CalVal Support System

In response to

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"INTER-COMPARISON DATA, PROTOCOLS & GUIDE LINES DEFINITION FOR CAL &VAL",
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Calibration Validation Requirements Consolidation

Deliverable D1-3

Deliverable D2-8

Deliverables Summary Sheet

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Definitions, Acronyms, Abbreviations

AAIA	Aerosol Absorbing Indicator Algorithm
AATSR	Advanced Along Track Scanning Radiometer
ACSG	Atmospheric chemistry subgroup
AERONET	Aerosol RObotic NETwork (NASA Goddard Space Flight Center)
AFRL/VSBT	Air Force Research Lab, Space Vehicles Directorate
AOT	Aerosol optical thicknesses
ARM	Atmospheric Radiation Measurement
ARVI	Atmospheric Resistant Vegetation Index
ASAR	Active phased array SAR
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer (Japan; NASA EOS)
ATSR	Along-Track Scanning Radiometer (ESA ERS)
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BRDF	Bidirectional Reflection Distribution Function
BIAS	Basic Infra-red Absorption Spectroscopy
BSST	bulk sea surface temperature
CalVal	Calibration Validation
CEOS WGCV	Committee on Earth Observation Satellites Working Group Calibration Validation
CNES	Centre National d'Études Spatiales (France)
CZCS	Coastal Zone Color Scanner system
DDV	Dense Dark Vegetation
DOAS	Differential Optical Absorption Spectroscopy
ECMWF	European Centre for Medium range Weather Forecasting
ENVISAT	Environmental Satellite
EO	Earth Observation
ERS	European Remote-Sensing Satellite (ESA)
ESA	European Space Agency
FOV	Field-of-View
GLI	Global Imager (Japan, ADEOS)
GMES	Global Monitoring Earth System
GOME	Global Ozone Monitoring Experiment
GOMOS	Global Ozone Monitoring by Occultation of Stars
HRV	Haute Résolution Visible
ICFA	Initial Cloud Flagging Algorithm
IOP	Inherent Optical Property
IPSL	Institut Pierre Simon Laplace
IVOS	Infrared and Visible Optical Sensors subgroup

LOWTRAN	LOW TRANsmittance model
LPV	Land Product Validation subgroup
LST	Land Surface Temperature
LUT	Look Up Table
MERIS	Medium Resolution Imaging Spectrometer (ESA Envisat)
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MISR	Multiangle Imaging Spectro-Radiometer (NASA EOS)
MOBY	Marine Optical Buoy
MODIS	Moderate-Resolution Imaging Spectroradiometer (NASA EOS)
MODTRAN	MODerate spectral resolution atmospheric TRANSsmittance algorithm and computer model
MSS	Multi-Spectral Scanner
MSSG	Sensors subgroup
MW	Microwave
MWR	Microwave Radiometer
NDVI	Normalized Difference Vegetation Index
NILU	Norsk institutt for luftforskning
NIR	Near Infrared (spectral region)
NRT	Near Real Time
POLDER	Polarization and Directionality of the Earth's Reflectances (CNES, ADEOS)
RSG	Remote Sensing Group
RTC	Radiative Transfer Code
SAM	Standard aerosol models
SAR	Synthetic Apertur Radar subgroup
SAR	Synthetic Aperture Radar
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor (USA)
SPOT	Système Probatoire d'Observation Terrestre (France)
SSST	Skin Sea Surface Temperature
SST	Sea Surface Temperature
ST	Surface Temperature
TM	Thematic Mapper *or* Telemetry
TMI	Thermal Microwave Instrument
TOA	Top Of the Atmosphere
TOMS	Total Ozone Mapping Spectrometer
UV/Vis	Ultra Violet /Visible (spectral region)
VISCAL	VISible CALibration system
VOS	Visible Optical Sencor

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Preface

It is first a literature review of current vicarious calibration practices. The initial goal was very ambitious because it encompasses a large variability of sensors (atmospheric, IVOS, SAR, MW). If we will all included them in this report, we will mostly focus on IVOS, which still remain a vast domain.

The calibration practices include many things starting from definitions and associated methodology and going through instrumentation, radiative transfer codes, test sites… This large diversity can not be fully described by a literature review not only because of the limited time allocated to this task but also the classical scientific literature does not focus primarily on calval issues. Too often, the calval activities are viewed as more technical than scientific. Therefore, the results are more likely published as technical reports or in the grey literature. In order to offer details on calval practices, we tried to involved well know scientists in the writing of this report. The available contributions will be annexed to allow the reader to go deeper in the knowledge of a specific aspect of calval. There are more contributions to be expected from the people how have been contacted already. By lack of time, the first solicitations only covered the solar domain. We will contact soon people working in the infra red. Of course, we will forget to contact many of you and obviously, we are fully open to submitted contributions (to be send at santer@mren2.univ-littoral.fr).

One important thing to be included in this analysis is to identify the requirements for level 1 and for level 2. We certainly need help from the scientific community to better address this point than it is now. To validate if the requirements are met, calval outputs need to include error bars. It is another critical point because too often there is confusion between sensitivity analysis and the production of error bars. To close the loop, calval results, within the error bars, should tell if the mission requirements are reached. Again, I need help from you through your on specific sensor and product

I already ask many things from you, and in return, we will be please to know how this project can help you? You will certainly not take advantage of personal analysis make here to give recommendations to improve current vicarious calibration practices. At the end, we will make some recommendations on what can be developed.

1. Introduction

GMES is addressing all aspects of environmental monitoring, including the biosphere and the atmosphere. Based on user demand the consolidation phase in 2003 and 2004 has lead 5 service elements, which will provide services to end users and which require data from Earth Observation satellites. These include application for marine and coastal services, land monitoring and forest monitoring. A large variety of sensors are necessary in order to fulfil the requirements coming from these GMES services: sensors for atmospheric chemistry, microwave and SAR sensors and optical sensors covering the visible and infrared part of the spectrum. ENVISAT includes – at least a subset of – the required sensors. More consequently, 5 new satellites have been proposed by ESA which will serve the data required by GMES: the sentinels. The lessons learned from ENVISATs and other sensors calibration and validation activities have strongly influenced the work of the CEOS WGCV, and the WGCV is accordingly organised in 6 subgroups, of which 5 can directly be mapped to the sensors on ENVISAT and the 5 proposed sentinel satellites:

CEOS-WGCV		**ENVISAT**	**Sentinel**
ACSG	Atmospheric chemistry subgroup	MIPAS, SCIAMACHI, GOMOS	Sentinel 3,4,5
IVOS	Infrared and visible optical sensors subgroup	MERIS, AATSR	Sentinel 2,3
LPV	Land Product Validation subgroup	MERIS, AATSR	Sentinel 2, 3
MSSG	Microwave Sensors subgroup	MWR	Sentinel 3
SAR	Synthetic Apertur Radar subgroup	ASAR	Sentinel 1
TM	Terrain Mapping subgroup	-	-

Table 1: satellite sensor classification

In a section 2, we will briefly describe the calval general approach for all of them as reported in ref. 1. Our work will mostly focus on the IVOS group, and in section 2, we will list the common features between the groups of sensors.

In section 3, based on a literature review, we will give in details the calval requirements for the IVOS sensors

In section 4, based on a literature review, we will report the existing calibration methods will be compiled with the expected associated accuracies. An applied sensitivity study to the different IVOS sensors will be made: the study will identify the influence of all the parameters involved in the process of vicarious calibration or cross-sensor calibration. Among others, the influence of the geometry, the BRDF, the terrain characteristics, the sensor response non linearity, the satellite and ground instrument spectral responses, the radiative transfer model assumptions (aerosol type, vertical structure, optical properties, vertical profiles of atmospheric gases, etc…) will be evaluated and documented.

In section 5, a review of required tools for calval first in terms of in situ data and associated protocols and second in terms of radiative transfer softwares/tools.

2. Generality on the CalVal

2.1. Relevant general information for calval for ENVISAT instrument

2.1.1 GOMOS

The Global Ozone Monitoring by Occultation of Stars (GOMOS) Instrument aims at ozone monitoring. It is a tool to provide altitude-resolved global ozone mapping and trend monitoring with very high accuracy, as needed for the understanding of ozone chemistry and for model validation. GOMOS operates in the 250 nm to 690 nm.

The basis principle of the occultation is first to aim a reference source outside of the atmosphere and second to see the same source on a slant path, tangent to a given altitude. The ratio gives a slant atmospheric transmission which by definition does not require any level 1 calibration. At a second stage, this slant atmospheric transmission is converted into a vertical atmospheric transmittance. Knowing the solar irradiance, it is then possible to get the irradiance at any level. But, again, this transformation does not require any specific radiometric calibration but an accurate knowledge of the solar irradiance.

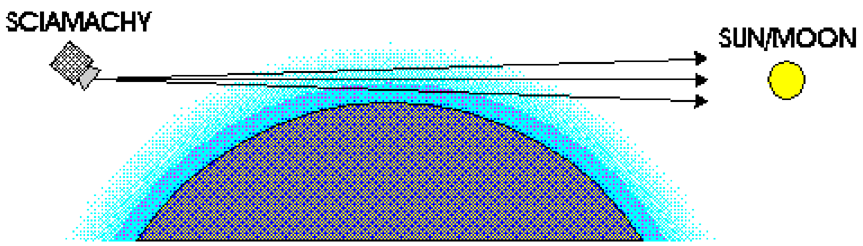


Figure 1: The principle of occultation (from ENVISAT web site, here for SCIMACHY)

Level 2 products are the vertical distributions of atmospheric gases and of the aerosols in the stratosphere and on the high troposphere.

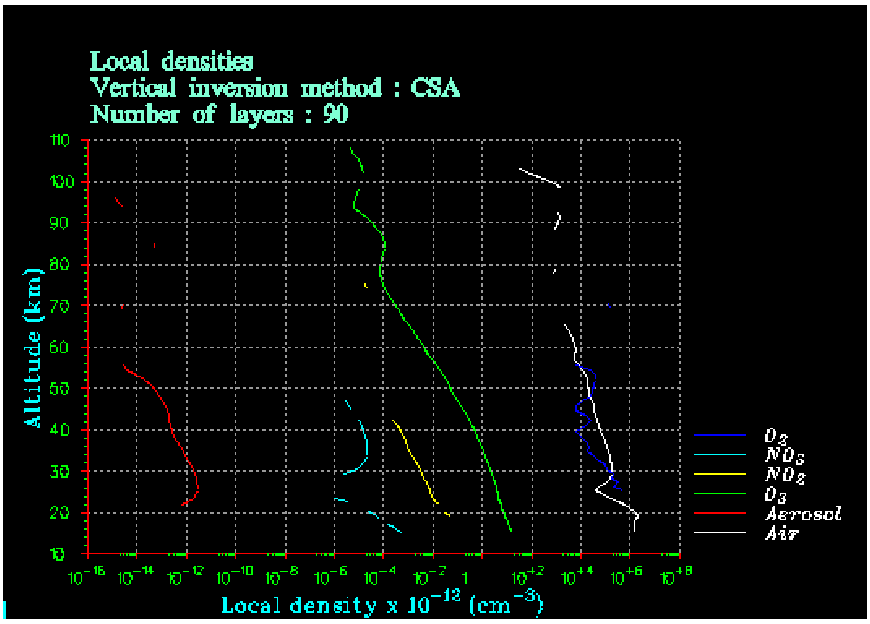


Figure 2: Profiles of local densities for all gases (from ENVISAT web site)

2.1.2 MIPAS

The **M**ichelson **I**nterferometer for **P**assive **A**tmospheric **S**ounding (MIPAS) is a Fourier transform spectrometer for the measurement of high-resolution gaseous emission spectra at the Earth's limb. It operates in the near to mid infrared where many of the atmospheric trace-gases playing a major role in atmospheric chemistry have important emission features.

MIPAS measures spectrally and radiometrically calibrated limb emission spectra in the 685-2410 cm^{-1} wave number range (5 bands: 685-970 cm^{-1}, 1020-1170 cm^{-1}, 1215-1500 cm^{-1}, 1570-1750 cm^{-1}, 1820-2410 cm^{-1}). Offset measurements are done looking at the deep space (a "cold": scene, i.e. a scene with negligible infrared radiance). The "warm" measurement, i.e. a measurement with a relatively high radiance, gives the gain. It is performed while the instrument is looking at an internal source. This source is a well characterized calibration *blackbody* with a controlled temperature. The baseline is to look at the internal calibration blackbody once a week.

Level 2 products are localized vertical profiles of *p*, *T*, O_3, H_2O, CH4, N2O, HNO3.

2.1.3 SCIAMACHY

SCIAMACHY is an imaging spectrometer whose primary mission objective is to perform global measurements of trace gases in the troposphere and in the stratosphere. The solar radiation transmitted, backscattered and reflected from the atmosphere is recorded at relatively high resolution (0.2 µm to 0.5 µm) over the range 240 nm to 1700 nm, and in selected regions between 2.0 µm and 2.4 µm. SCIAMACHY benefits from the GOME heritage but thanks to addition spectral domain and bands, SCIAMACHY offers the possibility to detect more gases as illustrated in figure 2.

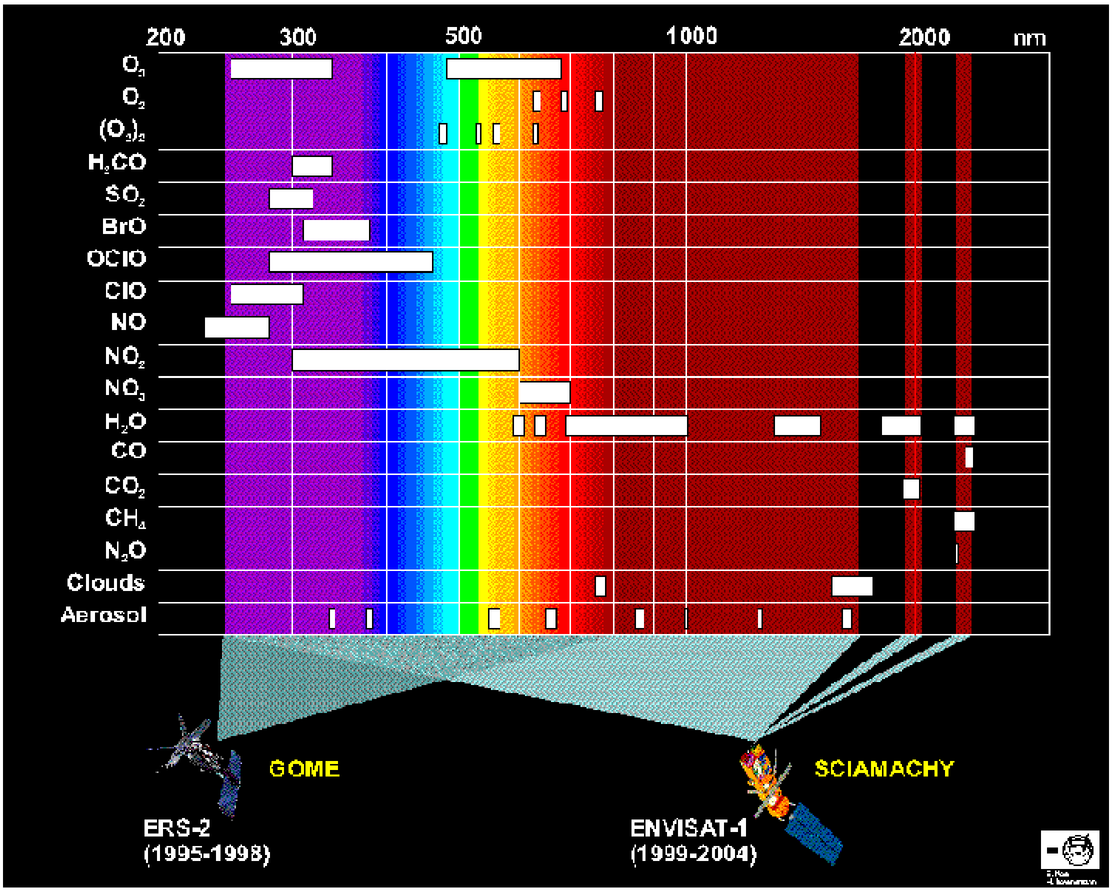


Figure 3: The new molecules detected by SCIAMACHY thanks to the new IR channels

(from ENVISAT web site)

In spite of the GOME heritage, SCIAMACHY is a new instrument to operate with new viewing geometries such as limb, including sun and moon occultations.

