AATSR Validation
Principles and Definitions

PO-PL-GAD-AT-005 (1)

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1. Scope of this document

Version 2.2 of the AATSR Validation Plan (PO-PL-GAD-AT-005) was issued on 15th May 1998. It included details of the principles, objectives and requirements of validating the AATSR instrument, and outlined the various activities necessary to validate the AATSR data products.

Since that time, the plan has been split into three parts. This was done as parts 1 and 2 are essentially static in nature, whilst part 3 is evolutionary, frequently updated as more details on validation activities become known. Three separate documents now exist.

- PO-PL-GAD-AT-003(1): AATSR validation principles and definitions. This sets out the principles and definitions of validation, and the objectives of the AATSR validation programme.

- PO-PL-GAD-AT-003(2): AATSR measurement protocol. This gives guidelines on making validation measurements, setting out the methodologies that should be used and the measurements required.

- PO-PL-GAD-AT-003(3): AATSR validation implementation plan. This describes the activities that make up the validation programme.

The first two documents comprise text from the original AATSR Validation Plan, with only minor modifications. As such, authorship has remained the same. The third document, the AATSR Validation Implementation Plan, is an almost completely new document, written by the AATSR Validation Scientist.

AATSR Validation Principles and Definitions

2. Executive Summary

AATSR Validation is defined as being the means of assessing by independent means the quality of AATSR data products. Over sea, the primary product of AATSR is considered to be sea surface temperature (SST). Over land, because of the developmental nature of the level 2 land products (land surface temperature and vegetation product), the primary product for validation purposes is considered to be top-of-the-atmosphere brightness temperatures (thermal infrared bands) or reflectances (visible and near infra red bands). It is validation of these primary products with which these documents are principally concerned.

For both land and sea products, an ideal validation programme can be defined. An ideal validation is envisaged as being one in which *in situ* measurements are made of the parameters required, both (i) for an end-to-end comparison between the geophysical quantity and its corresponding AATSR product and (ii) for an analysis of any discrepancies between them (it will be difficult to carry out a proper analysis of SST results if information is not available, for example, on top of the atmosphere fluxes and atmospheric conditions). Such a comprehensive suite of measurements is likely to require an extensive dedicated campaign. Moreover, the ideal validation would be made not just at one site on one occasion but in a range of sites and seasons, fully representative of conditions encountered by AATSR around the globe. For the purposes of this document, such an ideal situation is labelled a Class 1 Validation. In reality, on grounds of cost and logistics, it is unlikely that this ideal could be achieved.

A more practical level of validation is one in which the measurements are reduced to those parameters needed for an end-to-end comparison and are made in very limited (perhaps just one) number of sites and seasons. This is labelled a Class 3 Validation. By reducing the number of measurements it may be possible to obtain data in ‘piggyback’ mode as part of an existing campaign, or by the addition of specialist equipment to an existing campaign, significantly cutting costs.

A Class 3 validation has two weaknesses. Firstly, with its small number of sites and seasons, the validation cannot be considered as representative. Secondly, analysis of any discrepancies between the geophysical quantity and the corresponding AATSR product will be limited due to the reduced number of parameters measured. A useful but realistic level of product validation is therefore a blend of Class 1 and Class 3 Validation. This is labelled a Class 2 Validation and involves the careful selection of a number of *in situ* campaigns, both piggyback and dedicated campaigns, such that the resultant data set can be considered representative and such that the dataset includes instances where a comprehensive measurement set, useful in the full analysis of any discrepancies, is recorded.

Whatever the level of validation, there must be confidence in the accuracy of the *in situ* measurements. To help ensure this confidence, a protocol for making the measurements can be defined. This protocol is described in the **AATSR Validation Measurement Protocol**. It establishes the minimum requirements on instrumentation and recommends methodology and procedures for deployment. It emphasises particularly the need for external, traceable calibration of all measuring equipment. It is not intended to be overtly restrictive but more to ensure maximum exploitation of data obtained from validation campaigns.

In addition to the evidence gathered from *in situ* campaigns, validation from external sources (such as cross validation between satellites, use of analysis fields) and quality assurance using previously derived AATSR data products will be essential in gaining full confidence in the ATSR data set. The **AATSR Validation Implementation Plan** describes the activities that will be carried out in the commissioning and post-commissioning phases. These include dedicated campaigns, piggyback campaigns, external validation and quality assurance.

3. Disclaimer

The Validation Plan has been written by the AATSR Science Advisory Group and the AATSR validation team, on behalf of the UK Department of the Environment, Transport and the Regions (DETR). The information contained in the document is of an advisory nature only. Inclusion in the text does not indicate support of the DETR or of any other funding body. While every effort has been made to ensure that the information is accurate, the authors deny liability for any loss or damage, which may be incurred by any person acting in reliance upon the information. The material published is of a general nature and persons should not act in reliance on it without considering their own particular circumstances and consulting with the authors. Recommendation of instrumentation is made on the basis of the campaign experience of the authors and should not be seen as exclusive - suggestions of any other equipment meeting the specifications are welcomed.

4. Validation Definitions

The Committee on Earth Observing Satellites Working Group (CEOS) has endorsed the following definitions of calibration and validation:

Calibration is the process of quantitatively defining the system response to known, controlled system inputs

Validation is the process of assessing by independent means the quality of the data products derived from the system outputs.

