. 111, pp. 1-10.

The Absorbing Aerosol Index (AAI)

The TOMS aerosol index (see definition on http://toms.gsfc.nasa.gov/aerosols/aerosols_v8.html) is a measure of how much the wavelength dependence of backscattered UV radiation from an atmosphere containing aerosols (Mie scattering, Rayleigh scattering, and absorption) differs from that of a pure molecular atmosphere (pure Rayleigh scattering). Quantitatively, the aerosol index AI is defined to be the ratio between the measured 360 nm EP-TOMS radiance and the calculated 360 nm EP-TOMS radiance for a Rayleigh atmosphere. Under most conditions, the AI is positive for absorbing aerosols and negative for non absorbing aerosols (pure scattering).

As any index, the AAI is not subject to a validation but the outputs follow a common understanding.

2.2 The land surface pressure

Principle of the algorithm

The oxygen strongly absorbs around 761 nm. Two spectral bands are used to extract the O2 transmittance.

For bright land (ice, snow, sand), the O2 transmittance corresponds to the direct to direct path and directly provides the surface pressure[R. 5].

For regular land surfaces, there is a need to correct from the coupling between atmospheric scattering and surface reflection.

[R. 5] Santer R., Carrere V., Dubuisson P., & Roger J.C. (1999). Atmospheric correction over land for MERIS, International Journal of Remote Sensing, Vol. 20. Issue 9, p 1819-1840.

2.3 The water vapour

The water vapour retrieval uses it strong absorption around 930 nm. As for the oxygen, it is a differential method [R. 6]. The land surfaces are generally bright and the H2O transmittance corresponds to the direct to direct path. For a given P-T profile and a water vapour standard profile, we can associate to this H2O transmittance the integrated amount of water vapour in the atmospheric column.

The principle is the same than over land except that the ocean is dark therefore the results are very dependent upon the relative vertical distribution of the aerosols and of the water vapour.

[R. 6] Gao B., Kaufman Y., 2003, Water vapor retrievals using Moderate Resolution Imaging Spectroradiometer (MODIS) near-infrared channels. . *J. Geophys. Res.*, VOL. 108, NO. D13, 4389.

2.4 The cloud products

2.4.1 The cloud flag

Principle of the algorithms over land

The classification for white bright clouds is straightforward. The land is bright may be except in the blue which allows to set threshold values on the TOA reflectance. The series of tests is resumed with the spectral behaviour in the NIR to distinguish snow and clouds. [R. 7]

On an operational point of view, the tests can be sequentially applied to set a flag. On a more statistic basis, it is possible to predict the probability of clouds occurrence for example using neural networks [R. 8].

[R. 7] Ackerman, S. A., K. I. Strabala, W. P. Menzel, R.A. Frey, C. C. Moeller, and L. E. Gumley, 1998: Discriminating clear sky from clouds with MODIS*. J. Geophys. Res.*, 103, D24, 32141-32157.

[R. 8] Preusker R., Fischer J., Hünerbein A., Brockman C., Zühlke M. and Krämer U.NN Improved MERIS cloud detection http://earth.esa.int/cgi-bin/confm8.pl?abstract=208

Principle of the algorithms over ocean

The nature of the flag depends on the nature of the mission. For ocean colour mission, there is confusion between a cloud flag and a bright pixel flag because the use of this flag to trigger the atmospheric correction procedure [R. 9].

[R. 9] Santer R., Carrère V., Dessailly D., Dubuisson P, Roger J. C., 1997, Pixel Identification, http://envisat.esa.int/instruments/meris/atbd/atbd_2_17.pdf ATBD 2.17

Cirrus cloud flags

The MODIS band at 1.37 µm offers the opportunity to detect the high clouds[R. 10]: the signal bellows is eliminated by the strong water vapour absorption. The use of the oxygen band is also an opportunity to detect cirrus clouds both over land but more likely over the oceans.

[R. 10] Gao, B.C., Yang, P., Han, W., Li, R.R. and Wiscombe, W.J., 2002. An algorithm using visible and 1.38 µm channels to retrieve cirrus cloud reflectances from aircraft and satellite data. *IEEE Trans. Geosci. Remote Sens.* **40**, pp. 1659–1667.