Differential optical absorption spectroscopy is applied in sun and moon occultation measurements. This technique is very similar to GOMOS and outputs a slant atmospheric transmission which by definition does not require any level 1 calibration.

Both limb and nadir views give radiances which are calibrated first thanks to the calibration module. The calibration module provides spectral and relative radiometric calibration capability internal to the SCIAMACHY instrument. It is a series of mirrors and lenses which injects into the optical path the light of two possible calibration lamps: white lamp calibration and spectral lamp calibration. The occultation mode allows a radiometric calibration both on the sun and on the moon. Also, the sun is used in several instrumental arrangements and pointing modes by reflection on a standard panel as well as by attenuation through neutral density filters.

Calibration Mode	Description
Sun calibrations	At the end of each solar occultation,
Moon calibrations	At the end of the moon occultation
Sun measurement via a diffuser/ neutral density filter out	The geometry is similar to the above solar calibration modes except that the back side of the elevation mirror which quipped with a diffuser is used.
Sun measurement via a diffuser/ neutral density filter in	Same as above except that a neutral density filter is inserted in the optical paths.
Subsolar calibration	This solar calibration is performed by a special window and uses only the nadir/elevation mirror.
White lamp calibration	internal tungsten-halogen lamp which provides a smooth illumination (black body) over the whole SCIAMACHY spectral range
Spectral lamp calibration	internal platinium-chromium-neon lamp which provides thin emission lines with stable and known wavelengths

Table 2: SIAMACHY internal calibration protocols

Level 2 NRT products are based on nadir measurements only. Limb and sun/moon occultations will be processed by off-line processors. The main content of this product as detailed in the table below will be:

- Vertical column amounts of O_3, NO_2, H_2O,N_2O, CO, CH_4,OClO, H_2CO, SO_2
    - In the UV/VIS regions, the retrieval will be based on DOAS (Differential Optical Absorption Spectroscopy)
    - In the near-infrared, a new algorithm called BIAS is currently under development.
- Cloud fractional cover and top height
    - The algorithm will be based on ICFA (Initial Cloud Flagging Algorithm) which is currently used on GOME and is based on the absorption depth of the Oxygen A-band around 765 nm.
- Aerosol absorption indicator
    - The algorithm will be based on techniques already used for TOMS.

Level 2 Off-Line products are based on nadir/limb measurements and sun/moon occultations

NADIR

- Vertical column amounts of 0_3, NO_2,OClO, SO_2 , H_2CO, BrO
- In the UV/VIS regions, the retrieval will be based on DOAS (Differential Optical Absorption Spectroscopy)
- In the near-infrared an algorithm called BIAS (Basic Infra-red Absorption Spectroscopy) will be used.
- Cloud fractional cover and top height

- The algorithm will be based on ICFA (initial Cloud Flagging Algorithm) which is currently used in GOME. It is based on the absorption depth of the Oxygen A-band around 765 nm.
- Aerosol absorption indicator.
- The aerosol absorbing indicator algorithm (AAIA) will be used.
- Algorithms are identical to their NRT counterpart.

LIMB and OCCULTATION

- Stratospheric profiles of 0_3, NO_2, BrO, H_2O,N_2O,CO,CH_4, Pressure, Temperature
- Stratospheric profiles of Aerosol

2.1.4 MERIS

MERIS is a 68.5 o field-of-view push broom imaging spectrometer that measures the solar radiation reflected by the Earth, at a ground spatial resolution of 300m, in 15 spectral bands, programmable in width and position, in the visible and near infra-red. MERIS allows global coverage of the Earth in 3 days.

The MERIS Level1b data products consist of calibrated top of the atmosphere radiances, geo located and re sampled on a regular grid. The product will be structured by measurement data sets consisting of a complete orbital segment of a single spectral band.

The MERIS Level 2 products are a distributed mixture of geophysical products and reflectances. The product format is called distributed because the geophysical quantity found in the different data sets changes according to the different surfaces measured. The different product groups are: ocean colour products, land and cloud products. The classification between the different product groups, ocean, land and cloud will be made on a pixel by pixel basis by using the a priori determination of Level 1b further consolidated by the use of radiometric tests at level 2. The Level 2 classification information will be provided on a pixel by pixel basis in the flag measurement data set.

Ocean	**Land**	**Cloud**
Water vapour content	Water vapour content	Water vapour content
Algal pigment I	MGVI	Cloud top pressure
SM - YS *	BOAVI	Spare
Algal pigment II	Spare	Spare
FPAR	Surface pressure	Cloud albedo
Aerosol t & e	Aerosol t &e	Cloud t & type
Flags	Flags	Flags

Table 3: The MERIS level-2 geophysical products

The calibration is performed at the orbital South Pole, where the calibration diffusers are illuminated by the sun by rotating a calibration mechanism. Two identical diffusers are available. There are three types of calibration and associated operational scenarios.

Radiometric calibration will be performed every two weeks using diffuser one. A monitoring of the degradation of the *BRDF* of diffuser one will be performed every three months by deploying diffuser two and comparing the results.
Spectrometric calibration will be performed every three months by first performing a radiometric calibration with appropriate band settings for the spectral calibration under consideration, and deploying the erbium-doped diffuser with the same band settings on a second orbit. Two erbium spectral absorption features will be used, one in the green and one in the NIR. Additionally, a high-precision spectrometric calibration for the O2A absorption bands will be performed by exploiting the shape of the absorption band.

2.1.5 AATSR

The prime scientific objective of the **A**dvanced **A**long **T**rack **S**canning **R**adiometer (AATSR) is to establish continuity of the ATSR-1 and ATSR-2 data sets of precise sea surface temperature (SST), thereby ensuring the production of a unique 10 year near-continuous data set at the levels of accuracy required (0.3 K or better) for climate research and for the community of operational as well as scientific users who have been developed through the ERS-1 and ERS-2 missions. The SST objectives are met through the use of thermal infrared channels (centred on 1.6 microns, 3.7 microns, 10.7 microns, and 12 microns), identical to those on ATSR-1 and 2, plus the (A)ATSR's unique two-angle view of the Earth's surface. Atmospheric modelling for ERS-1 has shown that ATSR, with its thermal IR channels and two-angle viewing geometry, can achieve a global accuracy in SST of better than 0.5 K.
The second objective is to develop and exploit the science of quantitative remote-sensing of land surfaces, particularly vegetation, through the use of the improved visible-wavelength atmospheric correction that is achievable with AATSR's two-angle view. The principle two visible channels are at 0.87 microns and 0.67 microns respectively and provide measurements of vegetation index in the same way as AVHRR. With the atmospheric correction improvement, the system has the capability for making global measurements at 1 × 1 km resolution at nadir. An additional visible channel at 0.55 microns, to indicate, from chlorophyll content, the growth stage and health of vegetation, has also be incorporated.
The primary Level 1B product comprises calibrated and geolocated images of brightness temperature (for the three infra-red channels) or reflectance (for the near-visible and visible channels), together with cloud and land identification.
The thermal calibration is ensured by two black body reference targets viewed on each scan, with one at roughly at 265K and the other at 305K, as this is expected to encompass the full global range of SSTs. The calibration sources are designed such that

uncertainties in the radiance from them will not exceed an equivalent temperature error of more than 100mK throughout the mission. The visible calibration needs two sources for gain and offset measurements. By using one of the thermal calibration sources as a zero radiance calibration point, only one source of higher radiance is necessary. The calibration system for the reflection channels (VISCAL) provides a stable source for calibration once per orbit, using sunlight to illuminate a diffusing plate.

Level 2 products are as follows:

- Derivation of Sea Surface Temperature (SST) and other parameters from the regridded brightness temperatures.
- Generation of averaged brightness temperatures and reflectances from the regridded brightness temperatures and visible channel reflectances.
- Derivation of averaged SST from the averaged brightness temperatures, and of NDVI from the averaged reflectances.

2.1.6 MWR

The main objective of the microwave radiometer (MWR) is the measurement of the integrated atmospheric water vapour column and cloud liquid water content, as correction terms for the radar altimeter signal. In addition, MWR measurement data are useful for the determination of surface emissivity and soil moisture over land, for surface energy budget investigations to support atmospheric studies, and for ice characterization.

The MWR is a nadir-viewing, two channel, passive microwave radiometer operating at 23.8 and 36.5 GHz. At these two frequencies, it receives and measures microwave radiation generated and reflected by the Earth. The signals received can be related to surface temperature but, most importantly, combined together they provide an estimate of the total water content in the atmosphere, which will be used to correct for the altimeter measurements path delay. The MWR has a 20 km diameter field of view.

2.1.7 ASAR

ASAR consists of a coherent, active phased array SAR (i.e., distributed transmitter and receiver elements) which is mounted with the long axis of the antenna aligned with the satellite's flight direction (i.e., Y-axis). The SAR antenna with its two-dimensional beam pattern images a strip of ground to the right side of the flight path which has potentially unlimited content in the direction of motion (i.e., the azimuth direction) but is bounded in the orthogonal direction (i.e., the range direction) by the antenna elevation beam width. The objective of the SAR system is to produce a two-dimensional representation of the

scene reflectivity at high resolution, with axes defined in the range and azimuth direction. The ASAR operated at C-band (5.331 GHz). It can be operated continuously for 30 minutes in a high-resolution mode for each orbit. Its application covers observations of land and sea characteristics under all weather conditions.
The objective of the ASAR instrument internal calibration scheme is to derive the instrument internal path transfer function, and to perform noise calibration. This objective is realised by dedicated calibration signal paths and special calibration pulses within the instrument for making the required calibration measurements and by using these measurements to perform corrections within the ground processor.
The external calibration scheme with the objective to derive the overall calibration scaling factor uses the successful methodology developed for ERS-1/2 for the narrow swath mode. Three specially built high precision transponders with a radar cross section high enough compared to background backscattering coefficient and noise are deployed across the ASAR swath and observed several times during every 35 days orbit cycle. Images acquired over suitable area of the Amazon rain forest were be used to derive the in-flight elevation antenna pattern. Absolute calibration factors derived from transponder measurements and across swath correction derived from the radar equation were be used to calibrate the final image product. For the wide swath mode using the scansar technique the external calibration approach is similar to the one used for the narrow swath mode.

2.1.8 TM

Landsat satellites travel along a sun-synchronous orbit over the North and South poles, at roughly right angles to the equator, at an altitude of about 700 km. They circle the Earth 15 times a day, and return to their starting point every 16 days. Observed data are provided in 185 km X 170 km scenes. Landsat carries two instruments TM and MSS. TM has 6 bands from the visible to the medium infra red with 30 m spatial resolution. Band 6 is in the thermal domain (around 10 µm) with a spatial resolution of 120 m (60 m since Landsat-7).
Level 1 are radiances and, for band 6, the radiance is converted into a at satellite temperature. The internal calibration consists in the use of a lamp for the solar bands and a black body for band 6.

2.2 **Calibration synergy between sensors**

The driving point is to cover the same spectral domain. Table 4 provides an overview of the spectral domains cover by the different sensors. Except for the radars, we have clear spectral intersections between sensors. Therefore the synergy first exists through the onboard calibration approaches. The sun is used as a reference source for SIAMACHY, MERIS and AATSR, with for the three by the mean of a standard spectralon panel which reflects the solar irradiance. In the thermal domain, a back body cavity is used for several sensors (AATSR, MIPAS, SIAMACHY, TM).

SENSOR	**SPECTRAL DOMAIN**
GOMOS	UV-Visible (250 nm -675 nm, $\Delta\lambda$=0.3 nm) , Near Infra Red (756 nm -773 nm and 926 nm -952 nm, $\Delta\lambda$=0.05 nm)
SCIAMACHI	UV (240 nm-314 nm, $\Delta\lambda$=0.24 nm; 309 nm-405 nm, $\Delta\lambda$=0.26 nm) Visible (394 nm-620 nm, $\Delta\lambda$=0.44 nm; 604 nm-805 nm, $\Delta\lambda$=0.48 nm) NIR (785 nm-1050 nm, $\Delta\lambda$=0.54 nm;1000 nm-1750 nm, $\Delta\lambda$=1.48 nm) Medium Infra Red(1940 nm-2040 nm, $\Delta\lambda$=0.22 nm ; 2265 nm-2380 nm, $\Delta\lambda$=0.28 nm)
MIPAS	Thermal Infra Red (4150 nm -14600 nm, $\Delta\lambda$=30 nm) in 5 spectral domains
MERIS	Visible and NIR (390 nm-1020 nm, $\Delta\lambda$=1.25 nm), 15 bands are recorded
AATSR	Visible (0.55 nm and 0.67 nm), NIR (0.87 nm), MIR (1600 nm and 3700 nm), Thermal (10.7 µm and 12 µm)
MWR	23.8 and 36.5 GHz (12 m and 8 m)
ASAR	5.331 GHz (56 m)
TM	Visible (0.45-0.52 µm; 0.52-0.60 µm; 0.63-0.69 µm) NIR (0.76-0.90 µm) MIR (1.55-1.57 µm); Infrared (2.08-2.35 µm) Thermal Infrared (10.4-12.5 µm)

Table 4: The spectral characteristics

Cross calibration activities are allowed for sensors aiming the same target simultaneously or within a short time period. The nadir view is available for SIAMACHY, MERIS, AATSR and TM which makes it potentially available. The cross calibration mostly concerns radiometric calibration but may apply as well to spectral calibration. The high spectral resolution of SIAMACHY offers the possibility to achieve a spectral calibration of MERIS but also of AATSR.

2.3 Validation synergy between sensors

Between the atmospheric sensors, there is a clear set of common products corresponding to atmospheric gases. These experiments mostly concern the stratosphere which implies the common use of stratospheric balloons and high altitude aircrafts.

MERIS and AATSR are both oceanographic sensors. If the products are complementary, they can share the same cruise logistic for validation.
MERIS and AATSR provide both atmospheric products (mostly on aerosol) which can be compared with SIAMACHY outputs.

3. Detailed CalVal Requirements for the VOS sensors

3.1 Parameters subject to calibration

3.1.1 Basic definitions

The incoming signal is a radiance L ($W/m^2/sr$) integrated over the spectral response S(λ).Generally, we define the equivalent radiance $L^e(w/m^2/sr/\mu m)$ as:

$$L^e = \frac{L}{\int_0^\infty S(\lambda)d\lambda} \quad (1)$$

in order to normalize the radiance by the filter response.
Introducing the mean solar irradiance $E_S^e\ (w/m^2/\mu m)$:

$$E_S^e = \frac{\int_0^\infty S(\lambda)E_S(\lambda)d\lambda}{\int_0^\infty S(\lambda)d\lambda} \quad (2)$$

We can use as well the normalized radiance L^* (no unit), defined by

$$L^* = L^e \frac{\pi .d^2}{E_s}, \quad (3)$$

in which d is the Sun to Earth distance (in AU).

Two possible scenarios exist: the sensor has been calibrated on a reference source and therefore an accurate knowledge of E_S is required. That requires specific research activities (1, 2) and debates on what is the best solar irradiance data base. For selecting a suitable extraterrestrial solar reference spectrum for reflective channels of space sensors two sources of uncertainties have to be taken into account: the variation of the solar activity and uncertainties in the experimental data. The variation of the solar activity depends on time (e.g. the solar output change depending on the 11-year solar cycle and the 27-day solar rotation). This change causes a variation of the solar constant (E_0= 1366.1 Wm^{-2}) in a magnitude of about 0.4 % (maximum-to-minimum rage: 1363 to 1368 Wm^{-2})[i]. The solar output varies with time at a rate of change, which is a function of the wavelength. In the UV (1-400nm) the changes are in the order of 1-10% and in the VIS and SWIR less than 1%.