Accuracy is defined as the difference between a result obtained and the ‘true’ value.

Precision is defined as the difference between one result and the mean of several results obtained by the same method, i.e. reproducibility (includes random errors only).

Skin Sea Surface Temperature (SSST) is defined as the temperature of the top surface layer (a few tenths of a μm) of the sea. AATSR (and other infrared radiometers) detect radiation emitted by the layers of molecules close to the surface - these instruments therefore measure SSST.

Bulk Sea Surface Temperature (BSST) is defined as the temperature just below the surface layer. It is the BSST that is measured by conventional thermometers, usually at several tens of cm depth. The SSST and BSST can differ by typically several tenths of a degree.

The validation plan is written on the basis of these definitions.

5. The Calibration of AATSR

Before a more detailed consideration of the validation of AATSR products, it is appropriate to remark on the calibration of the AATSR instrument, i.e. the definition of the response of the system to known system inputs.

The AATSR instrument is completely spectrally characterised and radiometrically calibrated before launch and in-flight has self-calibration systems for the reflected and thermal channels. The pre-launch calibration plan for the thermal and visible channels are described in PO-PL-RAL-AT-0014 (Issue 2).

In-flight, it is necessary to verify that the in-flight calibration systems remain stable and are not subject to long-term drift. It is proposed that a *post launch* calibration of the optical channels is carried out over a stable land site (such as the Libyan desert site already used for AVHRR ATSR calibration). These data will be of use in determining the long term stability of the in-flight calibration systems and, through comparisons with data from other satellite instruments such as AVHRR, in the quality control of data (note that additional indications of these aspects may become apparent in the course of analysis of validation data).

6. AATSR Data Products

It is useful at this point to provide a summary of the AATSR data products. The following information has been extracted from Annex B of the AATSR Flight Operations and Data Plan (FODP).

Level	Product	Resolution	Comment
0	• Instrument Source Packet		
1b	• Gridded Brightness Temperature/Reflectance GBTR	1km	
	• Browse	4km	Nadir view composite
2	• Spatially Averaged Surface Temperature AST	17km/10 arc-min 50km/30 arc-min	Switches between sea and land record
	• Gridded Surface Temperature GST	1km	Switches between sea, land and cloud records

Table 1: AATSR Data Products

The AST and GST over sea are commonly referred to as the Average Sea Surface Temperature (ASST) and Gridded Sea Surface Temperature (GSST). Additional Level 2 products include the Land Surface Temperature (LST) product and a vegetation product (probably NDVI). The Land Surface Temperature product will be produced as a prototype product, during the commissioning phase of Envisat. The question of a vegetation product is still under review.

7. Validation Activities

Validation activities can be split into two – core validation activities and additional validation activities.

Core validation activities are defined as those which essential for the instrument's validation. Carried out throughout the commissioning phase of ENVISAT (initial core validation) and the mission itself (ongoing core validation), core validation activities establish whether AATSR is returning acceptable measurements and meeting its specifications.

Additional validation activities are defined as those that are carried out by the wider scientific community. They are additional to core activities and move towards a class 1 validation, where validation is carried out over a more extensive set of sites, seasons and using a variety of techniques.

Specifically, core validation activities are concerned with validating the level 1b and level 2 products listed in Table 1.

In terms of the GBTR product, core validation activities will seek to validate the 0.55, 0.66, 0.87 and 1.6 μm visible wavelengths, and the thermal 11 and 12 μm channels, over land surfaces. Procedures for measuring the 3.7 μm channel over the land are not well advanced and this channel is excluded from the core validation activities.

In terms of SST, core validation activities will validate the GSST and ASST products.

In addition to the level 2 data products listed, additional products are currently under review. These include an AATSR Browse Product, a Land Surface Temperature product, a vegetation product and a cloud product. Validation of yet undefined data-products (e.g. land radiation, aerosol products) is at present considered a scientific activity and will not form part of the core validation programme. Validation requirements will be developed as appropriate.

8. Validation of Sea Surface Temperature Data Products

8.1 Sea Surface Temperature Products

There are two AATSR sea surface temperature products: the Gridded Sea Surface Temperature (GSST) and the Spatially Averaged Sea Surface Temperature (ASST). The GSST is imposed on a 1 km grid. The ASST has cells of 17 km or 50 km. Detailed information on these products is given in the AATSR Flight Operations and Data Plan (FODP). Both products are, in the terminology of the FODP, geo-located, geophysical Level 2 data products.

It is the high resolution GSST that is the primary geophysical quantity measured by AATSR. Validation of GSST is therefore essential for validation of the AATSR instrument. In addition to the validation of GSST products, validation of ATSR ASST products will provide useful information on the performance of the AATSR instrument. Possibilities for ASST validation are discussed.

8.2 Validation of GSST and ASST Products

8.2.1 Classes of Validation

The ultimate validation dataset would be from a series of detailed *in situ* campaigns over a full range of sites and seasons. However, the cost of such an extensive validation would be prohibitive. Costs of £10-36K per day are not unreasonable for hiring an ocean going vessel. Costs of inshore vessels are much lower but such a vessel is limited to coastal waters.