2.4.2 The cloud top pressure (CTP)

Principle of the algorithms

The principle is the same than for the land surface pressure. On course, the penetration of the light in the clouds should be considered as well as the contribution of the surface in case of semi transparent clouds [R. 11].

For POLDER, an alternative algorithm is based on the polarized reflectance measurement [R. 12]. The Rayleigh strongly polarises at a scattering angle of 90° while the clouds generate no polarized light at this angle. The amount of Rayleigh polarisation is proportional to the CTP.

[R. 11] Fischer J., Schüller L., Preusker R., 1997, Cloud Albedo and Cloud Optical Thickness, MERIS. http://envisat.esa.int/instruments/meris/atbd/atbd_2_03.pdf

[R. 12] [R. 11] Buriez J.-C., C. Vanbauce, F. Parol, P. Goloub, M. Herman, B. Bonnel, Y. Fouquart, P. Couvert and G. Sèze , 1997: Cloud detection and derivation of cloud properties from POLDER. *Int. J. Remote Sensing*, **18**, 2785-2813.

2.4.3 The cloud optical thickness (COT)

The COT drives the amplitude of the TOA reflectance, or cloud albedo after correction of the atmosphere above the clouds. For semi transparent clouds, the contribution of the surface should be accounted for[R. 13].

[R. 13] Fischer J., Schüller L., Preusker R., 1997, Cloud Albedo and Cloud Optical Thickness, MERIS. http://envisat.esa.int/instruments/meris/atbd/atbd_2_03.pdf

2.4.4 The cloud phase

POLDER uses the polarization to distinguish spherical droplets from ice crystals. The retrieval is based on polarized bidirectional observations made by POLDER. First, normalized polarized radiances are simulated for cirrus clouds composed of ice crystals that differ in shape and are randomly oriented in space. Different values of cloud optical depths, viewing geometries and solar zenith angles are used in the simulations. This sensitivity study shows that the normalized polarized radiance is highly sensitive to the shape of the scatterers for specific viewing geometries, and that it saturates after a few scattering events, which makes it rapidly independent of the optical depth of the cirrus clouds [R. 14].

At 1.65 µm it possible as well to determine the shape of the cloud particles[R. 15].

[R. 14] Chepfer H., Goloub P., Riedi J., De Haan J.F., Hovenier J. W., Flamant P., 2001. Ice crystal shapes in cirrus clouds derived from POLDER/ADEOS-1. Journal of geophysical research. Vol. 106, n°D8, pp. 7955-7966

[R. 15] King M. D., Tsay S. C., Platnick S. E., Wang M., Liou K., 1997, Cloud Retrieval Algorithms for MODIS: Optical Thickness, Effective Particle Radius, and Thermodynamic Phase. *MODIS Algorithm Theoretical Basis Document No. ATBD-MOD-05. MOD06 – Cloud product.* http://modis.gsfc.nasa.gov/data/atbd/atbd_mod05.pdf

3 Validation of the atmospheric products

3.1. Aerosols

Principle of the validation

The AERONET net work through the CIMEL extinction measurements allows to produce the AOTs at 440 nm, 670 nm and 870 nm. These data are directly comparable with the aerosol product as delivered by the satellite sensors[R. 16]. But the protocol for comparison is not so direct.

The time correspondence is easy to ensure because of the high frequency of the CIMEL measurements and the possibility to get in a time interval of less than half an hour the two sets. The spatial correspondence is more difficult to reach:

(i) Over land the aerosol remote sensing is not conducted most of the time on a pixel by pixel basis.

(ii) Over water, it is unusual to have a CIMEL station in the open ocean. Some stable platforms exist in coastal areas (see the AERONET ocean colour network) or portable sun photometers can be used at sea[R. 17].

(iii) The AOT is integrated over the atmospheric column. Therefore, even if your radiometer is located in a given satellite pixels, the respective air masses for which the aerosol product is derived are not the same.