However, this solar variation in the VIS-SWIR is small when compared to the discrepancies in absolute spectral irradiance ($Wm^{-2}\mu m^{-1}$) between various experimental data. The uncertainties in the experimental data are attributed to (1) discrepancies between calibration standards and (2) problems in the measurement procedure and ageing.

1. Unfortunately there is a divergence between national calibration standards sources, which reach values of $\pm$2% in the VNIR spectral region[ii]. This discrepancy depends on the wavelength. In the UV and NIR the uncertainties are higher as in the VIS.
2. Discrepancies might occur because of uncertainties in the measurement procedures and solar observatory location, e.g. for ground observatories the absorption bands have to be accounted for and an ageing problem occurs for space sensors when performing the measurements in space environment.

The second possibility is that the radiometric calibration is done by reference to the sun. In that case, the introduction of the normalized radiance allows removing the knowledge of the solar irradiance, which is a source of error.

1. Neckel, H. and D. Labs, The Solar radiation between 3300 and 12500 Å, Sol. Phys. Vol. 90; pp. 205-258 (1984)

2. Thuillier, G., M. Herse, P. C. Simon, D. Labs, H. Mandel, D. Gillotay, and T. Foujols, The visible solar spectral irradiance from 350 to 850 nm as measured by the SOLSPEC spectrometer during the ATLAS-1 mission, Solar Physics, Vol. 177, 41-61, 1998

3.1.2 Calibration

We consider a perfect instrument with:

(i) No smear effect.

(ii) No stray light.

(iii) Perfectly linear.

The first parameter to characterize is the spectral response S(λ). Different representations exist. First, S(λ) is provided at discrete value with a step $d\lambda$. Second, S(λ) is represented as well by the mean wavelength λ_m defined as:

$$\lambda_m = \frac{\int_0^\infty S(\lambda)\lambda\, d\lambda}{\int_0^\infty S(\lambda)d\lambda}, \quad (4)$$

and by the bandwidth $\Delta\lambda$. S(λ) is subject to on board as well as to vicarious calibrations.

The basic calibration equation is:

$$L^e = A^e.DC \quad (5)$$

The digital counts DC recorded at sensors have been corrected from the dark current. Equation (5) states that the detector is perfectly linear. Of course, this calibration equation can be applied as well to the normalized radiance L^*:

$$L^*_{i,j} = A^*_{i,j}.DC_{i,j} \qquad (6\text{-a})$$

In Equation (6-a), we added the subscript j, for a given spectral band, and the subscript i, for a given detector. This Equation (6-a) applies when only one gain G is used. In cause of possible gain changes, G is introduced with:

$$L^*_{i,j} = A^*_{i,j}.G_{i,j}DC_{i,j} \quad (6\text{-b})$$

The other critical point is the equalization of the detectors. A uniform incident light should give the same radiance DC for the same spectral band. This detector equalization consists in correcting the digital counts as:

$$DC^*_{i,j} = EQ^*_{i,j}.DC_{i,j} \quad (7)$$

In Equation (7), we introduced a equalization factor $EQ^*_{i,j}$ which is derived for an uniform incident light. A reference detector i_0 is chosen to define it as:

$$EQ^*_{i,j} = DC_{i,j} / DC_{i_à,j} \qquad (8)$$

After the detector equalization, we introduce the calibration coefficient A^*_j for band j as:

$$L^*_{i,j} = A^*_j.DC^*_{i,j} \qquad (9)$$

Equations (7), (8) and (9) allow decoupling detector equalization and radiometric calibration.
The entire above calibration coefficient apply both to onboard and pre-flight calibration. While in space, the other calibration coefficients of interest are:

A corrective factor to the current calibration:

$$c^*_j(t) = L^*_{1,j}(t) / L^*_{sim,j}(t_o) \quad (10)$$

which correspond to the ratio of the current level 1 radiance to it estimation done during vicarious calibration. This corrective factor is independent of the detector and that implicitely suppose than the equalization of the detectors is well controlled else where (assumption that all the detectors degrade on the same way or possibility to monitor onboard the detector equalization).

The inter temporal calibration coefficient, which tracks the instrument degradation at time t by reference to an initial time t_o:

$$A_j^*(t,t_o) = A_j^*(t) / A_j^*(t_o) \quad (11)$$

As with any optical system, there will be degradation of the optical surfaces due to high energy particles and UV radiation, resulting in a gradual drift of the calibration level. Using data from a number of large, spatially uniform and temporally stable sites, we have been able to determine the calibration drifts (see ref. [2]). The analysis yielded a drift function of the form

$$D = exp(-kt/365) \quad (12)$$

where t is the number of days since launch and k the drift rate per year.

the inter band calibration, defined by reference to band j_o, as:

$$A_{j,j_o}^*(t) = A_j^*(t) / A_{j_o}^*(t) \quad (13)$$

Of course, both inter temporal calibration and inter band calibration can be defined on c_j^*

We now consider the spectral calibration. Ideally, we want to monitor the possible variation of the spectral response S(λ). On a practical point of view, a spectrally detailed description S(λ) is of is not always mandated depending on the sensors and/or on the product derived from a specific band.

3.2VOS mission specifications for the calibration requirements

The engineering requirements on one instrument are derived from the mission requirements. Actually, it is a compromise between the mission requirements and the possible technical/scientifical achievements. As example, for MERIS, they are as follows:

- Radiometric accuracy: Less than 2% of detected signal, relative to sun
- Band-to-band accuracy: Less than 0.1%
- Band-centre knowledge accuracy: Less than 1 nm

The requirements for SeaWiFS (3) has been for the visible range 5% for absolute value (McClain et al., 1992, 1998) and 2 percent for relative values (reflectance). We then retrieve the 2 percent MERIS requirement.This statement clearly refers to the sun and therefore this requirement applies to the normalized radiance and to the calibration coefficient as defined in Equation (6-a).

For SeaWiFS, the radiometric calibration requirement of 5% absolute is understood as starting before launch The radiometric calibration performed before launch and transferred to orbit is accurate to about 3% (4). The difference between 5% for absolute value and 2 percent for relative values

The band-to-band accuracy make reference to the interband calibration. The band centre knowledge accuracy to 1 nm results from the mission specification. It does not fully cover the spectral calibration which involves as well the bandwith.

3. McClain, W. E. Esaias, W. Barnes, B. Guenther, D. Endres, S. B. Hooker, B. G. Mitchell, and R. Barnes, *SeaWiFS Calibration and Validation Plan*, NASA Tech. Memo. 104566 3, S. B. Hooker and E. R. Firestone, Eds., NASA Goddard Space Flight center, Greenbelt, Md., 1992.

4. Barnes, R. A., R. E. Eplee Jr., S. F. Biggar, K. J. Thome, E. F. Zalewski, P. N. Slater, and A. W. Holmes, SeaWiFS transfer-to-orbit experiment, *Appl. Opt.*, 39, 5620-5631, 2000.

3.3Calibration requirement for a specific VOS level 2 product.

3.3.1 Ocean applications

Typically 90% of the measured radiance in the blue and green originates from the atmosphere and surface (5), i.e., does not contain any information on the water body. In other words, if the perturbing effects were removed perfectly, a 2% accuracy in top-of-atmosphere radiance would translate into a 20% accuracy in useful signal, which is in this case the water leaving radiance. The consequences on the water products are not so direct. For case one water, the chlorophyll concentration directly results from a two band ratio and therefore the interband calibration requirement is important as well. For ocean case 2, inverse techniques take advantages of the multispectral dimension of the sensor which involves again the interband calibration.

5. Gordon, H.R., Calibration requirements and methodology for remote sensors viewing the ocean in the visible, Remote Sensing of Environment, Vol. 22, 103-126, 1987

3.3.2 Land applications

They are no clear indications neither on the radiometry nor on the spectral requirements. When land applications rely on spectral indices (such as the well known NDVI), then once can believe than the requirements are mostly on the interband calibration. When a spectral index is very sensitive to the exact spectral response of the bands, then a good spectral calibration should be ensured. It is the case in the so-called red edge: the MTCI product proposed in the MERIS level 2 is sensitive to the smile and therefore requires a good spectral characterization. When land products rely on reflectance, then it is widely accepted that the requirements driven by an ocean mission are sufficient to ensure the quality of the product. Because often, ocean and land missions are combined, land people are more than happy with the ocean people requirements.

3.3.3 Atmospheric applications

The situation is quite similar to the land. Specific requirements arise when an atmospheric product is based on absorption lines. In those cases, the spectral response of the involved band should be accurate. For example for MERIS, the specification in the knowledge on the central wavelength is 1 nm. The use of the oxygen band at 761 nm imposes to do better than that, around 0.1 nm.

🗐✍Methodologies for VOS sensor calibration

4.1 On board calibration

4.1.1 Dark current measurements

In the complete dark, a sensor measures a signal which has to be substracted. Different techniques to measure this dark current are available. Deep space can be observed under different circumtances: maneuvre of the spacecraft (for example within the frame of the moon calibration); edges of the camera for large FOV sensors; camera shutters; over nigth views of non illuminated targets (open ocean, deserts);…

4.1.2 Lamp as reference source

Standard lamps were used for onboard calibration. For SPOT-1-HRV, the inter temporal calibration was monitored by a lamp (6).

6. Dinguirard M., Maisonneuve J.M., 1980 ; Dispositif d'étalonnage sur le soleil de la camera HRV du projet SPOT. *XXth International Scientific Meeting on Space, Rome.*

4.1.3 Sun as reference source

Solar-illuminated diffuse reflectance panels are used for in-flight calibration of imaging systems used in earth-observing satellite instruments (7). Spectralon diffuse reflectance material was developed specifically for this application, and has become the material of choice in the remote sensing community.
Typically, a Spectralon diffuser panel is deployed into the instrument's field of view at specific points in the orbit of the satellite platform. The panel is illuminated by the sun at precisely-known angles and irradiance levels. The spectral reflectance factor of the Spectralon panels is calibrated on-ground (8 and annex 4.1.3), so that the reflected radiance presented to the instrument is known. The response of the instrument to this known spectral radiance can therefore be used to verify the instrument's calibration, and to recalibrate as-needed.

7. Barnes, R.A., and R.E. Eplee Jr., The SeaWiFS solar diffuser, In R.A. Barnes, E-N. Yeh, and R.E. Eplee Jr. Eds., SeaWiFS Calibration Topics, Part-1, NASA Technical Memo-104566 (NASA/GSFC-Goddard Space Flight Center), Greenbelt (MD), Vol. 39, 1703-1712, 1996.

8. G. Bazalgette Courrèges-Lacoste, J. Groote Schaarsberg, H. V Brug, R. Vink, B. Snijders. Spectral Features on Reference Diffusers. Procceding of the MERIS AATSR calval workshop, Frascati, 2003. Available at: http://envisat.esa.int/workshops/mavt_2003_ver1/Session1.pdf.

4.1.4 **Moon as reference source**

The moon is an invariant source with an appropriate radiance range for Earth-viewing instruments. From a polar orbit, the moon is a non uniform objet of 6 km size. At the same phase angle, in order to remove the angular dependance of it reflectance, the moon is a reference target for intertemporal calibration (9,10) and for inter sensor comparison. Absolute calibration with the moon still requires accurate characterization of it complex photometric behavior.

9. Kieffer, H.H., and R.L. Widley, Establishing the moon as a spectral radiance standard, Journal of Atmospheric and Oceanic Technology, Vol. 13, 360-375, 1996.

10. Barnes, R.A., R.E. Eplee Jr., F.S. Patt, and C.R. McClain, Changes in the radiometric sensitivity of SeaWiFS determined from lunar and solar-based measurements, Applied Optics, Vol. 38, 4649-4664, 1999.

4.1.5 **Spectral calibration**

One cause for the loss of radiometric sensitivity of an instrument can be a variation of its filter response. For example, the long term effect of vacuum on the interferometer filter of the SPOT (Satellite Probatoire pour l'Obversation de la Terre) HRV (Haute Résolution Visible) sensor resulted in a narrowing of the filter's bandwidth, This effect was characterized in laboratory which twin filters to those than equipped SPOT-4 HRV. These filters were kept in vacuum and spectrally characterized. Of course, a more direct way of monitoring an instrument's filter response is to embark a specific device for spectral calibration as was done for MODIS where a spectrometer is used (http://modis.gsfc.nasa.gov/about/srca.html).

The spectral calibration of MERIS (annexe 4.1.5) is done in two steps using the on-board Erbium doped diffuser plate. First, the instrument is configured to have 15 adjacent bands - at the highest spectral resolution - centred on the selected spectral feature, and the pixels are calibrated using the radiometric "white" calibration diffuser, the following orbit the "pink" diffuser is deployed and the signal from this spectral feature acquired. Processing on ground determines the position on the detector array of the peak of the Erbium absorption feature.

S. Delwart Introduction: MERIS 1 st Year Calibration Results. Presentation during the MERIS AATSR calval workshop, Frascati, 2003 Available at:http://envisat.esa.int/workshops/mavt_2003_ver1/Session1.pdf

4.1.6 The on board calibration of the VOS

Table 6 overviews the onboard calibration devices use by different sensors. The standard lamp is no longer used while the most frequent reference for radiometric calibration is the standard panel illuminates by the sun.

sensor	(a)	(b)	(c)	(d)
AATSR			X	
ASTER		X		
GLI			X	
Hyperion		X		
MERIS			X	X
MISR		X	X	
MODIS		X	X	X
SeaWiFS		X	X	

Table 5: The onboard calibration on different sensors:
(a) lamp, (b) moon, (c) sun and (d) spectral calibration.

4.2 Vicarious calibration

4.2.1 Using brigth land test sites for absolute calibration

4.2.1.1 Methodology

The radiance based method

The principle is very simple:

(i) you have a radiometer equipped with the same spectral bands than the satellite sensor you want to calibrate or a spectrometer (see Annex 4.2.1.1.a).

(ii) this reference radiometer is well calibrated in laboratory and

(iii) you flight with your radiometer at the same time and in the same geometry that the satellite sensor. The approach has the following advantages: (a) the measured radiance of aircraft and the space sensor can be compared directly when both view the same ground pixel at the same time, (b) the uncertainty because of temporal effect due to changing atmospheric parameters can be reduced when aircraft sensor is flying well above the boundary layer of the atmosphere, (c) aircraft sensors allow sampling over a large ground site what is obligatory for the calibration and validation of coarse spatial resolution sensors (e.g. MERIS, MODIS) and (d) in contrast to the space borne counterpart

Of course the higher the aircraft is and the closer you are from the space conditions. For land observations over bright sites, (12), such as White Sands, NM, USA, we can directly compare the two sensors after ozone absorption correction which is the unique atmospheric effect which differentiates the two measurements.

They are two disadvantages to this method. First, the use of aircraft is very expensive and (ii) you loss accuracy when transferring from a lamp to the sun your calibration. It is the debate between calibration in radiance and reflectance.

The reflectance based method

For the SPOT1-HRV sensor, the inter calibration with the lamp (on board calibration) was assumed to provide the relative sensitivity loss with time. In order to get absolute value of calibration factors, data obtained from lamp measurements was completed with field measurements on a routine basis using test sites like White Sands [13] (New Mexico) and La Crau [14] (France). The main problems encountered by these kinds of campaigns are the fact that it takes a lot of time and human resources to lead one and they are subjected to meteorological conditions. These are the reasons why, the data base given by these campaigns is reduced. In principle, vicarious calibration associates digital counts recorded by the satellite sensor to prediction of the incoming radiance to the sensor. To evaluate this signal, we must both characterise the atmosphere and the ground. Details on this method are provided in Annex 4.2.1.1.b

The radiance based method can be applied as well from the surface level. The surface leaving radiance has to be transported to the satellite level and the atmospheric contribution to be added. Example is given is [15] and an inter comparison between radiance and reflectance based method is reported in [16].