Five classes of validation procedure have been identified that can be applied to AATSR SST data. These range from the ultimate data set (Class 1) through to quality assurance (Class 5). The class 1 validation dataset is in line with the recommendations of the first CASOTS (Combined Action to Study the Ocean’s Thermal Skin) workshop. This is a concerted action project funded under Theme 3 of the European Commission Framework IV Programme, Environment and Climate.

Class 1 Validation: validation using a comprehensive dataset from *in situ* campaigns over a full range of sites and seasons, for night and daytime overpasses. A comprehensive data set is one in which measurements are made of the parameters required both (i) for an end-to-end comparison between the *in situ* sea surface temperature and the AATSR SST and (ii) for an analysis of any discrepancies between them

Class 2 Validation: validation in a more restricted but representative range of sites and seasons with some (but in general not all) campaigns measuring a comprehensive dataset. Also included will be campaigns where only a minimal data set (ie sufficient to allow end-to-end comparison between *in situ* sea surface temperature and AATSR SST) is obtained. A Class 2 Validation is in effect a blend between Class 1 and Class 3. It involves the careful selection of a number of *in situ* campaigns such that the resultant data set can be considered representative.

In general, validation campaigns should consider:

- A range of techniques, each satisfying the measurement protocols and calibration demands
- A range of atmospheric column conditions (total water vapour, aerosol)
- A range of temperatures
- A range of timescales from seasonal to decadal
- A range of locations from high to low latitudes

Whenever possible, regions of low SST variability should be used. Regions of high SST variability should be avoided for the following reasons:

1. Regions of high SST variability make the in situ measurement unreliable both spatially and temporally
2. Frontal water mass regions are notorious for concentrating surfactant materials (i.e. slicks), possible affecting the emissivity of the sea water.
3. Regions of high SST variability also suffer a greater chance of poor weather and clouds, hindering the AATSR SST retrieval.

Class 3 Validation: validation using a minimal set of campaign data in a small number (one or more) of sites and seasons.

Class 4 Validation: validation against external sources of SST e.g. UKMO SST analysis (ASST)

Class 5 Validation: quality assurance using previously derived AATSR SST fields

The **AATSR Validation Implementation Plan** sets out the activities that make up the core validation programme for SST validation. Together they broadly represent class 3, 4 and 5 validation. As external validation activities are added, it is hoped that validation will move towards a Class 2 and then a Class 1 validation.

8.2.2 Parameters for measurement in *in situ* campaigns

Listed below are the parameters, which should be included in the measurements of any *in situ* validation campaign. The list is divided into those measurements necessary (i) to make an end-to-end comparison between the *in situ* sea surface temperature and the AATSR SST and (ii) those additional measurements valuable for an analysis of any discrepancies between them. Both sets of measurements are needed.

(i) to make end-to-end comparison of SST product and *in situ* skin sea surface temperature (SSST):

- radiometric temperature of the sea surface (i.e. SSST)
  - ~ upwelling infrared radiance from sea surface
  - ~ downwelling infrared radiance from the sky
- emissivity
  - ~ roll and pitch
  - ~ wind speed (also needed for flux calculations)
  - ~ sea state (including observations of surface slicks)
- sky state (amount and nature of cloud cover)
- position

- sun angle (to determine effects of sunglint)
- wind direction (so that data collected when the measurements are corrupted by the influence of the observation platform can be screened out, also needed for flux calculations).

AATSR detects the temperature of the sea surface skin (the top few tenths of μm). The skin sea surface temperature (SSST) can differ from the bulk sea surface temperature (BSST) of the water just a few cm below - typically by several tenths of a degree. Therefore, validation of the AATSR SST requires measurement of the skin or radiometric temperature. Data in which only bulk temperature measured by conventional thermometers in the sea are available are much less satisfactory than skin measurements, because of this skin-bulk temperature difference (known as the skin effect).

Note: although in general validation measurements should be of SSST's, in certain circumstances (i.e. high wind speeds) BSSTs can be used to add to the stock of data available for establishing the performance of AATSR. It is believed that at sufficiently high wind speeds the skin effect breaks down (e.g. Donlon and Robinson (1997, J Geophys Res, in press). The critical wind speed at which the skin effect becomes zero is a matter of much current debate, however most authors agree that a wind speeds of greater than $10ms^{-1}$ the skin effect can be considered negligible.

(ii) for detailed analysis of results of comparison :

- Radiosonde profile of atmosphere
    - ⇒ air temperature profile
    - ⇒ humidity profile
    - ⇒ pressure profile
- Air temperature, humidity and pressure at sea level
- Solar radiation
- Aerosol loading and particle size distribution
- Bulk SST (BSST) - ideally a 2m vertical profile (also essential for heat flux calculations and investigations of skin effect)
- Salinity (to provide information on local hydrography, which is valuable in interpretation of the satellite imagery)

Details of how these parameters should be measured can be found in the **AATSR Validation Measurement Protocol**.

9. Validation of AATSR Land Surface Data Products (Reflected)

The principles of AATSR validation of land surface data products described below are broadly similar to those developed for sea surface temperature. They differ in two main respects:

(i) The land surface data products based on the reflected channels of AATSR mean the co-ordinates of the sun must be accounted for.