[R. 16] Kokhanovsky A.A., Bréon F. M., Cacciari A., et al., 2007: Aerosol remote sensing over land: A comparison of satellite retrievals using different algorithms and instruments. Atmospheric Research, 85 (3-4), 372-394.

[R. 17] Deschamps P. Y., Fougnie B., Frouin R., Lecomte P., and Verwaerde C., 2004, SIMBAD: a field radiometer for satellite ocean-color validation. Vol. 43, No. 20 _ APPLIED OPTICS

It is relevant to conduct a validation not on a pixel but on what we can call a daily level 3 product. This product already exists for MODIS. For other sensors, it needs to be processed. A daily level 3 product can not be a simple average on a micro pixel of the aerosol product[R. 18]. Figure 1 gives an example of a direct comparison between MERIS average AOT at 442 nm and CIMELL measurements. The size of the window is 10 km*10 km. The error bars corresponds on CIMEL to the temporal variability of the AOTs and on MERIS on the spatial variability. The two sets of data are not well correlated and the comparison is biased.

The production of the daily level 3 requires for the aerosol product validation requires applying a data screening based on:

(i) The removal of cloud shadows which is a morphologic mask.

(ii) The removal of cirrus clouds which can rely on the use of an O2 band when available.

(iii) A criteria on the spatial variability of the AOTs. In the vicinity of clouds, the AOT increases artificially.

On the same data set than for figure 1, we can see on figure 2 a good validation of the MERIS AOT at 440 nm.

[R. 18] Ramon D., Santer R., Dilligeard E., Jolivet D., Vidot J. (2003). Validation of MERIS products over land, MERIS user workshop, ESA ESRIN, 10-13 november 2003, Frascati, Italy. http://envisat.esa.int/workshops/mavt_2003_ver1

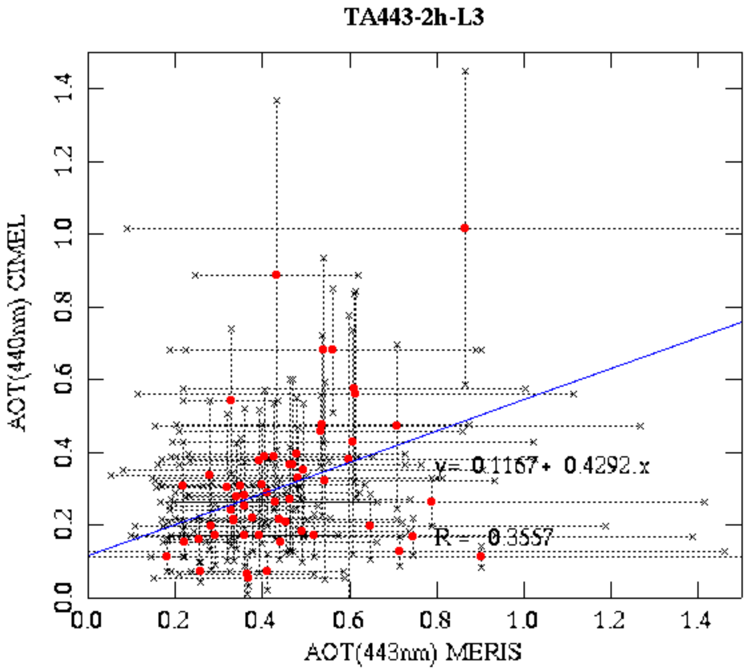

Figure 1: AOT 443: CIMEL versus MERIS at different AERONET stations (from Ramon D. and R. Santer, "Validation of the MERIS aerosol product over land", *MERIS-AATSR workshop, ESRIN, Frascati, September23, 2008)*