12. Hovis, W. A., J. S. Knoll, and G. R. Smith, Aircraft measurements for calibration of an orbiting aircraft. Appl. Opt., **24**, 407-410, 1985.

13. Begni G., Dinguirard M., Jackson R., Slater P., 1986 ; Absolute calibration of the SPOT-1 HRV cameras. Proc. SPIE 660:66-76

14. Santer R., Deuzé J.L., Devaux C., Vermotte E., Guyot G., Gu X., Verbrugghe M. (1991). In-flight calibration of SPOT1-HRV over La Crau. Remote Sens. Environ., 41, p 227,237.

15. Biggar S.F., Santer R.P., Slater P.N. (1990). Irradiance-based calibration of imaging sensors. Proceedings of IGARS meeting. Washingtown DC, mai 90.

16. Slater P.N., Biggar S.F., Holm R.G., Jackson R.D., Mao Y., Moran M.S., Palmer J.M. Yuan B., 1987; Reflectance and Radiance based methods for the in-flight absolute calibration of multispectral sensors. Remote Sensing of Environment **22**:11-37

4.2.1.2 Sites

The description of the main land sites use for calibration is available at: http://www.ncaveo.ac.uk/calibration/radiometry/in-flight. Details on the La Crau site are provided in annex 4.2.1.2

4.2.2 Using dark ocean test sites for absolute calibration

4.2.2.1 Methodology

The so-called radiance based method applies over any type of targets and therefore it is a good candidate for vicarious calibration over dark target (17).

The so-called Rayleigh scattering method

The radiance of the light scattered by the air molecules (Rayleigh scattering) can be accurately predicted by radiative transfer codes. Over the ocean, most of the light reflected by the earth-atmosphere system comes from the Rayleigh scattering, and it is possible to minimise the other contributors. The Rayleigh method thus compares the model predicted radiance to the observed radiance to derive an estimation of the absolute calibration coefficient. This method cannot be applied to wavelengths above 700 nm since the Rayleigh scattering radiance becomes too small in the near infrared. The calibration targets are selected in order to minimise the non molecular radiance sources: a clear atmosphere is necessary, above a dark target (ocean, with a low wind speed to avoid foam).

The main error sources for the calibration method are the water reflectance and the aerosol effects. In order to better define the water body contribution, the method is applied to oceanic zones where the chlorophyll concentration is stable and quite well known. The aerosols are the most variable part of the atmospheric radiance and could induce errors in the absolute calibration. Very clear atmospheres are selected using a threshold on the radiance measured in a near infrared band (around 850 nm). Besides, for the selected pixels, the 865 nm radiance is used to determine the expected aerosol radiance in the calibrated band (17). For this extrapolation, it is necessary to rely on an aerosol type. The M98 (Maritime model with 98% of humidity is generally used as the most likely. The overall uncertainty on this calibration method (from 440 to 650 nm) is estimated to 4%).

The Rayleigh based method is generally applied for large FOV sensors. In this case, the method is applied as described in the paragraph above and the outputs are averaged on a significant number of images. But the Rayleigh method can be applied as well to small FOV sensors. It is mostly land sensors which occasionally acquires, on purpose, images over the open ocean. On way to get informations on the aerosol model as well on the water contribution is to use simultaneous images of “ocean colour” sensors which provide at level 2 the relevant information: aresol model and chlorophyle a amount. Annex 4.2.2.1.a illustrates this approach.

17. Green, R., and T. G. Chrien, High altitude measurements of radiance at high spectral and spatial resolution for SIMBIOS sensor calibration, validation, and inter-comparisons, in *SIMBIOS Project 1998 Annual Report*, NASA Tech. Memo. 208645, C. R. McClain and G. Fargion, Eds, 1999.

18. Vermote, E.F., R. Santer, P.Y. Deschamps, and M. Herman, In-flight calibration of large field of view sensors at short wavelengths using Rayleigh scattering, International Journal of Remote Sensing, Vol. 13 (18), 3409-3429, 1992.

19. Hagolle, H., P. Goloub, P.-Y. Deschamps, H. Cosnefroy, X. Briottet, T. Bailleul, J.-M. Nicolas, F. Parol, B. Lafrance, and M. Herman, Results of POLDER in-flight calibration, IEEE Trans. Geosci. Remote Sen., 37, 1550-1566, 1999.

In situ measurements associated to the satellite signal prediction

What is done for vicarious calibration over land (see 4.2.2.1) can be done at sea. Marine reflectance and water leaving radiances can be realized during sea cruises. From a boat, it is possible as well to measure the solar extinction. It is even better to use a platform at sea because of it stability (see annex 4.2.2.1.b). Using a buoy gives access to the marine reflectance and some crude description of the atmosphere thanks to measurements of the downwelling irradiance.

From the in situ data collected at the time of overpass, a RTC can be used to predict the signal at sensor. This approach has been used in the context of the validation of the MERIS onboard calibration (20, 21).

(20) J-M. Nicolas, G. Becu, Vicarious Radiometric Calibration of MERIS Using In-situ Measurements from SIMBADA Radiometer.
Proceedings MERIS AATSR calval workshop, Frascati, 2003 Available at: http://envisat.esa.int/workshops/mavt_2003_ver1/Session1.pdf

(21) D. Antoine, Vicarious Calibration of MERIS over Boussole.
Presentation during the MERIS AATSR calval workshop, Frascati, 2003 Available at: http://envisat.esa.int/workshops/mavt_2003_ver1/Session1.pdf

In situ atmospheric measurements for vicarious calibration in the NIR

Because the water body is dark in the NIR, the satellite results from the atmospheric scattering. Ground based optical measurements, on the coast line or even better in small inlands, offer the opportunity to characterize at the best the atmospheric scattering. The satellite signal over water can be predicted for close pixels to these ground base stations (21, 22 and annex 4.2.2.1.c).

21. Parada, R., K.J. Thome, and R. Santer, Results of dark target vicarious calibration using lake Tahoe.Proceedings of the European Symposium on Aerospace Remote Sensing (SPIE Conference on Image and Signal Processing for Remote Sensing), EUROPTO-III, Taormina (Italy), Vol. 2957, 332-343, 1997

22. Santer, R and N. Martiny, Sky radiance measurements for ocean colour calibration-validation, Applied Optics, Vol. 42 (6), 896-907, 2003.

4.2.2.2 Sites

For the Rayleigh scattering method

This method is applied routinely by CNES. In the southern hemisphere,10 geographic zones have been selected (23) with stability and uniformity criteria, using two whole years (1998,1999) of SeaWIFS level 3 products. All the zones are situated in open ocean regions and correspond to oligotrophic waters. Calibration data from the northern hemisphere that often include desertic or continental aerosols have been discarded.

23. Fougnie, B., P. Henry, et al. (2002). Identification and Characterization of Stable Homogeneous Oceanic Zones: Climatology and Impact on In-flight Calibration of Space Sensor over Rayleigh Scattering. Ocean Optics XVI, Santa Fe, New Mexico.

Measurements at sea

The Venice tower (annex 4.2.2.1.b) offers a permanent facility equipped both to characterize the water leaving radiance and the atmosphere. Boussole (in the Mediterranean Sea) and Moby (Off shore of Hawaii) are two well known buoys devoted to calval activities for ocean colour.

Atmospheric measurements for vicarious calibration in the NIR

The AERONET network, http://aeronet.gsfc.nasa.gov/, (24) contains a substantial number of CIMEL stations set on the coast or in small inlands.

24. Holben, B., T. Eck, I. Slutsker, D. Tanré, J.-P. Buis, A. Setzer, E. Vermote, J. Reagan, Y. Kaufman, T. Nakajima, F. Lavenu, I. Jankowiak, and A. Smirnov, A federated instrument network and data archive for aerosol characterization, Remote Sen. Environ., 66, 1-16, 1998.

4.2.3 Using clouds for absolute calibration

Under certain circumstances (25), it appears possible to predict the satellite signal over clouds. Over ocean, the boundary conditions are known. The other variables are the pressure at the cloud top to derive the Rayleigh contribution above the cloud, the mean size of the droplets and the optical thickness of the clouds. ATSR-2 data has demonstrated that the visible and thermal channels can be combined to estimate a number of specific properties within the cloud field. These include:

- Optical Depth, broadly related to the vertical dimension of the cloud;
- Phase, which determines whether the cloud contains ice or water;
- Particle Size, the effective radiative dimension of the cloud particles; and,
- Pressure, reflecting cloud top pressure or altitude.

The dual views provided by AATSR also offer a stereo viewing capability that can be used to discriminate between the different layers and structures within the cloud and also to estimate cloud top height. AATSR potentiality to be calibrate at high latitudes over cirrus clouds are reported by :

25. C. Poulsen, P. Watts. MERIS/AATSR calibration using Arctic stratus and Tropical Cb clouds.

4.2.4 Using deserts for inter temporal calibration

4.2.4.1 Principle

Some desertic areas are known to have stable reflectances. It is the case for ice and fresh snow. Aerosol type and loading may vary but, except some specific events such as dust storms over deserts, these targets are bright enough to limit the impact of possible temporal variations of the aerosols. At a first order, these targets are lambertian. At a second order, depending on the required accuracy, once have to consider the bi directionality of such sites. Two options are possible:

(i) to keep the same geometrical conditions, then it can be only bi annual survey because of the cycle of the solar elevation.

(ii) to have a BRDF model. Actually, it is a relative BRDF model of the surface+atmosphere system which can be realized at a reference time by a multi view angle sensor such as MISR or POLDER.

4.2.4.2 Desertic sites

Twenty desert sites in North Africa and Arabia have been selected by CNES for their spatial uniformity and temporal stability, using Meteosat data [*26*]. These desertic sites are also quite lambertian and the directional variations of their reflectance can be monitored using another satellite. The best suited instrument for this task is POLDER. Since POLDER data makes a very complete sampling of the directional conditions, it is nearly always possible to find a POLDER acquisition with solar and viewing angles very close to the angles of any sensor measurement. An interval of 2 degrees is generally used for the zenith angles and 5 degrees for the azimuth angles. Reciprocal geometries are also allowed.

In order to estimate the uncertainty of the method, the reciprocity principle on top of atmosphere reflectance has been applied to POLDER data: the error ranges from 3.4% for blue bands to 1.84% for near infrared.

Alternatively to sand sites, dry lakes are very good calibration sites (annex 4.2.4.2)

26. Cosnefroy H., Leroy M., Briottet X., 1996; Selection and characterization of Saharan and Arabian desert sites for the calibration of optical sensors. Remote Sensing of Environment, **58**:101-114.

4.2.5 Using brigth and white targets for inter band calibration

4.2.5.1 Sunglint

The sun glitter radiance is high and spectrally flat and is thus a suitable target for interband calibration. It depends mainly on the geometrical conditions and on the surface roughness. A mirror-like ocean would have a high radiance in the exact specular direction, whereas an agitated sea scatters a lower radiance in a wider cone. Since the surface roughness cannot be accurately predicted, the sun glitter calibration method cannot be used as an absolute calibration method, but only as an interband calibration method. If the Fresnel reflection is white, the interband corrective factor $c^*_{i,j}$, of band j relatively to band i, is simply the ratio of the TOA normalized radiances observed in the sunglint spot:

$$c^*_{i,j} = L^*_{1,i} / L^*_{1,j} \qquad (20)$$

The presence of the atmosphere first reduces the Fresnel reflection (by attenuation on the direct to direct path) and second gives an additional contribution due to the scattering. The TOA reflectance is no longer white and the two band ratio $(L^*_{sim,j} / L^*_{sim,i})$ has to be simulated in order to derive a better corrective factor $c^*_{i,j}$:

$$c^*_{i,j} = (L^*_{1,i} / L^*_{1,j}) * (L^*_{sim,j} / L^*_{sim,i}) \qquad (21)$$

The main error source is the aerosol scattering and you have to rely on one aerosol model. For a multidirectional sensor such as POLDER, measurements outside the sunglint gives some information about the aerosols first to exclude turbid days and then to validate or not the aerosol model used in the signal computation in the sunglint. In an attempt to apply this interband calibration method to MERIS, MERIS and SeaWiFS are coupled in order to reduce the uncertainties related to aerosol scattering. SeaWiFS level

3 daily data allow discarding the entire sun glint observations for which the aerosol model and optical thickness are very different from the one used in the simulations.
The sun glint calibration procedure is currently used by CNES to complement the Rayleigh calibration at short wavelengths. This method is detailed in Hagolle et al., 2004.Calibration points are selected in the same oligotrophic zones as for the Rayleigh method, with of course geometrical criteria to ensure the viewing direction is close to the exact specular direction. The absolute accuracy of the method is estimated to 5%.

27. Kaufman Y.J., Holben B.N., 1993; Calibration of the AVHRR visible and near-IR bands by atmospheric scattering, ocean glint and desert reflection. *International Journal of Remote Sensing 14 :21-52*

4.2.5.3 Clouds

Clouds are white at least in the visible range. The atmosphere above slightly change the spectral dependence. The most favourable circumstance is high convective clouds which are very bright and high. Such targets have been used by different authors to perform inter band calibrations. (28, 29)

28. Vermote, E. and Y. Kaufman, Absolute calibration of AVHRR in the visible and near infrared using ocean and cloud views, *Int. J. Remote Sen*., **16**, 2317-2340, 1995.

29. Lafrance, B., H. Hagolle, B. Bonnel, Y. Fouquart, and G. Brogniez, Interband calibration over clouds for POLDER Space Sensor, *IEEE Trans. Geosci. Remote Sen*., **40**, 131-142, 2002.

4.2.6 Spectral calibration

4.2.6.1 Fraunhoffer lines

The Fraunhoffer absorption lines can be used for medium/high resolution spectrometers. MERIS was configured both for Earth and diffuser observations and acquired data for only a limited number of orbits. This procedure was repeated for different band settings covering a number of Fraunhofer absorption lines. (see annex 4.2.6.1)

4.2.6.2 Gaseous absorption lines

Again, for medium/high resolution spectrometers, specific absorption lines can be used.
Using Oxygen (O2A) absorption Earth observation data, two different approaches were developed for MERIS, one based on the retrieval of surface pressure and one based on

the shape of the O2A absorption band. Both methods were developed for clear sky land observations, but their performances are improved over bright land targets. Both methods agree to within an accuracy of 0.02 nm. Results for the two above methods are reported in (30) and in annex 4.2.6.2.

30. Delwart S., Preuker R., Bourg L., Santer R., Ramon D., Fischer J., MERIS In-flight Spectral Calibration. Accepted for publication to the International Journal of Remote Sensing.

4.2.6.3 Cross spectral calibration

The general idea is the following: We have a reference sensor which a high spectral resolution and a sensor to be spectraly calibrated with broader spectral bands. Several nano spectral bands from the high spectral resolution radiometers are convoluted to simulate one spectral band of the other. The narrowing of the SPOT-HRV filter bandwidth was confirmed by re-constructing the wide SPOT bands using AVIRIS measurements over coloured vicarious calibration sites (31). The two sensors were first cross calibrated over La Crau. Then, over colored landspaces, the spectral response of SPOT was adjusted at the best thanks to AVIRIS. This technique is ever easier to apply when the two sensors are flying on the same space platform. The spectral calibration is even better when perform on features which varies suddenly with the wavelength such as a strong absorption band. Such opportunity is offered in the cross spectral calibration between MERIS and SCHIAMACHY as mentionned in the ENVISAT calval plan. http://envisat.esa.int/support-docs/calval/CalVal.pdf

31. Soufflet-Willart V. and Santer R (1993). Using AVIRIS for in-flight calibration of the spectral shifts of SPOT-HRV and of AVHRR? Proceedings of the fourth annual JPL airborne Geoscience workshop, October 25-29, 1993, JPL publications 93-26-Vol 1, p197-200.