(ii) The vegetation data products are not measures of a single physical parameter but are indices of a complex of biophysical characteristics. The process of validation must allow for this indirect association.

As the physical principles to be applied in the thermal channels are different from the reflected channels, they are considered separately. Some of the procedures applied for sea surface temperature may still be appropriate, but application on land will also have to account for variations in emissivity and the greater complexity and heterogeneity of the surface.

9.1 AATSR Land Surface Data Products (Reflected)

AATSR land surface data products outlined in the Scientific Requirements document are:

- ToA reflected fluxes from the land surface in channels at 0.55, 0.66, 0.87 and 1.6 µm. wavelengths
- A vegetation data product (as yet unspecified) to assess vegetation quantity and possibly state.

The ability to measure the temperature of burning vegetation is also specified as a science requirement and, while not actually specified, the ability to measure land surface temperature (LST) is clearly implicit in the existing specifications of AATSR.

9.1.1 Principles of Land Surface Validation

Validation studies at the land surface require precise knowledge of the physical characteristics of the surface and of the state of the atmosphere at the time of satellite observation. Validation studies of vegetation data products must also account for a range of biophysical characteristics of the vegetation.

9.1.1.1 Reference Site Selection

Reference sites must be flat surfaces that can be regarded as uniform over an extended area of 5 by 5 pixels in all directions. The residual variability of these sites must be well characterised by appropriate sampling procedures.

9.1.1.2 Validation Logistics

Full validation campaigns require large resources in terms of equipment and qualified manpower to be deployed in the field, with a relatively short window of opportunity for measurement. The parameter that changes most rapidly is the state of the atmosphere, which must take priority over other measurements at the time of overpass. Surface characteristics usually change more slowly and can be spread over a period of a few days, but allowance may sometimes be required for diurnal variations.

9.1.1.3 Surface Characteristics

Very few natural surfaces meet the specifications of a Lambertian surface, and in general the spectral bi-directional reflectance distribution function (BRDF) depends on the nature of the surface and is a function of solar zenith angle, viewing zenith angle and their relative azimuth. Much of the behaviour of the BRDF can be described in terms of the phase angle (sun - surface - sensor), which depends on latitude, season, time of day and sensor orientation. For a given solar zenith angle, the shape of the BRDF is usually a smoothly varying function, with two nodal points: (i) As the phase angle approaches zero, a marked increase is observed in bi-directional reflectance due to the disappearance of shadows apparent from the viewing positions as it converges on the solar direction, a phenomenon is known as the "Hot Spot"; (ii) A component of specular reflection may also be observed over smooth surfaces (although these are not common on land) when the view direction is towards the sub-solar point.

Characterisation of the surface for AATSR validation studies requires the BRDF of the surface to be measured, at least at the two angles viewed by the satellite.

9.1.1.4 Vegetation Parameters

The vegetation parameters having the greatest effect on the BRDF and for which several models have been developed are the leaf area index (Total, one-sided leaf area per unit area of ground), the leaf angle distribution, and the optical properties of leaves and soil. The effect of stems and other structural elements of a canopy can be treated in a similar way (but usually as a separate component) to leaf area index. The leaf optical properties are sometimes broken down to their functional dependence on moisture and pigment contents and soils, similarly, to moisture, roughness and type. Modelling of the "Hot Spot" requires an additional parameter to account for self-shading by leaves and this can be described in terms of the ratio of leaf size to its height above the surface.

9.1.1.5 Atmospheric Parameters

The atmosphere affects the signal by attenuating the component coming from the surface and by adding a component of its own, termed the path radiance. A secondary process which can also be important in heterogeneous landscapes is scattering of radiation reflected by neighbouring surfaces into the return path from the target pixel, although this process is less important for the dimensions of ATSR pixels. Measurement of surface reflectances by AATSR requires correction for these effects.

The atmospheric correction is a function of solar and viewing angles and generally increases towards shorter wavelengths. The principles of radiative transfer are well understood and with suitable atmospheric data, the required correction can be modelled. The data requirements for atmospheric models are information on water vapour content and the type and concentration of aerosol. While adequate water vapour data can be obtained from meteorological sites, the aerosol type and loading is not measured on a routine basis.

Two approaches to determine aerosol effects can be used in validation. The more precise method is to measure the aerosol optical depth directly with a sun photometer. This measurement in effect bypasses the need for concentration estimates by using optical depth directly in the model, while aerosol type, which is critical in determining the scattering phase function, can be inferred from the spectral variation of the optical depth. The second method, used when optical depths are not available, is to estimate aerosol loading using a surrogate measurement such as horizontal visibility.

The two views of AATSR offer the possibility of determining the atmospheric correction directly from inversion of the image data. Such a procedure requires some component of the image data to be invariant with angle. Various techniques are currently under investigation. Their validation will require very precise measurements of surface reflectance and atmospheric attenuation and scattering.

9.1.1.6 Satellite Factors

One consequence of the conical scanning of the AATSR instrument is an asymmetry between the northern and southern hemispheres in the viewing geometry of the instrument, because the forward look of the instrument on the day side of the earth is always along the track towards the south. At northern latitudes the forward view is always towards the sun, i.e. in the general direction of the sub-solar point, whereas at southern latitudes the view is away from the sun (Figure 1). When ATSR was primarily a thermal instrument, this asymmetry was of little consequence, but in the reflected solar wavebands, the phase angle is fundamental to the determination of atmospheric corrections and is a primary parameter in the description of the surface BRDF. Table 2 shows the range of angles encountered in an example of a single scan.