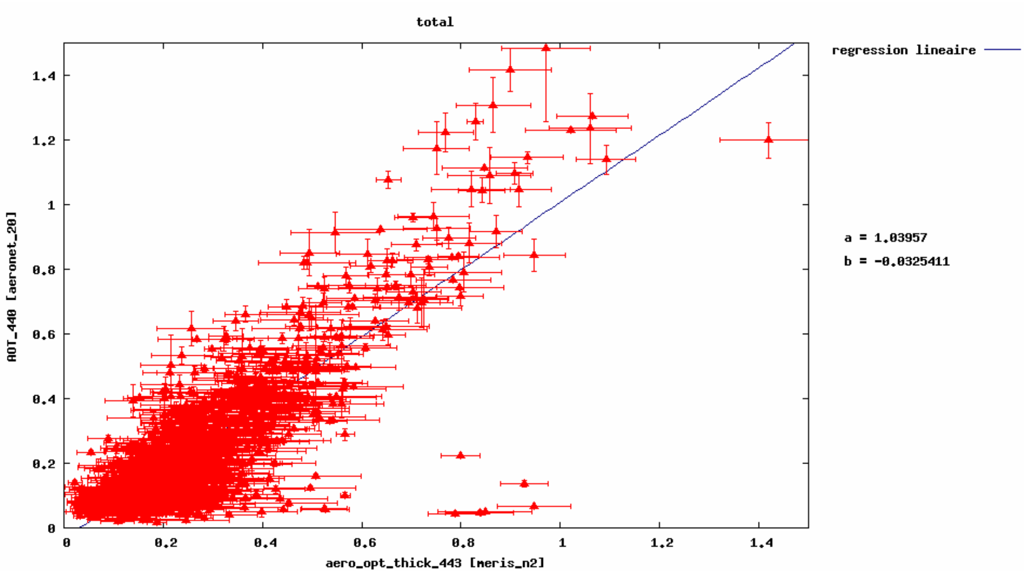

Figure 2: AOT 443: CIMEL versus MERIS (after level 2 filtering) at different AERONET stations (from Ramon D. and R. Santer, "Validation of the MERIS aerosol product over land", *MERIS-AATSR workshop, ESRIN, Frascati, September23, 2008)*

Of course, this comparison between satellite and ground based aerosol products can be generalised to several sensors as shown in figure 3.

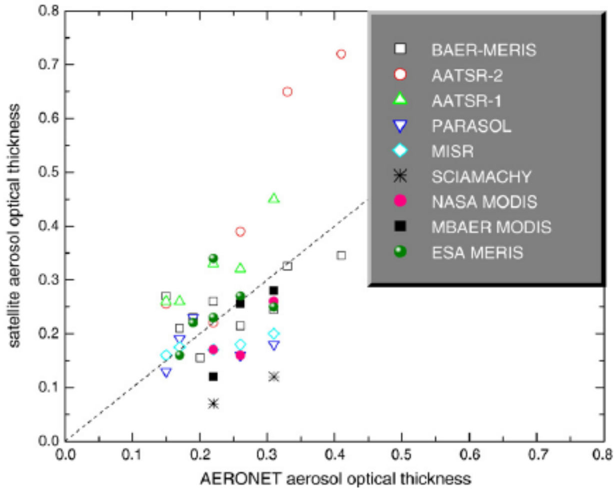

Figure 3: AOT 443: CIMEL versus different satellite sensors [R. 16].

Inter comparison with other sensors

The aerosols strongly vary in space and time. An inter comparison between sensors requires to be conducted on a common site and within a short time difference in the overpasses. The ocean sensors present favourable conditions to this inter comparison because:

(i) the crossing times at equator are similar
(ii) It is possible to match the geometrical condition.
(iii) The spatial homogeneity of the aerosols is very good.
(iv) The aerosol models are similar.

This last point is critical because the extracted aerosol path reflectance is proportional to the AOT time the aerosol phase function. With similar aerosol models, we ensure the comparability of the aerosol phase function. Therefore, it is not surprising to reach a good agreement between sensors as illustrated in figure 4[R. 19], [R. 20].

[R. 19] P. Goloub, M. Herman, J.L. Deuzé, P. Lallart, Validation of POLDER-2 basic aerosol parameters over ocean, submitted to Rem. Sens. Environ., 2005.