4.3 Sensor inter calibration.

4.3.1 Principle

Ideally, two similar sensors view the same scene at the same time in the same geometry. In this case, you can directly compare the TOA radiances. It is more or less the case for SPOT-4 and SPOT-5 between HRV and Vegetation. They are simultaneous because on the same platform. At nadir, they both view the same scene and, finally, they have common spectral bands. But, most of the time, two sensors do not view simultaneously the same scene with the same geometrical conditions. More over the spectral bands are not exactly identical. Also, to be sure than the same scene is viewed by the two sensors, you need to rely on the collocation. Errors on the collocation are reduced when aiming homogeneous targets. Small discrepancies on the spectral responses are reduces for "white" targets. The main problem then is to correct from the BRDF in order to compare two different geometries.

4.3.2 Brigth land sites

For heliosynchron sensors, the scanning mode (or one of them) is cross track. Collecting images during a couple of weeks allows to derive the bidirectionality of the surface in the cross track direction. When the times of over pass of the two sensors are quite close, then you can correct one of the geometry to match the second.

4.3.3 Ice and snow

It is very similar to the desertic sites with the advantage to be at high latitudes and therefore to have possible several orbit per day. The BRDF are then very well described. The disadvantage is that snow and ice are certainly less lambertian than sand.

Over polar snow and ice sites, the radiometric performance of space sensors can be compared relatively to that of other sensors. As calibration site large snowfield in the polar region can be used, where space sensors in polar orbits view the same ground target on the same day with small differences in the local crossing times. When during the satellite crossing times, ground-truth experiments are performed, e.g., measurements of ground reflectance, BRDF, aerosol optical thickness (AOT), the sensor output can be compared directly assessing the atmosphere by radiative transfer code.

Nieke, Aoki, Tanikawa, Motoyoshi, and Hori A Satellite Cross-Calibration Experiment IEEE GEOSCIENCE AND REMOTE SENSING LETTERS, VOL. 1, NO. 3, JULY 2004

4.3.4 Ocean

The signal is very high both over desert and over snow, even if in this second case low solar elevation reduces it. At low level, it is adviced to cross calibrate over ocean. It is necessary as well if you want to ensure the compatibility between higher levels products. It is of course better to compare in the same geometry. If the geometricl conditions differ (it is for example difficult to compare directly SeaWiFS with the other ocean colour sensors because SeaWiFS is tilted along track), then over clear water, we need to account for the BRDF of the water and more important of the BRDF of the aerosols. Intercomparison will certainly be improved when ground based optical measurements are collected such as through the AERONET network.

Many examples of satellite intercalibration have been reported during the MERIS AATSR calval meeting held in Frascati, 2003. http://envisat.esa.int/workshops/mavt_2003_ver1.

4.3.5 Cross calibration between large FOV sensors and small FOV sensors

The vicarious calibration of small FOV sensors (mainly land sensors) with good spatial resolutions is classical using land test sites The size of the pixel allows to characterize the reflectance of several of them thanks to in situ surface reflectance measurements. Nevertheless, they are several operationnal contraints: have a reference site well characterized, organise field campaings,… The cross calibration between small fov sensors is difficult to realize because only few occurences are possible over a given test site. Alternatively, it is convinient and cheep to cross calibrate a small FOV sensors with a large FOV sensor. Ocean colour sensors have to be well calibrated. They may offer a daily overpass (SeaWiFS, MODIS) or a few day revisiting time (MERIS). So, it is easy to use them.

But the different nature of the two families of sensors requires several adjustments:

(i) the quasi simultaneous views differ most of the time in geometry. The necessary geometrical normalization imposes that the bidirectiopnnality of the site to be known.

(ii) the filter band widths are much more larger for the small FOV sensors than for the large FOV sensors. A spectral matching is required in which the spectral behaviour of the surface has to be known and for which the gaseous absorption has to be accurately accounted for.

Annex 4.3.5 gives an example of the intercalibration between AVNIR on ALOS and MERIS on ENVISAT.

5. Methodology for VOS sensor validation

5.1 Validate the tools

The validation of the level 2 products is understood as the strict validation of these products. It is as well very relevant to validate the assumptions used in the different algorithms designed to deliver those level 2 products. The following list gives examples of such generic validation activities:

Validation of the radiative transfer codes

Most of the level 2 algorithms rely on LUTs generated with RTCs. Through RTC, we include the generation of the inputs as well as the the resolution of the radiative transfer equation. Before going into an intercomparison exercice, a preliminary step consist to:

(iv) check the initial inputs to the code.

(v) control breack points to ensure that the inputs to the RTC it self are the same (vertical distribution of the atmospheric components, aerosol phase matrix, boundary conditions,…).

(vi) Validate that a given code converges depending on specific adjustable parameters of the code: length of the different series expansion used, discretization in optical depth, angular discretisation,…

(vii) Validate that the same assumptions are used in different codes. For example, you expect to have difference between a scalar code and a vector code (including the polarization) mainly in the blue.

If the comparison between codes is not conclusive, then it is necessary to evaluate the impacts of the code uncertainties on the product. Such exercice was conducted for MERIS both for the ocean products (32) as well as for the land products (33).

Finaly, if we accept that a radiative transfert code may generate errors, then let us try to be consistent. Example: if the atmospheric correction is achieved with a given code, then make vicarious calibration with the same code.

32. Dilligeard, E., Zagolski F., Fischer J. and Santer R., Uncertainties in radiative transfer computations: Consequences on the ocean colour products, Proceedings of the European Symposium on Aerospace Remote Sensing (SPIE Conference on Ocean Remote Sensing and Applications), Hangzhu (China), Vol. 4892, 546-556, 2002.

33. Santer,R., Zagolsky F., Ramon D., Fischer J., Dubuisson P., Uncertainties in Radiative Transfer Computations, Consequences on the MERIS products over land. International Journal of Remote Sensing,. In press.

Validation of the aerosol models

Standard aerosol models (SAM) are used for processing over water in order first to remote sense the aerosols in the near infra red and second to perform the atmospheric correction for ocean colour analysis. The same need to rely on SAM exists over land.

There are numerous papers and works dealing with aerosol remote sensing. All use SAMs of different kinds based on the micro physical characterization of the aerosols. Basis aerosol components are mixed to define SAMs. Both components and SAMs have roots in the scientific literature but are not use in a consistent way between satellite missions. Some type, the objective is to characterize a SAM, other time, once want to determine the mixing ratio between basic components. For a specific mission, the SAMS are different between land and ocean. Even over ocean, the SAMs differ from the ocean branch (in the atmospheric correction) and from the atmospheric branch. With as results: (i) inconsistencies in the aerosol products and (ii) a poor traceability of what is done in the algorithms. It is a key issue in the build up of aerosol global product and secondary, it may impact as well on the atmospheric correction (34).

Beside the consistency of the aerosol models, there is a need to validate if such models are able to correctly retrieve the aerosol optical properties. Some works intend to validate the optical properties of these aerosol models through the use of the AERONET network Extinction measurements are first used to derive the aerosol optical thicknesses (AOT). The spectral dependence of the AOTs between 670 nm and 865 nm allows selecting a SAM. A radiative transfer code is used to simulate the sky radiance in the principal plane. For each CIMEL data set of sky radiances, comparisons at different wavelengths illustrate the ability of the SAMs to retrieve the aerosol path radiances. This has a direct impact on the AOT retrieval from satellite observations at 865 nm over sea or in the blue over land.

34. R. Santer and F. Zagolsky Derive aerosol phase functions from sky radiance measurements in the frame of MERIS aerosol remote sensing validation. Proceedings of the MERIS workshop, Frascati, September 2005.

Validation of the IOP for water

Within the ocean colour community, there are debates and of course concensus on the IOP to be used. But of course, the characterizations of the IOPs are still in the research domain. There are for example clear requirements to measure the phase function in the water body.

Validation of the land surface reflectance model for aerosol remote sensing

The aerosol remote sensing will be performed over dense dark vegetation (DDV). The pixels of such targets contain mostly radiance backscattered by aerosols and are particularly dark both in the blue and in the red bands. Such DDV pixels are identified using a threshold applied to a spectral index, the Atmospheric Resistant Vegetation Index (ARVI). For the pixels on which aerosol remote sensing will be applied, we need to accurately know the BRDF. We initiate the game with a first LUT of surface albedo. Then, this first set of LUTs can be validated by combining satellite imagery to ground based atmospheric measurements. These last one are use to achieve at the best the atmospheric correction and then validate the albedo LUTs (or propose new LUTs)

Flags

Flags are kep parameters because first they oriente a specific pixel in a given branch (ocean,land,cloud,…) and second they give usefull pieces of information on a given product. A validation strategy for flags is not easy to define for several reasons:

(i) some flags are quite specific to a given sensor. Therefore, any cross comparison with other sensors is posible.

(ii) the binary nature (yes/no) of a flag makes it very dependant upon the treshold value above it you raise this flag.

(iii) quality flags are more qualitative than quantitative. The validation results on the feeling that they are raised on purpose.

(iv) if a validation is possible, it has to be done on a statistical basis.

Let us give two examples:

(i) the cloud flag is critical to select what process you will apply on a pixel.

The flag setting criteria depends on the primary mission of the sensor. For ocean colour, once want to disregard brigth pixels with a level of signal which will jeopardize the atmospheric correction. Therefore it is not exactly a cloud flag even if it covers the presence of clouds. Despite of that, the validation is mostly oriented towards the cloud detection using supervision techniques and/or crosscomparisons with other sensors.

5.2 Validation of the ocean level 2 products

Validation of ocean colour products involves optical buoys, *in situ* data collection during research cruises, and instrumentation on board third party vessels. Data from these platforms will include:

Aerosol optical thickness and type,

Water-leaving radiances and down welling irradiances in visible and infra-red channels.

Aerosol optical thickness (AOT) is a product and can be directly measured from sea surface. Aerosol type is validated through the retrieval of the Angstroem coefficient α because α is used to select an aerosol type. Water leaving radiances L_w in the ocean colour spectral bands is a product. Some time L_w is converted into reflectance and that why the down welling irradiances are measured.

The first set of measurements covers the same requirements than for the vicarious calibration. Coupled to a RTC in the forward mode, it is possible to predict the signal at the entrance of the sensor.

The two next sets of measurements are devoted to describe the water body:

Concentrations and inherent optical properties (absorption and volume scattering function) of chlorophyll,

Suspended particulate matter and yellow substance concentrations,

For details:http://seabass.gsfc.nasa.gov/docs/Protocols_Ver4_VolVI.pdf,
http://envisat.esa.int/workshops/mavt_2003_ver1/Session4.pdf

5.3 Validation of the land level 2 products

Although pseudo surface reflectances are L2 products, they cannot really be validated in the field and will only be compared when possible with similar products produced by other satellite sensors. The only circumstances during which once can validate the surface reflectances correspond to land vicarious calibration. If you deeply rely on onboard calibration, then such measurements can be used to validate the atmospheric correction.

For the land products, most of the validations go through inter comparison between sensors. More biological parameters, deduced from EO observations, rely on specific algorithms. Therefore the validation rely more on intercomparison of algorithms.

For details: http://envisat.esa.int/workshops/mavt_2003_ver1/Session5.pdf

5.4 **Validation of the atmospheric level 2 products**

Aerosol products

The aerosol properties are in first determined from the CIMEL stations of the AERONET network, used in the validation of POLDER and MODIS. Complementary in the open ocean, aerosol optical thickness and type will be measured from merchant and research ships using SIMBAD radiometers, which have been used extensively for the calibration and validation of POLDER and SeaWiFS.

Water Vapour

Water vapour content is derived from EO data over ocean and over land. The accuracy of the retrieval algorithms with respect to transfer simulations is in the order of 1.6 kg/m2 over land and about 2.5 kg/m2 over water surfaces. The accuracy of the retrieval is ascertained through comparisons with collocated radio soundings, GPS, MWR and Lidar estimates. Over water surfaces, the use of the nadir looking MWR gives the derivation of collocated accurate retrievals of the columnar water vapour path.

Cloud optical thickness and cloud albedo

The accuracy of operational retrieval algorithms is in the order of 0.01 for cloud albedo and of 3 - 5 for cloud optical thickness. The validation of cloud albedo and cloud optical thickness mainly relies on aircraft campaigns.

Cloud Top Pressure

The cloud top pressure is derived from the oxygen absorption at 761 nm. Accurate retrieval is dependent upon the penetration depth of solar radiation into the cloud, the transparency of thin clouds within the oxygen and reference channels, and the spectral slope of the underlying surface. The comparison of cloud top temperatures of thin clouds, retrieved from AATSR measurements, with cloud top pressures retrieved from MERIS, together with pressure and temperature profiles from radiosoundings, will be applied to estimate the accuracy of the retrieval of optically thin clouds as well as to estimate the impact of the surface albedo slope.

Surface Pressure

The determination of surface pressure is also based on a differential method involving the ratio of the radiance in the O2 absorption band at 760 nm and that in the adjacent non-absorbing band at 753.75nm. Because the main contribution to the signal is the direct reflection from the ground for bright land surfaces at these wavelengths, the ratio between the two MERIS bands almost corresponds to the O2 transmittance. Bright desert sites, with meteorological stations, for which the transmission factor predominates and the surface pressure is known and homogeneous, are used to accurately calibrate the pressure products and correct any potential spectral shifts.

For details: http://envisat.esa.int/workshops/mavt_2003_ver1/Session5.pdf

5.4 The level 3 as a validation tool.

If the level 3 are primilary consived as a global product, they are very usseful to evaluate the quality of a level 2 product simply because they provide implicitely a statistical tool for validation. Of course, the validation is at first qualitative but can help to identify possible bias trough the geographycal distribution at places where w can expect to see some thing. Atmospheric products do not rely on the same algorithms over land and over sea. Therefore, the land sea transition is a good indicator. Under other circumtances, auxiliary data can be spatialy dependant (abledo map, SAM,…) and again visual inpections on the boundaries are more than usefull.

There are some circumtances under which the calibration is adjusted in order to retrieve a specific product. Let us gives two examples:

(i) The SeaWiFS absolute calibration is realized at the MOBY site. For absolute calibration, the approach previously applied to CZCS (35), is followed. The instrument is not considered separately from the atmospheric correction scheme but part of the same system, since both are necessary to retrieve water-leaving radiance. In this "vicarious" calibration method, radiometric sensitivity is adjusted so that water-leaving radiance estimates agree best with data from the Marine Optical Buoy (MOBY) located 15 km west of Lanai (36).

35. Evans, R. H., and H. R. Gordon, Coastal Zone Color Scanner system calibration: A retrospective examination, *J. Geophys. Res.*, 99, 7293-7307, 1994.

36. Eplee, R. E. Jr., W. D. Robinson, S. W. Bailey, D. K. Clark, P. J. Werdell, M. Wang, R. A. Barnes, and C. R. McClain, The calibration of SeaWiFS. II. Vicarious techniques, *Appl. Opt.*, 40, 6701-6718, 2001.

(ii) The nominal MOS-A spectral response in the oxygen bands does not allow to correctly retrieve the pressure at surface. This assesment was stated after a comparison between the MOS derived surface pressure and the barometric pressure provided by ECMWF. The test site was a plateau northern of Sahara. The way to ensure the agreement between the two was to slightly move the nominal central wavelength of the MOS-A band (37).

37. Dubuisson P., Borde R., Schemchtig 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.

These exercices conducted on the radiometric calibration or on the spectral calibration can be as well applied to ensure the compatibility of a given product between to sensors. Of course, this trick has to be conducted with all ther necessary care and has to work on an extensite data set.

6. In situ measurements and tools for calval of VOS

6.1 In situ measurements and RTC for vicarious calibration of VOS

6.1.1 RTC

We start from the level 1 and as already mentioned, through equation (?), we get the normalized radiance L^*. A second step is to account for the gaseous absorption resulting primarily from the stratospheric ozone and from the water vapor. Finally, we convert L^* into a TOA reflectance ρ^*:

$$\rho^* = L^* / (T_g * \mu_s) \qquad (23)$$

where T_g is the gaseous transmittance and μ_s the cosine of the solar zenith angle. In equation (23) scattering and gaseous absorption are decoupled. Therefore the two computations can be conducted separately. In order to compute T_g we need to known the amont of the relevant absorbing gases. Ozone content is a standard data delivered by meteorological office (for example ECMWF) as well as water vapour content. Local water content can be determined as well from in situ measurements.