Table 2

Solar-viewing geometry for the satellite at 44°N, northern midsummer (solar declination 23.44°). Pixel nos. 224 and 778 represent the nadir view limits; 1316, 1686 and 1501 represent the two limits and the central point, respectively, of the forward view. The local latitude and longitude (relative to the sub-satellite track) indicate pixel location: The forward view is about 8° south of the nadir.

Pixel no.	Solar Zenith	Solar Azimuth	View Zenith	View Azimuth	Phase Angle	Latitude	Relative Longitude
224	25.5°	44.6°	21.8°	104.6°	23.4°	43.4°	3.3°
778	28.5°	55.5°	21.8°	238.4°	50.3°	42.7°	-2.9°
1316	24.5°	64.1°	52.3°	189.5°	68.5°	36.7°	-1.5°
1501	22.1°	61.1°	55.0°	171.5°	64.9°	36.0°	1.5°
1686	21.0°	53.6°	52.3°	153.4°	58.5°	37.4°	4.2°

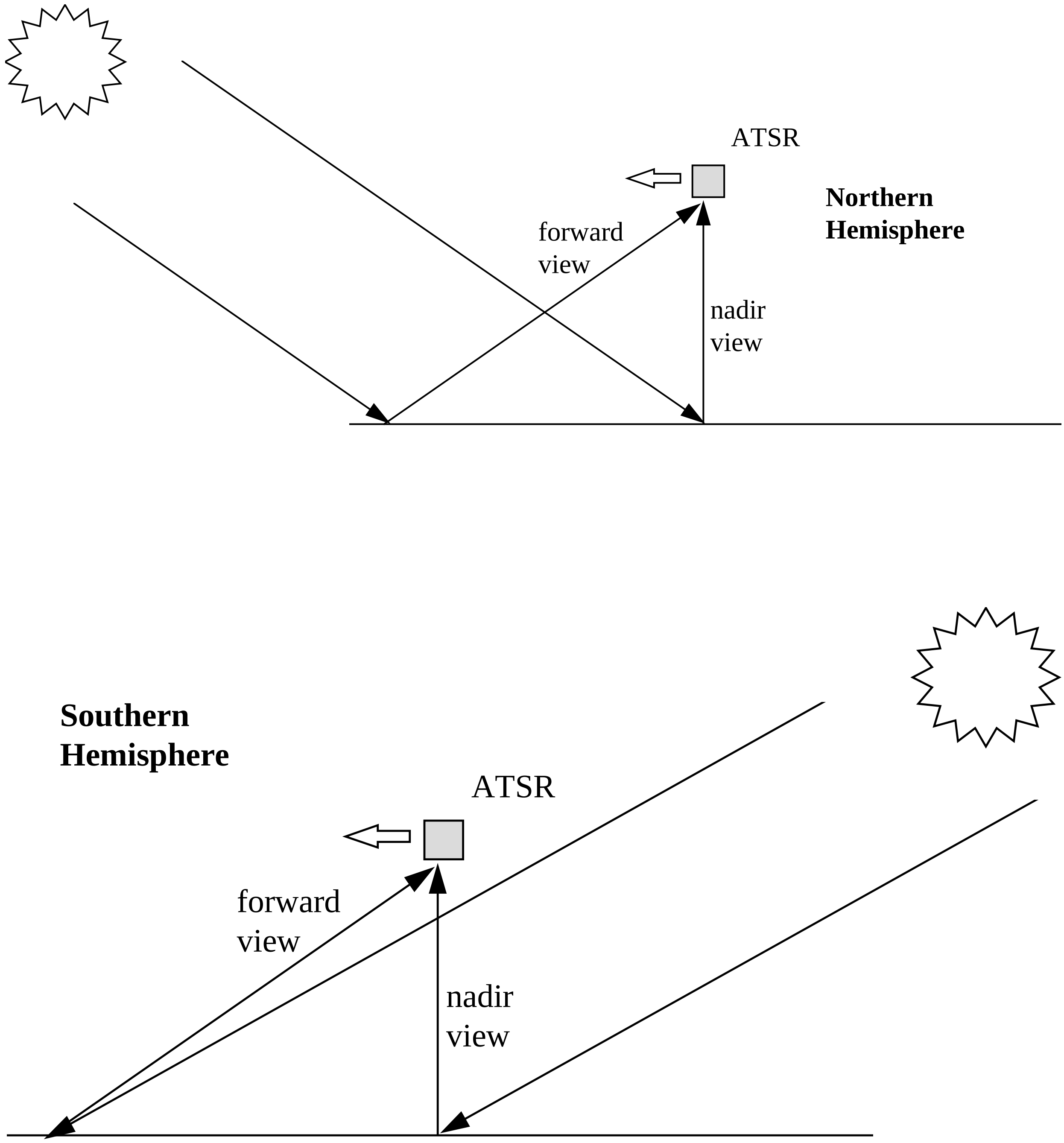

Figure 1 Outline of ATSR2 sun-surface -sensor geometry in the Northern and Southern Hemispheres

For a particular site, the two views are made up of the forward part of one scan and the nadir part of a second scan a few minutes later. Table 2 shows the forward viewing, solar and phase angles at the equinoxes and summer and winter solstices for two hypothetical sites at 44° N and S.