[R. 20] Gerard B.; Deuzé J.-L.; Herman M.; Kaufman Y. J. ; Lallard P. ; Oudart C. ; Remer L. A. ; Roger B. ; Six B. ; Tanré D. **,** 2005, Comparisons between POLDER 2 and MODIS/Terra aerosol retrievals over ocean. Journal of geophysical research. Vol. 110, n°D24, pp. D24211.1-D24211.15.

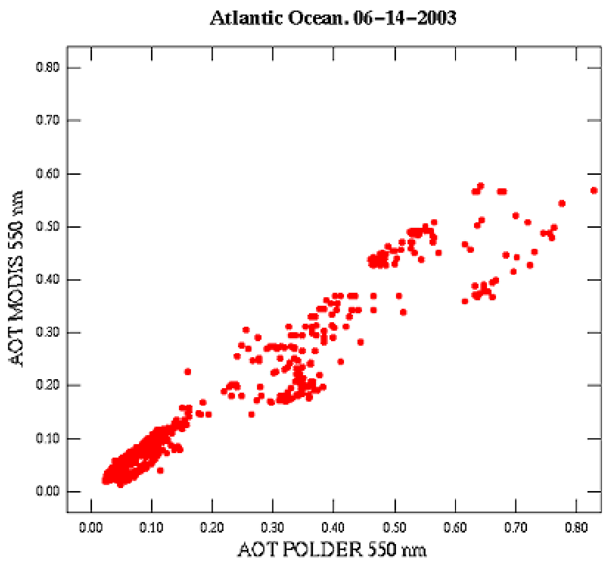

Figure 4: Validation of Aerosol Retrieval Over Ocean Using AERONET network [R. 19]

The inter comparison is more difficult over land because of:

(i) The spatial heterogeneity of the land surface.

(ii) The residual contribution of the surface which is modelled differently following the algorithms.

(iii) The use of different standard aerosol models.

An agreement between different sensors appears to be a pure coincidence except of course if the algorithms and associated LUTs are identical. A validation (or evaluation) of the aerosol product over land requires the output of break points: surface reflectance, aerosol reflectance, aerosol phase function.

3.2 Land surface pressure

The validation goes to the comparison of the satellite derived pressure and the meteorological pressure [R. 21]. This last one has to be corrected from the surface elevation thanks to a DEM. Because the coupling between atmospheric scattering and reflection is marginal for bright surfaces, this validation is mostly conducted over bright targets (ice, sand).

Because the meteorological pressure is in any case more accurate than the satellite derived pressure, the validation results in a vicarious adjustment of the instrument characteristics (spectral characterization of the O2 bands, [R. 22]) or of the level 1 treatment (stray light correction model, [R. 23]).

[R. 21] Ramon, D. Cazier, L. Santer, R., 2003, The surface pressure retrieval in the MERIS O_2 absorption: validation and potential improvements**.** Geoscience and Remote Sensing Symposium, 2003. IGARSS '03. Proceedings. 2003 IEEE International. Vol. 5, p3126- 3128**.**

[R. 22] Dubuisson P., Borde R., Schmechtig C., Santer R. (2001)." Surface pressure over land using the oxygen absorption, application to MOS", J.G.R., Vol. 106, No D21, 27 277-27286.

[R. 23]

3.3 Water vapour

Using in situ data

The traditional approach was to use radiosondes [R. 24]: the water vapour content is measured at different pressure levels and a vertical integration provides the total amount of water vapour in the atmospheric column. This radiosondages are routine measurements performed in the weather forecast network.

Complementary, GPS derived water vapour contents can be now used [R. 25]. GPS satellite radio signals are slowed by the Earth's atmosphere. The signal delays depend on the constituents of the atmosphere that are a mixture of dry gasses and water vapour.. A record of the total delay, surface pressure, surface temperature, and total precipitable water vapor is available at each site every 30-minutes.

Microwave ground based sensors are also used [R. 26]

[R. 24] Li Z., Muller J.P., Cross P., and P. Albert, 2003,Comparison of precipitable water vapour derived from radiosondes, GPS, MODIS and MERIS measurements. Geophysical Research Abstracts, Vol. 5, 00690, 2003

[R. 25] Wang Xinming; Cong Pifu; Lin Wenpeng; Wang Changyao; Niu Zheng. Comparison of atmospheric water vapor estimated from GPS and MODIS sensors over Fangshan, Beijing Geoscience and Remote Sensing Symposium, 2005. IGARSS apos;05. Proceedings. 2005 IEEE International. Volume 4, Issue , 25-29 July 2005 Page(s): 2719 – 2721.