Over land, ρ^* can be linearized as:

$$\rho^* = \left[\rho_{atm} + T * \rho_l)\right], \qquad (24)$$

where ρ_{atm} stands for the atmospheric contribution (multiple scattering contributions from the molecules, the aerosols and the Rayleigh-aerosol coupling T is the total atmospheric transmittance. For, these atmospheric terms the inputs are:

(ii) The barometric pressure to compute the Rayleigh optical thickness.

(iii) The aerosol optical thickness.

(iv) The vertical distribution of the aerosols; generally a standard one.

(v) The aerosol phase function (or matrix).

In equation (24), the surface is assumed to be lambertian (described by ρ_l) but a more sophisticated formulation can deal with surface BRDF.

In ocean colour remote sensing, we simply replace the land surface reflectance by the water reflectance ρ_w and we add the direct to direct contribution of the Fresnel reflection:

$$\rho^* = \left[\rho_{atm} + T * \rho_w + \exp(-m\tau)\rho_g\right], \qquad (25)$$

here ρ_{atm} also includes the coupling between atmospheric scattering and Fresnel reflection. The Fresnel reflection is associated to a wave slope distribution model triggered by the wind vector which is generally known at least at a synoptic scale.

Among the different RTCs, we propose to use the 6S (38 and annexex 6.1.1.a and 6.1.1.b) code because it is a popular code easily accessible for free. 6S decouples gaseous absorption and scattering as described in equation (23). The computation of the gaseous transmittance is enough accurate when the EO are not in strong absorption bands. The computation of the scattering is conducted using a scalar version of the sucessive order (39) of scattering method. It is a clear limitations as pointed out in the introduction to §5.1.

(38) E Vermote, Tanré D., Deuzé J.L., Herman M., Morcrette J.J.1997; Second Simulation of the Satellite Signal in the Solar Spectrum, 6S User Guide.

(39). J.L Deuzé, M. Herman, and R. Santer, Fourier series expansion of the transfer equation in the atmosphere-ocean system, Journal of Quantitative Spectroscopy & Radiative Transfer, Vol. 41 (6), 483-494, 1989.

6.1.2 Measurements

6.1.2.1 Calibration of a reference radiometer.

The prefligth calibration of a satellite sensor is achieved using laboratory calibration facilities. The so called radiance based vicarious calibration as well. Laboratory calibrations are mainly achieved using integrating spheres. Alternatively, a standard panel, ligthed by a standard lamp, can be used.

6.1.2.2 Experimental characterization of the atmosphere.

The meteorological data are the first characterization of the atmosphere. They are generaly provided by meteorological office but in situ data of the barometric pressure and of the relative humidity may complement them at local scale.
Aerosol optical properties are needed. The minimum is to collect multispectral extinction measurents it order to get the AOTs and also from their spectral dependance to select one aerosol type. Sky radiances are used as well. They provide, through inversion technique, information on the aerosol inherent optical properties (R1).
Polarization measurements are also a plus in the validation of the aerosol model.
One parameter derived from the atmosphere characterization is the PAR. An experimental validation of the PAR can be conducted thanks to in situ measurement of the solar irradiance at sea –(R2). Annex 6.1.2.2 describes another approach to validate the PAR based on the use of the CIMEL AERONET instrument to provide the AOT and thanks to a modified 6S version.

(R1) **SANTER R. and MARTINY N.** (2003) "Sky radiance measurements for ocean colour calibration-validation". Applied Optics, Vol. 42 (6)., pp. 896-907.

(R2) Bouvet M., MERIS Photosynthetically Available Radiation: a product quality assessment, MAVT, 2006

6.1.2.3 **Land surface reflectance measurements.**

Most of the determinations of the surface reflectance ρ_g relies on a cross measurements on a reference panel of well known reflectance ρ_p in the geometrical conditions of the measurements. What is provided by the plate manufactor is the albedo; therefore a specific characterization of the BRDF of the panel is required. A simple ratio is then applied on the recorder digital counts:

$$\rho_g = DC_g * \rho_p / DC_p \qquad (26)$$

The reflectance panel should be perfectly horizontal and it is most of the time viewed at nadir.

Alternatively, a surface reflectance can be derived from well calibrated radiance L_g In that case, the definition of the reflectance applies with:

$$\rho_g = \frac{\pi L_g \uparrow}{\phi \downarrow} \quad (26)$$

The total irradiance at surface $\phi \downarrow$ can be measured or estimated. In this case, $\phi \downarrow$ decoupled into:

$$\phi = \phi_D^{\downarrow} + \phi_d^{\downarrow} \qquad (27)$$

where the direct irradiance $\phi_D^{\downarrow}$ is directly measured (solar extinction) while the diffuse irradiance $\phi_d^{\downarrow}$ can be first computed. The RTC uses to predict the TOA signal computes as well $\phi_d^{\downarrow}$ in a consistent way. More directly, L_g can be input as boundary conditions in the RTC.

Alternatively, the definition of $\phi_d^{\downarrow}$:

$$\phi_d \downarrow = \int_0^{2\pi}\int_0^1 \mu L(\mu, \varphi) d\mu \, d\varphi \quad , \qquad (28)$$

can be used when sky radiance measurements exist.

As an exemple, the specific CIMEL instrument installed in La Crau, France, proposed to characterize automatically the surface reflectance (see annex 6.2.3) .

6.1.2.4 **Radiometric measurements at sea.**

The land approach can not be duplicated at sea as it is.

First, the so-called remote sensing reflectance of the water does not include the Fresnel reflection of the sky dome. This terms as to be removed. The most popular approach is the so-called "quick and easy method". A second twin radiometer is looking up with the same view angle and in a same plane. What it measure time the Fresnel reflection coefficient corresponds to the reflection of the sky done collected by the first radiometer. This term is removed from the water leaving radiance measurement. Alternatively, the SIMBAD radiometer principle is based on a polarized measurement to remove, in specific geometrical conditions, this sky dome reflection.

Second, it is not very convenient to cross compare on a panel at sea, more over, the requirement to have a panel perfectly horizontal on a boat is impossible.

Because of the above two reasons, there are several alternatives for protocol measurements.

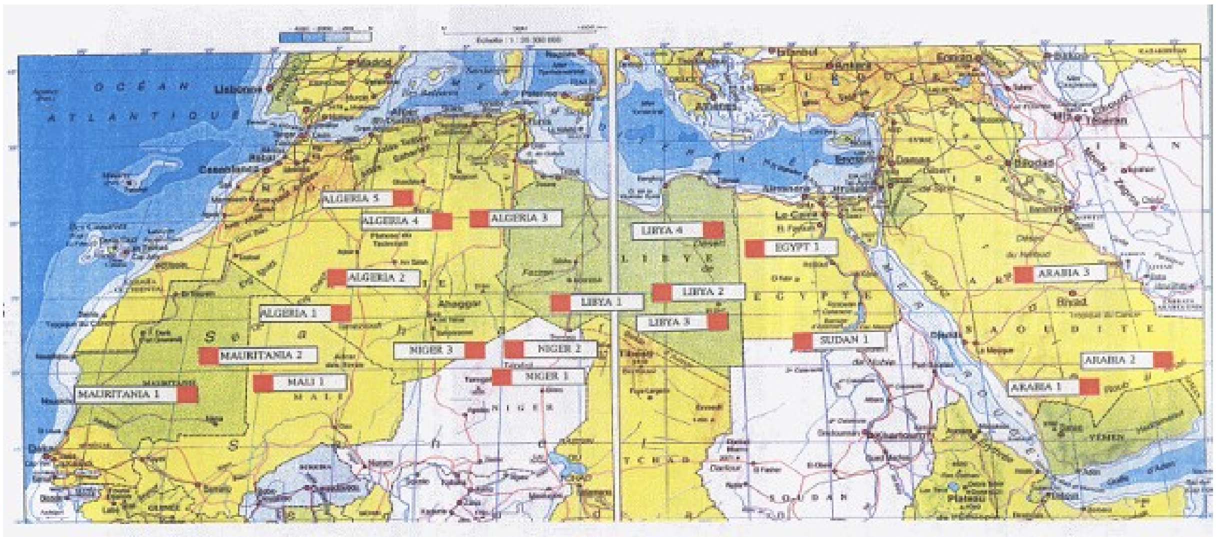
Another approach, widely used, is to measure the marine reflectance just below the surface. There are at least two advantages: (i) the temporal variety of the signal is less heratic below water than above and the sky dome reflection does not exist. Both downwelling and upwelling irradiances are simultaneously measured. The marine reflectance is just the ratio of the two. There are disadvantages: (i) the self shading effect, (ii) the uncertainty in the conversion of marine reflectance into a remote sensing reflectance.

As an exemple, the CIMEL instrument installed on the Venice tower, Italy, proposed to characterize automatically the surface reflectance (see annex 6.2.4) .

6.1.3 Data base

For calibration activities, CNES generates a data base: SADE for : "Structure d'Accueil de Données d'Etalonnage". A systematic collect of satellite acquisitions over the 20 sites, as reported in the map below, was undergone with:

– *POLDER 1* (oct. 1996- june 1997) – *POLDER* 2 (2003)
– Since 1990 : 'some' SPOT high resolution
– Since 1998 : *SeaWiFS*, *VEGETATION 1 & 2*, *AVHRR 14 & 16*
– Since 2001 : *MERIS*, *MODIS*
+ *MISR*, *ATSR2*, *AATSR*…
+ Meteo data



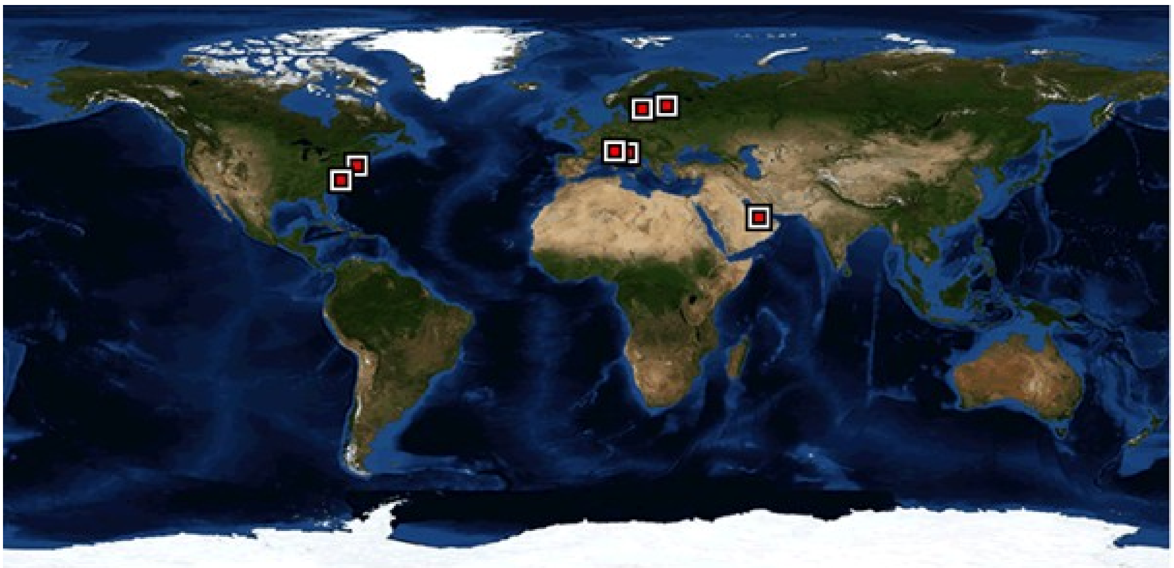
The SADE data base also includes calibration measurements over ocean, sun glint, clouds and snowy sites. More than 150000 multi spectral acquisitions are available in SADE. Functionalities in SADE include:

– Easy data management,

– Link between satellite measurements and calibration results (traceability).

AERONET data base provides an extensive data base, build up thanks to the CIMEL sunphotometers, of pieces of information on the aerosols.

The Venice tower approach has been extended to others platforms at sea as shown in the map below. These measurements are now available on the AERONET web site.



The localisation of the CIMEL radiometers in the AERONET “ocean colour” network.

To some how, the surface reflectance is an “atmospheric ” parameter. If the in-flight radiometer is perfect, the retrieved surface reflectance, after the atmospheric correction, mostly depends upon the atmosphere composition. The “meteorological” parameters (ozone, water vapour, barometric pressure, wind speed) are generaly known. The uncertainty is in the aerosol model. AERONET provides this piece of information. The derived aerosol model can be inputed in a RTC in the prediction of the TAO radiance.

Holben, B., T. Eck, I. Slutsker, D. Tanré, J.-P. Buis, A. Setzer, E. Vermote, J. Reagan, Y. Kaufman, T. Nakajima, F. Lavenu, I. Jankowiak, and A. Smirnov, A federated instrument network and data archive for aerosol characterization, *Remote Sen. Environ.*, **66**, 1-16, 1998.

6.2 In situ measurements and tools for ocean colour validation

6.2.1 Parameters subject to validation

As a standard, we will use the globcolor project, http://www.globcolour.info/. One possible classification is to distinguish two groups of products:

(i) « Atmospheric » products

- Fully normalised water leaving radiances:

Actualy, we are taking about water remote sensing reflectance (wrsr) defined as the reflectance measured above water without direct sunglint and after correction of the Fresnel reflexion of the sky dome. As an input of the atmospheric correction process, the wrsr can be considered as “an atmospheric” product.

- Photosynthetic Available Radiation

The PAR is defined above water. Therefore, it can be considered as an atmospheric parameter. We talk about an instantaneous PAR as for MERIS. In this case, the PAR is an usefull parameter to interpret the fluorescence as measured by MERIS. We talk about a daily PAR which is the relevant parameter for marine primary production.

- Aerosol optical thickness over water

the AOT is primary defined at 865 nm and the spectral dependence is described by the Angstroem coefficient.

- Cloud Fraction

In the delivery of level 3 products, CF is the percentage of pixels identified as cloud within the level 3 macro pixel.

(ii) “Water” products

- Fully normalised water leaving radiances

The fully normalized water leaving radiances is defined as the normalized (incident solar irradiance of 1) radiance observed at nadir for a sun at zenith. It is still considered above water, without direct sunglint and after correction of the Fresnel reflexion of the sky dome. The bidirectional correction requires to model the BRDF of the oceanic body, with, for the case 1 water, the knownledge of the Chla concentration.

- Relative excess of radiance at 555 nm

Knowing the Chla concentration for case 1 water, it is possible to predict the water leaving radiance at 550 nm. EL550 gives the relative excess of radiance at 555 nm.

- Chlorophyll-a (CHL_1 and CHL_2)

CHL1 is the usual Chla concentration for case 1 water as proposed by the ocean colour sensors. CHL2 is the Chla concentration, originally specifically produced with a NN for case 2 water, as proposed by MERIS.

- Coloured dissolved and detrital organic materials (CDM)

CDM is the coloured dissolved and detrital organic materials (m^{-1}) available from MERIS.

- Diffuse attenuation coefficient (Kd(490))

Kd(490) is the diffuse attenuation coefficient at 490 nm (m-1). It is one indicator of the turbidity of the water column. The merged Kd(490) is computed directly from the merged CHL1,

- Particulate back-scattering coefficient (b_{bp}) -and Total Suspended Matter (TSM)

b_{bp} is the particulate back-scattering coefficient at the reference wavelength λ_0 = 443nm (in m^{-1}). The TSM in standard MERIS L2 product is calculated using the case 2 water neural network. The assumption of the neural network is that there is a constant ratio between total particulate scattering (BP) and particulate back-scattering (BBP): BBP/BP = 0.015. TSM as dry weight of all water constituents is then calculated as TSM (g.m-3) = 1.73*BP.

6.2.2 Measurements and protocols to validate the "atmospheric products"

- WRSR

Assuming that the satellite sensor is well calibrated and that we are able to correctly predict the gaseous absorption, the atmospheric scattering and the Fresnel reflection, then, we can perform accurate atmospheric corrections and correctly provide the wrsr.