Table 3

(a) Seasonal variations in solar and viewing view geometry on the forward sub-satellite track (pixel no. 1501) at a site of latitude 44° N.

	Solar Zenith	Solar Azimuth	View Zenith	View Azimuth	Phase Angle
Equinox	47.7°	28.7°	55.0°	171.5°	95.5°
Summer solstice	26.7°	46.5°	55.0°	171.5°	72.5°
Winter solstice	69.7°	20.4°	55.0°	171.5°	118.3°

(b) Seasonal variations in solar-view geometry on the forward sub-satellite track (pixel no. 1501) at a site latitude 44° S.

	Solar Zenith	Solar Azimuth	View Zenith	View Azimuth	Phase Angle
Equinox	47.8°	151.3°	55.0°	171.5°	17.3°
Summer solstice	27.1°	134.0°	55.0°	171.5°	36.2°
Winter solstice	70.1°	159.7°	55.0°	171.5°	18.3°

Note: solar zenith angles are not quite identical in the two hemispheres because the angles were calculated for the nearest day

Table 3 demonstrates that the range of phase angles encountered in the Southern hemisphere are not reproduced at other seasons in the northern hemisphere. In particular, the "Hot Spot" effect will be much more evident in the forward view when the satellite is over the Southern hemisphere, where the phase angles are smaller.

To provide an adequate test of operational conditions, validation campaigns must aim to span the range of phase angles expected in operational use of AATSR.

9.1.2 Categorisation of Validation Procedures

In keeping with the classification procedure applied to validation schemes for sea-surface temperature, it is possible to identify five classes of a comparable nature.

Class 1 - validation using the full data set from *in situ* campaigns over a range of reference targets, including vegetated surfaces. This would be the primary validation procedure for AATSR. Campaigns of field measurement would be conducted over a representative set of sites and seasons, including sites in both hemispheres. Atmospheric attenuation and scattering and surface bi-directional spectral reflectance would be measured coincident with the acquisition of ATSR-2 data. To validate vegetation data products, the sites selected would have to include a suitable range of vegetation covers in which variables such as foliage density, canopy structure, leaf and soil properties etc. would be measured.

Class 2 - validation using a reduced set of campaign data over a more restricted range of targets. Class 2 validation campaigns would be a reduced version of Class 1 over a limited set of surfaces, probably at one site. However, the measurements must be of sufficient quality to allow proper validation of AATSR procedures. Using the **AATSR Validation Measurement Protocol** a set of independent Class 2 campaigns could be brought together into a full class 1 validation.

Class 3 - validation using targets of known constant reflectance with routine meteorological data to determine the atmospheric correction. Where a set of standard, non-vegetated reference sites have been previously studied to establish their full bi-directional reflectance distribution function, and subject to it being established that the BRDF of these sites is relatively invariant over time, it should be possible to use the reflectance estimates from AATSR with atmospheric corrections derived from local meteorological data, to provide an intermediate validation.

Class 4 - validation against other sources of reflectance and vegetation cover data. The only other routine sources of surface reflectance and vegetation data are from other satellites, of which the NOAA AVHRR is the most obvious candidate for routine comparison. A weaker form of comparison for validation could use seasonally expected values of reflectance and vegetation cover, but this approach is open to the criticism that it does not allow for the unexpected.

Class 5 - quality assurance using previous measurements by AATSR. Spatially averaged AATSR reflectance and vegetation fields can be validated for quality assurance against previous AATSR measurements in a similar way to the SST data. Apparent changes that exceed an expected rate threshold can be flagged for closer examination. It should be noted however that sudden change in reflectance need not imply an error as such changes can occur, for example, with rain or snow. Also, depending on the spatial aggregation scheme employed, retrieved values in heterogeneous landscapes may be quite unstable.

In a similar way to SST, the **AATSR Validation Implementation Plan** details the validation activities that will form part of the core validation programme. These activities are of Class 2, Class 4 and Class 5 validations. Again it is hoped as the mission progresses, external validation campaigns will mean a Class 1 validation is approached. Campaigns should follow the **AATSR Validation Measurement Protocol** to ensure results can be collated and compared.

9.1.3 Parameters for measurement in in situ campaigns

A validation measurement set must measure either the surface-leaving spectral radiance or the surface spectral reflectance, and characterise the atmosphere well enough to permit an accurate atmospheric correction by a radiative transfer code.

The atmospheric correction must include scattering and absorption by aerosols for all four shortwave AATSR channels, and must include Rayleigh scattering for the 0.55, 0.67 and 0.87 micron channels. Ozone absorption significantly affects the 0.55 and 0.67 micron channels and carbon dioxide absorption affects the 1.6 micron channel.

Water vapour has a minor effect: the transmittance of water vapour at the modest amount of 30 Kg m^-2 is 0.995 at the 1.6 micron channel .