[R. 26]

Inter comparison with other sensors

The use of the water absorption band in the NIR is common to different VOSs (POLDER, MODIS, MERIS,…) and result in inter comparison exercises [R. 27] . Beside this direct inter comparison, it is relevant to use sensors which provide in other spectral domains an evaluation of the water vapour content. The Infrared Interferometer Spectrometer (IRIS) provides the water-vapour content with an error of about + 3kg/m^2. This performance can be achieved with other infrared sensors, as for example IASI (http://wdc.dlr.de/sensors/iasi/). Also, microwave sensors offers the capability to derived the water vapor content [R. 28].

[R. 27]

[R. 28]

[R. 29] Wang, J.R. Sharma, A.K., 2002. Water Vapor Profiling Over Ocean Surface with 90 Ghz and 183 Ghz Measurements Under Clear and Cloudy Conditions. Geoscience and Remote Sensing Symposium, 1992. IGARSS '92. International. Volume: 2, 1366-1368.

3.4.Clouds

3.4.1 The cloud flag

The detection of the clouds for VOS is challenging over land for thin clouds or finite clouds. A clear limitation is to conduct a classification on a pixel basis. The visual (or supervised) identification of clouds is always based on the spatial heterogeneity.

Alternatively, an inter comparison of the cloud flags between sensors is an option as far as it is possible to ensure the spatio temporal requirements. A good match in time is offered by a multi sensor platform: a thermal camera helps to detect semi transparent clouds[R. 30]. The pixel matching is more difficult to ensure.

The evaluation of a cloud flag is linked to the use of the flag. If the primary objective of the satellite mission is the surface observation (water or land), the flag is used as a quality check of the atmospheric correction. It can be a non conservative flag and let pixel contaminated by semi transparent clouds to be processed. The quality control is downstream on the product themselves.

[R. 30] Parol, F., J. C. Buriez, G. Brogniez, and Y. Fouquart, 1991: Information content of AVHRR channel 4 and 5 with respect to the effective radius of cirrus cloud particles. *J. Appl. Meteor.*, **30,** 973–984..

2.4.2 The cloud top pressure

Using in situ data

The cloud top pressure is validated by airborne lidar measurements. Validation flights ,temporally and spatially synchronized with the satellite sensor, are performed. The maximum flying altitude is generally around 3000 m (10 000 feet); therefore, the validation measurements are limited to situations with low-level clouds only[R. 31].

The radar-lidar cloud measurements can be very informative. For example, the Southern Great Plains ARM data (http://www.arm.gov/sites/sgp.stm) were used for checking the cloud thermodynamic phase and the cloud pressures (Oxygen pressure)

[R. 31] Lindstrot R. ; Preusker R.; Ruhtz T. H.; Wiegner M.; Lindeman C.; Fischer J.; 2006. Validation of MERIS cloud-top pressure using airborne lidar measurements. Journal of applied meteorology and climatology. Vol. 45, n°12, pp. 1612-1621.

Inter comparison with other sensors

The use of the oxygen band in the NIR is common to different VOSs (POLDER, MODIS, MERIS,…) and result in inter comparison exercises [R. 32] . Beside this direct inter comparison, it is relevant to use sensors which provide in other spectral domains an evaluation of the CTP. The apparent temperature with thermal sensor is

[R. 32]

2.4.3 The cloud optical thickness (COT)

Using in situ data

[R. 32]

Inter comparison with other sensors

2.4.4 The cloud phase

Inter comparison with other sensors

Riedi, J., P. Goloub, and R. T. Marchand (2001), Comparison of POLDER Cloud Phase Retrievals to Active Remote Sensors Measurements at the ARM SGP Site., *Geophys. Res. Lett.*, *28*(11), 2185–2188.