What are the required inputs required to transform the level 1 data into wrsr?

(i) The auxiliary data, attached to the satellite data or available from wheather services, provide the barometric pressure (input for the Rayleigh), the ozone amount (input for correction of the gaseous absorption) and the wind components (input for the Fresnel reflection).

(ii) A ground based radiometer is required to describe the optical properties of the aerosols. From the CIMEL instrument, in AERONET,

PAR

Different possibilities to validate the PAR:

(i) use of in situ measurements of the downwelling solar irradiance. These measurements exist at sea in order to transform water leaving radiance in reflectance. It can be monochromatic values. In this case, the monochromatic values have to be integrated over the PAR spectral domain. It can be integrated spectral values, and in this case a conversion factor has to be applied to convert these data into PAR.

(ii) We use the "atmospheric" pieces of information as described in the WRSR section to predict with a RTC the PAR.

AOT

Nominally, it is the AOT at 865 nm directly measures by a sun phometer. Aditionnaly, it can be the Angstroem coefficient validates by the measured AOT at 670 nm.

CF

It can be validated by surpervised classification.

6.2.3 Measurements and protocols to validate the "water products"

Fully normalised water leaving radiances

Starting from the measurements of the marine reflectance, we need to the pass the water/air interface and to transform the above water reflectance into a normalized water leaving radiance.

•Chlorophyll-a (CHL_1 and CHL_2)

CHL1 is the usual Chla concentration for case 1 water as proposed by the ocean colour sensors. CHL2 is the Chla concentration, originally specifically produced with a NN for case 2 water, as proposed by MERIS.

•Coloured dissolved and detrital organic materials (CDM)

CDM is the coloured dissolved and detrital organic materials (m^{-1}) available from MERIS.

•Diffuse attenuation coefficient (Kd(490))

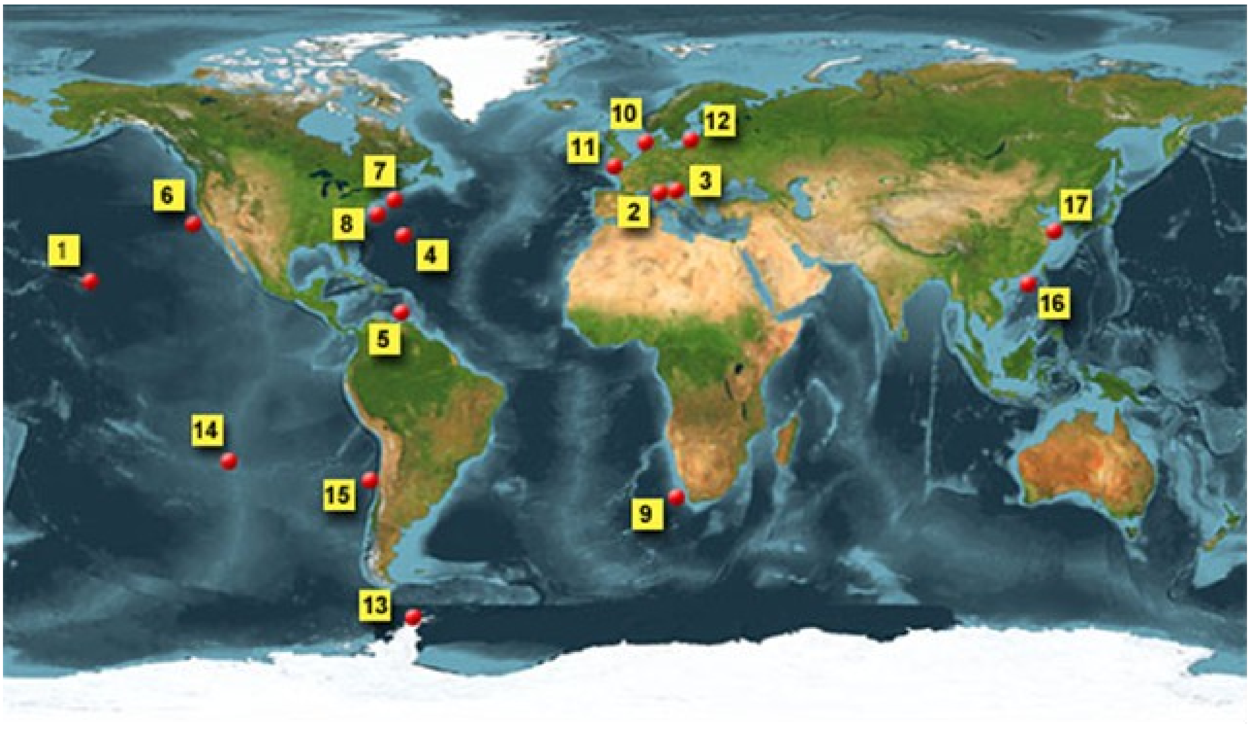
Kd(490) is the diffuse attenuation coefficient at 490 nm (m-1). It is one indicator of the turbidity of the water column. The merged Kd(490) is computed directly from the merged CHL1,

•Particulate back-scattering coefficient (b_{bp}) and Total Suspended Matter (TSM)

Instruments on the Bousolle buoy*, simultaneously collecting data in a continuous way, include the following:

- Radiometers of the Satlantic 200 series, measuring E_s (at 4.5 meters above the water surface), and E_d, E_u, and L_u (nadir) at 2 depths (4 and 9 m).
- Two-axis tilt and compass at 9 m.
- A Sea-Bird Electronics CTD at 9 m for temperature, conductivity and pressure.
- Fluorometers at 4 and 9 m for a proxy to the chlorophyll *a* concentration.
- Transmissometers, at 4 and 9 m for a proxy to the particle load.
- Backscattering meter at 9m measuring a proxy to b_b at two wavelengths (442 and 560nm).

6.2.4 Data base



7 The IOS

7.1 Basic equations and algorithms

The atmospheric windows

The use of thermal infrared channels (centred on 1.6 microns, 3.7 microns, 10.7 microns, and 12 microns), corresponds to the atmospheric windows as illustrated in figure 5 in which the AATSR bands are located. Using the atmospheric windows, the goal here is to observe the surface temperature. Another objective is to characterize the clouds.

The fundamental calibration equations

The calibration of the thermal channels aims to characterise, for each channel separately, the relationship between the radiation incident on the detector and the detector output. The signal in counts from a radiometer channel whose spectral passband is $\Delta\nu$observing a blackbody target at temperature T_{bb} is:

$$S(T_{bb}) = GL(T_{bb}) + S_0$$

where G is the radiometric gain , (or calibration coefficient including the gain), $L(T_{bb})$ is the radiance from a target, and S_0 is the radiometric offset of the channel. Thus radiometric calibration of the instrument consists of determining the linear relationship between the radiance and detector counts from each channel.

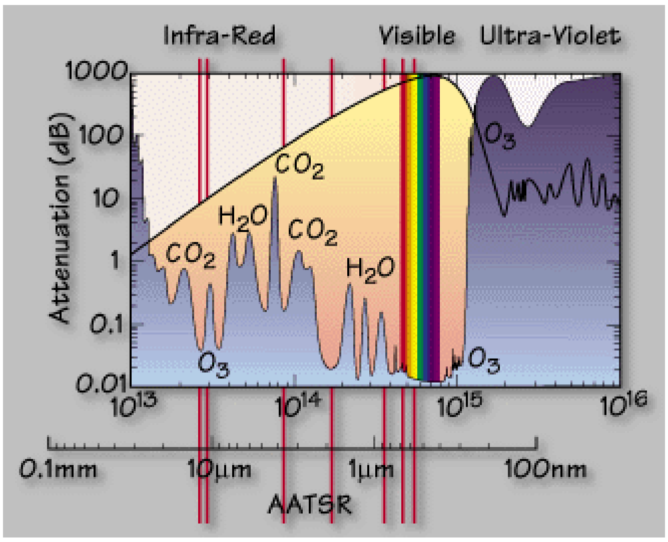


Figure 5: The AATSR bands and the atmospheric windows.

One traditional way to do this might be to allow the instrument to view a zero radiance target, such as a cold space view, to determine the radiometric offset S_0 (i.e., $L(T_{bb})$ =

0). Then the radiometer views a hot calibration target to determine the radiometric gain of the channel, given by:

$$G = (S_{hot} - S_0)/L_{hot}$$

The major limitation of this approach comes from the assumption that the radiometer's response is linear over a wide range of scene temperatures, 0 to 350K in the case of an Earth viewing instrument. In practice there is always some non-linearity that, if not treated properly in the ground processing algorithms, results in errors in calibration.

A different approach is therefore adopted to minimise the sensitivity of the calibration to any non-linearity in the radiometer characteristics. This has been done both by careful design of the signal processing electronics and careful pre-flight determination of the non-linearity for beginning of life and end of life conditions on the satellite, and also through designing the calibration system so that the on-board calibration is optimised over the limited range of temperatures that span the expected range of ST observations. This is done by the use of two blackbody calibration targets, rather than a single target hot target and space view. One of these targets operates at a temperature lower than the lowest expected ST and the one other warmer than the highest. With this arrangement the calibration is most precise over the normal range of observed temperatures, and the effects of any non-linearity in the system are minimised because linearity is only assumed over a small range of measurement space. Outside this range the calibration is no worse than using the space view and single target approach, but the precision is concentrated into the portion of the measurement space where the most accurate measurements are required. Outside this range the precision of the observations is less critical, so the larger calibration errors resulting from extrapolation can be tolerated. (40).

40. G. Mason, ATSR Test and Calibration Report, ER-RP-OXF-AT-0001, September 1991

law:

$$L_{BB\lambda}(T) = \left(\frac{2\pi hc^2}{\lambda^5}\right)\left(e^{\frac{hc}{\lambda kT}} - 1\right)^{-1}$$

determine the body's true surface temperature, through:

$$L_\lambda(T) = \varepsilon(\lambda) L_{BB\lambda}(T)$$

$L_\lambda(T)$ is the spectral radiance as a function of temperature.

$\varepsilon(\lambda)$ is the emissivity as a function of wavelength.

$L_{BB\lambda}(T)$ is the spectral radiance of the blackbody as a function of temperature.

From TOA brightness temperature T_B. to surface temperature

There are three major limitations in using radiance measurements from an orbiting platform to estimate the surface temperature. First, clouds block infrared radiation from the surface. Second, the intervening atmosphere absorbs some of the radiation emitted by the surface and it also emits radiation some of which goes directly to the satellite radiance sensor and some of which is reflected from the surface back up to the satellite. Third, solar radiation is reflected from the surface to the sensor (Fig. 6).

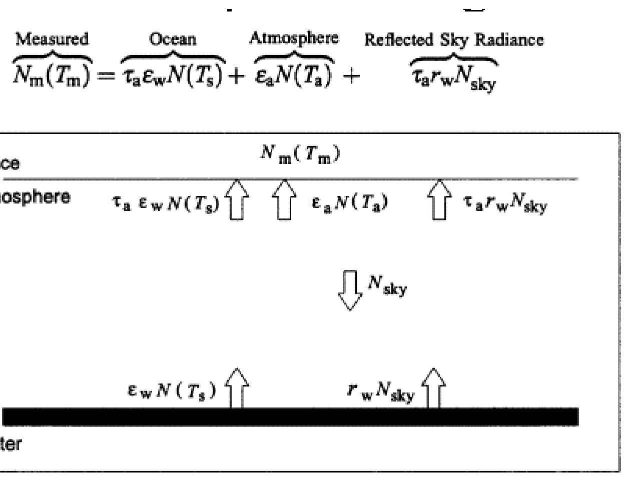


Fig. 6: Measured radiances in the thermal

During day-time at the 3.7μm channel a mixture of emitted thermal radiation and reflected solar radiation is measured. This makes the use of this channel at day-time more complicate (Fig. 7).

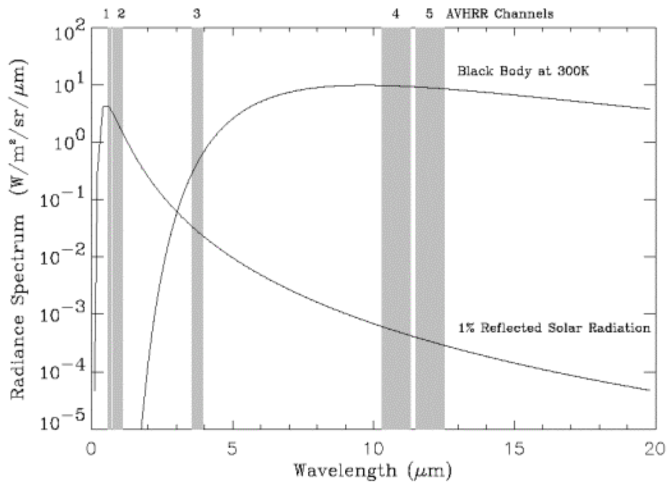


Fig. 7: Black body radiation spectrum, reflected radiation spectrum and the wavelength channels of AVHRR

Considering cloud free conditions the latter two limitations depend on the constituents of the atmosphere, and the most variable one, the water vapour distribution, is not known with sufficient precision to correct the radiation temperature measured by the satellite at the top of the atmosphere (TOA) to physical surface measurements.

In general there are three classes of sea surface temperature algorithms. The `split-window'' algorithm uses the brightness temperature of two sections of the atmospheric window between 10μm and 12μm, the `dual-window'' algorithm uses measurements at 3.7μm and 11μm to correct for the atmosphere. Finally, the `triple-window'' algorithm uses measurements at 3.7μm, 11μm, and 12μm. The corresponding brightness temperatures are called $T_{3.7}$, T_{11} and T_{12} in the following.

Improvements to atmospheric correction can be achieved by making two observations of the same ocean surface through different atmospheric path lengths. As a result, AATSR also employs a 'dual view' technique to achieve the best possible atmospheric correction.

The meteorological products

Since the first weather satellites in the 1960's, thermal imagery has been an invaluable source of information on cloud heights and storm severity. One can locate the approximate top of an opaque cloud by observing its effective blackbody temperature ("brightness temperature") at some wavelength that passes easily through air (e.g. 10.12 μm), and matching this to a local atmospheric sounding (41) to obtain a height. This continues to be a mainstay of cloud related research, due to the wide availability of infrared data and simplicity of the method.

More elaborate cloud products combine solar and thermal observations to give cloud phase, optical thickness and effective radius as it is for the MODIS instrument, (42).

41. Smith, W. L., and C. M. R. Platt, Comparison of satellite-deduced cloud heights with indications from radiosonde and ground-based laser measurements, *J. Appl. Meteorol.*, *17*, 1796–1802, 1978.

42. http://modis-atmos.gsfc.nasa.gov/MOD06_L2/index.html

7.2 Calibration requirement for surface temperature.

SST requirements

The scientific principles behind the design of the thermal instruments are dominated by the need for the high accuracy SSTs required for global climate monitoring and research. Accurate SST measurement is of great importance for climate research; for example, in modelling climatic phenomena such as the El Niño Southern Oscillation, in the monitoring of global warming due to the enhanced greenhouse effect, and in the investigation of ocean-atmosphere heat transfer. For example (43) , the AATSR instrument and ground processing system are required to produce SST retrievals routinely with an absolute accuracy of better than 0.3K, globally, both for a single sample and when averaged over areas of 0.5° longitude by 0.5° latitude, under certain cloud free conditions (i.e. >20% cloud free samples within each area).

43. http://envisat.esa.int/dataproducts/aatsr/CNTR1-1-2.htm#eph.aatsr.ug.htcad.scibg

LST and atmospheric requirements

The status is very similar than for the VOS: the requirements on the SST retrieval drive the others.