(i) Minimum list of measurements to predict the TOA reflectance:

- Either:
    - Upwelling spectral radiance in the AATSR view directions

or:
    - Surface spectral reflectance in the AATSR view directions

- Aerosol optical depth and size distribution
- Surface air pressure (to determine the Rayleigh scattering)
- Column ozone amount
- Column water vapour amount
- Sky state

(ii) Additional measurements to be combined with (i) to make a comprehensive set permitting the analysis of discrepancies:

- Aerosol single-scattering albedo or imaginary part of the refractive index
- Diffuse-to-global irradiance ratio (broadband or spectral)
- Solar radiation (broadband irradiance)

Details of how these measurements should be undertaken are given in the **AATSR Validation Measurement Protocol.**

10. Validation of AATSR Land Surface Data Products (thermal)

Algorithms for deriving land surface temperature (LST) using split-window radiances are sufficiently advanced that accuracies of 1-3 K are possible. Better accuracies (about 1 K) are obtained at night, when differential surface heating is absent. Since surface spectral emissivities are not known to sufficient accuracy and not measured over large parts of the land surface an algorithm that has no explicit emissivity dependence is required. Angular effects on directional temperature and surface emissivity are also difficult to include, so the LST algorithm will rely only on the nadir AATSR split-window radiances. Further research will investigate incorporation of the forward view AATSR data into the LST algorithm.

In many respects the validation procedures required for LST are similar to those for SST, however there are some important differences. Paramount of these are the problems of sampling (LST is a notoriously variable quantity in space and time) and of scaling-up. Typical validation measurements will include point radiometer measurements or contact temperature measurements-these must be suitably averaged for comparison with AATSR measurements.

There are three kinds of validation of the thermal channels that are required over the land surface:(i) Validation of 'at surface' brightness temperatures, (ii) Validation of TOA brightness temperatures, and (iii) Validation of a geophysical product- the LST.

This section deals only with validation of the AATSR 11 and 12 micron data over clear land surfaces. Procedures for using the 3.7 micron channel over the land are not well-advanced and this channel is excluded from the land validation plan.

10.1 AATSR Land Thermal Products

Brightness temperature products over the land will be TOA Level 1b gridded data at 11 and 12 microns in both the nadir and forward views. An 'at surface' brightness temperature product is not currently proposed but the validation procedures outlined below do permit some limited validation of this quantity.

The LST product will be a pixel-by-pixel product requiring Level 1b gridded nadir brightness temperatures.

The LST algorithm proposed is a regression algorithm with coefficients that will be updated from time to time. The algorithm will be applied only to vegetated surfaces and will only be validated for these surfaces. The form of the algorithm will be,

$$LST = a + b\,T11N + c\,T12N,$$

where the coefficients a, b and c will vary with water vapour amount. Coefficients for vegetated surfaces only will be supplied. Other surfaces may be included at a later date.

The accuracy requirement of the algorithm will be 1 K at night and 3 K during the day for vegetated surfaces. Snow covered surfaces, deserts, mountainous regions and surfaces of mixed type are not included in the validation plan.

10.1.1 Principles of Validation of Land Thermal Products

Validation of the AATSR land thermal products requires the use of well calibrated radiometers with bandpasses matching the AATSR thermal channels. In addition, low-cost surface-mounted contact temperature transducers and wideband (10-12 micron or 8-14 micron) radiometers are needed to capture spatial variability at 1-3 km scale. The use of a well-calibrated interferometer is strongly recommended.

Atmospheric data required includes temperature and moisture atmospheric profiles, aerosol optical depth and an indication of cloudiness (either visual observation or vertical viewing all-sky camera). Validation of the TOA and 'at surface' brightness temperatures will involve the use of a radiative transfer (RT) code. While it is acknowledged that trace gases (CO_2, O_3, CH_4, N_2O) do contribute to the accurate determination of the brightness temperatures, it is expected that in most cases climatological values of the column abundances or satellite-derived abundances will be available and used in the RT calculations.

Validation must take place over uniform land areas. Spatial uniformity requirements suggest that the site should have low thermal variability at scales from a few metres to a few kilometres. This implies that mountainous terrain, undulating land or land of mixed surface type (e.g. containing small lakes, roads or forests) would be unsuitable. Directional effects are known to be important in sensing thermal radiation from the land surface. Sites with significant shadowing effects, slopes, or structured vegetation (e.g. crops) should be avoided.

10.2 Categorisation of Validation Procedures

As for other AATSR products, five classes of validation can be identified for the land thermal products,

Class 1 - Full validation comprising campaign based experiments utilising narrowband radiometers, radiosonde equipment, optical depth measurements, cloudiness data over a range of land thermal targets at night and day.

This is the most comprehensive form of validation and aims to quantify the accuracy of the LST product and provide an estimate of the quality of the TOA and surface brightness temperatures. A range of targets with varying degrees of vegetative cover are needed, including crops, pasture, grassland and forests. A range of atmospheres is required including arid conditions and moderate to high water vapour and aerosol loadings, typical of tropical climates. Because of the variability in atmospheric structure, it is important to conduct validation for both the ascending (night-time) and descending (daytime) AATSR acquisitions. The use of airborne mounted radiometers above the boundary layer and preferably about 5 km is strongly desired and recommended. Class 1 validation should not be conducted over surfaces of mixed type (at scales of 3 km or less), in mountainous terrain, snow-covered or desert surfaces.