7.3 Radiometric calibration.

7.3.1. On board black body

In order to fulfill the calibration requirements as described in 8.1, two reference temperatures have to be used. The first approach was to use the cold deep space as a reference point and an onboard black body. For AVHRR, the internal calibration operates approximately at the temperature of the radiometer’s internal environment, which varies usually between 286 K and 300 K. The thermal detectors are typically maintained at a temperature of 107 K by a radiant cooler subsystem. The critical issue is the accuracy of the BB temperature monitoring. The BB responds to thermal forcing caused by changes in solar heating and radiative cooling, which in turn depend on solar illumination conditions along an orbit and the relative position between the Sun and orbital plane for a given time of the year. Several works (44, 45) are devoted to correct these effects.

The two limitations of the AVHRR internal calibration are first the accuracy of the BB temperature and the reference to the deep space value. The two reference points are quite distant from each other which imply to rely on the linearity of the detector (or to the pre-flight characterization of the instrument). For more recent sensors, two reference temperatures are used. For AATSR, two black body reference targets are viewed on each scan, with one at roughly at 265K and the other at 305K, as this is expected to encompass the full global range of SSTs. The calibration sources are designed such that uncertainties in the radiance from them will not exceed an equivalent temperature error of more than 100mK throughout the mission. The main component is a Planckian blackbody, an aluminum v-groove plate with a very high, well known emissivity and precise temperature. The temperature of the blackbody can be related to the radiance by integrating Planck's function over the bandpass of the individual detector array being calibrated. This results in a radiance for a corresponding temperature, one point on the calibration curve. This blackbody can be varied in temperature between 273K and 315K (46). Most of the time, the temperature of the blackbody will only be monitored, not controlled in the cavity. Every few weeks the blackbody will heat to 315K to check a high temperature gain and bias. Detailled on the onboard calibration for ASTER are given in (47).

43. A. P. Trischenko and Z. Li. A method for the correction of AVHRR onboard IR calibration in the event of short-term radiative contamination. Int. j. remote sensing, 2001, vol. 22, no. 17, 3619–3624

44. Walton, C. C., Sullivan, J. T., Rao, C. R. N., and Weinreb, M. P., 1998, Corrections for detector nonlinearities and calibration inconsistencies of the infrared channels of the Advanced Very High Resolution Radiometer. *Journal of Geophysical Research*, **103**, 3323–3337.

45. Barbieri, Richard: "MODIS Level 1B Algorithm Theoretical Basis Document (Ver 2.0)." [http://modarch.gsfc.nasa.gov/MODIS/ATBD/atbd_mod01.pdf]. Greenbelt, MD, February 13, 1997.

46. Julia Barsi. A Review of the Thermal Components on MODIS and ASTER http://www.cis.rit.edu/class/simg707/Web_Pages/barsi.htm

7.3.2. Vicarious calibration

Principle

The vicarious calibration in the thermal follows the same principle (47) than in the visible:

(i) homogeneous sites are selected.

(ii) the surface is characterized in emissivity, temperature and radiance.

(iii) The atmospheric parameters are measured (here vertical profiles of temperature and water vapour)

(iv) A RTC is used to predict the TOA radiance

47. Tonooka, H. Palluconi, F.D.Hook, S.J. Matsunaga, T. Vicarious calibration of ASTER in the thermal infrared bands. Geoscience and Remote Sensing, IEEE Transactions, 2005, Vol 43, 12, 2733- 2746

Land test sites

Land test sites are most of the time common between vicarious calibrations in the solar and in the thermal domain. They are desertic areas (sand or salt lake). First, the spatial homogeneity in radiance also corresponds to a spatial homogeneity in temperature and emissivity. Second, because the atmosphere is generally dry. Third, a same satellite platform may contain both visible and thermal instruments. For logistical and financial reasons, the two calibrations are combined on the same site. It was the case with TM on White Sands (48) in the eighteens. It is now the case, for MODIS-ASTER and others, on the new sites (49) used by the RSG at the University of Arizona.

48. J.M. Palmer, "Calibration of Thematic Mapper band 6 in the thermal infrared,", Proc. SPIE 1938, 109 (1993).

49. Eliel Villa-Aleman, Robert J. Kurzeja and Malcolm M. Pendergast. Assessment of Ivanpah Playa as a site for thermal vicarious calibration for the MTI satellite.
http://www.ntis.gov/help/index.asp

Water test sites

A large body of water is an excellent target due to its high emissivity and thermal mixing. Lake Tahoe offers these conditions and also because of it elevation the water vapour amount is reduced. Of course, for one calibration day, Lake Tahoe, because of it thermal homogeneity offers only one point. Lake Ontario, (50), but the Great Lakes provide a unique thermal opportunity. The thermal bar, a phenomenon of large temperate zone bodies of water, provides a separation of warm and cool water in the spring warming season. This period provides at least two points, perhaps more depending on the resolution of the system, to check the calibration curve.

50. Zhengming Wan, Yulin Zhang, Xialin Ma, Michael D. King, Jeffrey S. Myers, and Xiaowen Li Vicarious calibration of the Moderate-Resolution Imaging Spectroradiometer Airborne Simulator thermal-infrared channels. Applied Optics. Vol. 38, No. 30.

7.3.3. Cross calibration

Since ASTER and MODIS are on the same platform, the same vicarious calibration methods can be used (51). Although the instruments are slightly different, this can be taken into account in the calculations of predicted top of the atmosphere radiance. The same airborne will be taking the measurements for two instruments of slightly different spectral characteristics. As long as the airborne instrument has spectral characteristics encompassing the spectral range of the orbiting instruments, the differences can be factored into the integration over bandpass of Planckian spectral exitance.

51. Ono, A., Sakuma, F., Arai, K., Yamaguchi, Y., Fujisada, H., Slater, P.N., Thome, K.J., Palluconi, F.D, and Kieffer, H.H.: Preflight and In-flight Calibration Plan for ASTER. *Journal of Atmospheric and Oceanic Technology*, **13**, 321-335, 1996.

7.4 Validation of the surface temperature.

7.4.1 Validation of the SST

7.4.1.1 Using in situ data

An IR radiometer is sensitive to the temperature of the sea surface skin (the top few tenths of µm), which can differ from the bulk sea surface temperature (BSST) of the water just a few cm below the skin/surface by several tenths of a degree. Therefore, validation of the SST product has to be carried out through comparisons with skin SST (SSST) measurements retrieved from high-precision radiometer measurements collected during *in situ* validation campaign. Of course, such an approach leads to substantial efforts and financial resources. Such approaches were conducted for example to validate AATSR SST. (52, 53)

In certain circumstances (i.e. high wind speeds) BSST measurements can be used, as it is believed that at sufficiently high wind speeds the skin effect breaks down (54). The critical wind speed at which the skin effect becomes zero is a matter of many current debates, however most authors agree that at wind speeds of greater than 10 ms-1 the skin effect can be considered negligible. Under these circumstances, we can use the in situ network from meteorological institute as it is done by the UK met office for AATSR (55).

52. I. Barton, A. Pearce. Validation of Satellite-derived Sea Surface Temperatures from AATSR Data.
Proceedings http://envisat.esa.int/workshops/mavt_2003_ver1/Session4.pdf

53. T. Nightingale SCIPIO – Validation of ATSR-2 and AATSR with SISTeR. http://envisat.esa.int/workshops/mavt_2003_ver1/Session4.pdf

54. C.J. Donlon and I.S. Robinson, "Observations of the Oceanic Thermal Skin in the Atlantic Ocean," *J. Geophys. Res.*, 102, pp. 18585 – 18606, 1997.

55. A. O'Carroll, J. Watts, R. Saunders, L. Horrocks. Near-real time Validation of the AATSR Meteo-product at the Met Office.
http://envisat.esa.int/workshops/mavt_2003_ver1/Session4.pdf

7.4.1.2 Sensor intercomparison

The sensor inter comparison is a critical issue to study long term series at a global scale. A number of global fields are available for comparison: AATSR, ATSR-2, AVHRR, MODIS and the Thermal Microwave Instrument (TMI) instruments exploiting mainly infrared but also microwave measurements in the case of the TMI. The datasets considered can be averaged to monthly means at half-degree resolution to produce level 3 products.

56. J. Remedios, J. Aylmer-Brewin, D. Levett, D. Ridle, B. Mannering, M. Edwards, D. Llewellyn-Jones. Global Comparisons of (A)ATSR Data Sets With Other Sensors. http://envisat.esa.int/workshops/mavt_2003_ver1/Session4.pdf

7.4.2 Validation of the LST

7.4.2.1 Using in situ data

Land test sites are equipped wih IR radiometers to validate the LST derived from satellite sensors. Examples of test sites used are reported in (57).

57. F. Prata. The AATSR LST Product
http://envisat.esa.int/workshops/mavt_2003_ver1/Session4.pdf

7.4.2.2 Sensor intercomparison

The same needs and requirements than above oceans exist. They are facilitate when the two sensors are on the same platform like ASTER and MODIS.

58. Jacob, F., F. Petitcolin, T.J. Schmugge, E. Vermote, A.N. French and K. Ogawa. (2002). Comparison of land surface emissivity and radiometric temperature derived from MODIS and ASTER sensors. Remote Sensing of Environment.

7.4.3 Validation of the meteorological products

Cloud boundaries can be retrieved from radiosonde profiles, radar, lidar and ceilometer (59) Test sites are used to collect data on a routine basis such as the ARM site at the Southern Great Plaines (US). SIRTA (60) is the atmospheric observation and research site of Institut Pierre Simon Laplace (IPSL) located in Palaiseau, 25 km south of Paris. This site hosts a suite of passive and active remote sensing instruments such as lidars, radars and radiometers

59.http://www.photogrammetry.ethz.ch/research/cloudmap/ws_zurich/abstracts/abstracts.html

60. http://sirta.lmd.polytechnique.fr/

7.5 Tools for calval activities.

7.5.1 Measurements

Characterization of the surface

Surface temperature measurements can be made with contact sensors, broadband radiometers, and IR spectrometers. The contact sensors are thermistors with data loggers for surface temperature measurements of water body and flat land surfaces such as the silt playa 1–2mm beneath the surface. Temperature is recovered directly from the contact sensors.

Field IR spectrometers or radiometers measured the radiance in the spectral range of 3.5–14.5 nm, (61, 62) Some IR spectrometers are equipped with a scanning mirror to provide temporal and angular spectral surface radiance.

Intercomparison of measurements ,collected by different IR radiometers, (63), is as well a critical issue

61. Sicard, M., P.R Spyak, G. Brogniez, M. Legrand, N.K Abuhassan, C. Pietras, J.P Buis, "Thermal-infrared field radiometer for vicarious cross-calibration: characterization and comparisons with other field instruments", *Society of Photo-Optical Instrumentation Engineers*, 38, pp 345-356, 1999.

62. Hook, S.J. and A.B. Kahle. (1996). The micro Fourier transform interferometer (μFTIR) - A new field spectrometer for acquisition of infrared data of natural surfaces. Remote Sensing of Environment, 56(3): 172-181.

63. S. Hook, F. Prata. AATSR Validation Results at Lake Tahoe CA/NV, USA
http://envisat.esa.int/workshops/mavt_2003_ver1/Session4.pdf

Characterization of the atmosphere

The main atmospheric inputs to a RTC are the vertical profile of temperature and water vapour. Standard radio sondes provide both. Some field IR spectrometers can measure the atmospheric down welling irradiance with a diffuse reflector. The measured downwelling irradiance is used in the atmospheric correction of the ground based measurement data. It can be used as well to validate the atmospheric correction.

7.5.2 RTC

The MODTRAN code (64, 65) **(MOD**erate spectral resolution atmospheric **TRANS**smittance algorithm and computer model), developed by AFRL/VSBT (Air Force Research Lab, Space Vehicles Directorate) remains the state-of-the-art atmospheric band model radiation transport model. MODTRAN4 has been available to the public since Jan 2000. MOTRAN is capable of predicting atmospheric transmittance and radiance for frequencies from 0 to 50,000 cm-1 at moderate spectral resolution (primarily 2 cm-1; UV at 20 cm-1). Its design was driven by a need for higher spectral resolution than LOWTRAN. Except for its molecular band model parameterization, MODTRAN adopts all the LOWTRAN 7 capabilities, including spherical refractive geometry, solar and lunar source functions, and scattering (Rayleigh, Mie, single and multiple), and default profiles (gases, aerosols, clouds, fogs, and rain)

The $300 fee includes user-support, all receiving parties (Universities, Corporations, and Government Agencies) If any single CORPORATION has disparate research groups, each using MODTRAN4 in a different capacity, then the fee applies separately to each group. This is a limitation in our project.

64. Abreu, L. W., et al. (1991). MODTRAN. The Proceedings of the 1991. Battlefield Atmospherics Conference, El Paso, TX,

65. http://www.vs.afrl.af.mil/ProductLines/IR-Clutter/modtran4.aspx

8. The micro wave sensor: SMOS

9. The radar sensor: ASAR

10. Recommandations for improvements

10.1. General statements

Improve state of the art of each method

There are a substantial amount of onboard and vicarious calibration methods and activities. Of course, it is the scientific responsibility of each of the users to ensure the quality of a given method and, when possible to propose improvements. One important thing is to attach to each calibration point an estimation of the quality. Idealy, it is to provide an error bar while in most of the cases what is provided is the outputs of a sensitivity study. A sensitivity study attributes to each of the parameters required in a calibration process a domain of uncertainty. This domain of uncertainty offen results from the "wet finger" approach. An error analysis requires a detailled and mathematical approach which aims to determine for each input parameter the domain of confidence. It is not an easy task.

Encourage routine procedures

A vicarious calibration which aims to produce absolute calibration offen relies on field activities. Therefore logistical problems and associated costs greatly reduce the accumulation of calibration points. The possibilities to automatise measurements, to transmit them and to developp automatic processings render possible to have a substancial amount of calibration points on which statistical approaches are possible both to reject dubious points and to have idea about the dispersion of the results.

Elaborate for each sensor a calibration strategy

On board and vicarious calibration have to be conbined to produce the "official" calibration.It is in the domain of experise but we should help by providing usefull tools to conduct this expertise.

Contribute to ensure consistancy between the calibration of different sensors

To elaborate EO products at high level, we need to combine different sensors. Starting from a reference sensor, we have to ensure the consistancy with the other relevant sensors. The requirement here is to developp tools to facilate this intercomparison.

8.2. Practical considerations

In the solar domain

We propose devellop an operational tool to perform the following calval activities:

(i) vicarious calibration over bright land sites.

(ii) Vicarious calibration over dark targets.

(iii) Satellite intercalibration over bright targets.

(iv) Satellite intercalibration over dark targets

(v) All the above procedure can be used to validate the atmospheric correction.

The software will be organized around different modules. It relies on the '6S' code therefore common modules of this code will be used. The software package is generic and we will report the changes need to be done for other purposes.

In the thermal domain

What we proposed just above for the solar domain can be develop as well in the thermal domain:

(i) Vicarious calibration over bright land sites.

(ii) Vicarious calibration over water, including inland water.

(iii) SST validation over ocean.

(iv) LST over land (including lakes)

(v) TOC pressure.

For the two first applications, it is required to rely on a RTC code and MODTRAN can be used. The limitation in the use of MODTRAN is the 300 USD fee. That implies than MODTRAN will be run locally by a specific end user and that the role of this project is first to prepare the data for inputs to MODTRAN and second to use the MODTRAN output for calval purposes. The last three points are more satellite data and field measurement extractions and analysis.

9. Conclusion

It is certainly a good reference document for people willing to get information on the calval activities for the IVOS. As it was suggested, all additionnal contributions are welcome as well as comments on this manuscript.

The recommandation section suggests some tools to be developped and the description of those tools will be the next step.

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[i]. C. Fröhlich and J. Lean, "Total solar irradiance variation: the construction of a composite and its

comparison with models", International Astronomical Union Symposium 185: New eyes to see inside the sun and stars, Kluwer Academic Publ., Dortrecht, The Netherlands, 89-102 (1998).

[ii]. T. Riley and S. Bailey, "The sixth SeaWiFS/SIMBIOS Intercalibration Round Robin Experiment (SIRREX-6) August - December 1997", NASA Technical Memorandum: TM—1998–206878 (1997).