Class 2 - Validation using a reduced set of campaign data over a more restricted range of targets and times. Class 2 campaigns may be a reduced version of Class 1 campaigns where aircraft data or particular sites are not available. The important parameters that must be measured are: spatially averaged surface temperatures (radiometric and contact thermodynamic), atmospheric moisture and temperature profiles (preferably collocated or within 100 km of the site), optical depth and cloudiness.

Class 3 - Validation at key selected sites using routine meteorological data and infrared or contact surface temperatures over an area comparable to the FOV of the AATSR. Conducted at specially selected sites close to routine radiosonde launches where multiple infrared or surface contact temperature measurements are being made.

Class 4 - Validation against other sources of thermal land data, e.g. AVHRR-3, MODIS, ASTER and GLI data. Comparisons with LST's from other satellites are possible provided that the measurements are made at the same time. This excludes the possibility of using the AVHRRs, which have overpass times up to several hours before or after ENVISAT. However it is anticipated that the EOS/MODIS and ADEOS-II/GLI will be operational during the time-frame of ENVISAT allowing inter-comparisons of LST products and brightness temperatures to be made at selected targets.

Class 5 - Quality assurance using previous AATSR measurements. Routine monitoring of AATSR brightness temperatures over ocean and land surfaces will provide some quality assurance for Class 5 validation, using previous AATSR BT fields.

10.3 Land Surface Temperature (LST)

The AATSR LST algorithm will provide a surface temperature that is independent of the wavelength of measurement, the geometry of measurement and the surface and atmospheric structure. Validation of the LST using ground-based radiometers is required but is problematic because surface-mounted radiometers may still suffer from the effects of viewing geometry and surface spectral emissivity. These problems can be alleviated by using surface-mounted, contact temperature transducers. Sufficient numbers of these devices will be needed to ensure that the correct amount of spatial sampling is being made. A recommended strategy is to use a combination of multiple wideband radiometers and contact devices spread over a large uniform, flat land target.

Accuracy of the surface radiometric measurements and corrections can be assessed by comparison of the radiometer measurements with the contact measurements. Spatial sampling can be validated by statistical means using sub-samples of the contact temperature measurements. During the morning overpass in summer months it is likely that wind effects will cause temperature fluctuations of several Kelvins in time intervals as short as 1 minute. These fluctuations must be smoothed out by either spatial or temporal averaging over time intervals short enough to prevent errors caused by temperature changes due to solar heating/nocturnal cooling. It is recommended that during Class 1 and 2 validation campaigns, temporal sampling by the surface-based radiometers and contact devices be as short as 1 s.

11 Airborne Measurements

11.1 Introduction

At the current time, airborne measurements do not form part of the core activities described in the AATSR Validation Implementation Plan. However, it is hoped that as the mission progresses, some airborne measurements will be obtained and analysed.

Aircraft with radiometers capable of simulating AATSR measurements provide a powerful tool not only for validating TOA radiances but also are capable of measuring a range of *in-situ* properties of the atmosphere in order to validate products. Additionally they provide a means of fully testing the atmospheric corrections needed for almost all applications. Combination of aircraft campaigns with other ground or ship experiments gives the opportunity for intercomparing the radiometers used in the validation.

The minimum set of objectives outlined below amount to about 54 hours of flying time. Some additional flight time may be needed to transit to particular locations. With forward planning these transits could be shared with other aircraft activities. The MRF C130 has all the instrumentation needed to undertake this work including SAFIRE, a radiometer specifically built for this purpose in mind funded by the oil industry (IPIECA).

11.2 Cloud Free Conditions over Ocean

11.2.1 Objective

To provide validation of TOA radiances for IR channels and a single validation point for SST. Provides atmospheric data to check atmospheric corrections are being applied correctly.

11.2.2 Measure

- Upward radiances at all IR AATSR channels at a variety of altitudes from 15m to 10km for level runs of 20km length. During satellite overpass time, measurements should be made at either highest or lowest altitude (highest for TOA validation, lowest for SST validation).
- Temperature, humidity, ozone mixing ratio and aerosol properties including size distribution and scattering and absorption cross section.
- Downward direct and diffuse solar irradiance. Measurements at the highest altitude can be used to check for the atmospheric aerosol above the aircraft, measurements between 15m and 10km can be used to check the measured aerosol loading.

11.2.3 Flight time

The flight time needed is a minimum of 2 x 6 hours. It is desirable to repeat measurements in both mid latitudes and tropical atmospheres.

11.3 Measurements over marine stratocumulus

11.3.1 Objective

To provide validation of the TOA radiances for the solar channels on AATSR

To provide validation of cloud properties products (cloud optical depth and effective radius)

11.3.2 Measure

Cloud sheet should be extensive, homogeneous and thick. Upward radiances at solar AATSR channels should be measured at either 10km or just above cloud top (Highest level providing best information of TOA radiances, lowest level providing best validation of cloud properties).

Measurements at least 3 levels in cloud of the liquid water vapour content and cloud particle size distribution on level runs about 20km in length.

Measurements above the cloud should include the temperature, humidity, ozone mixing ratio and aerosol properties including size distribution and scattering and absorbing cross section.

Measure downward direct and diffuse solar irradiance. Measurements at the highest altitude can be used to check for the atmospheric aerosol above the aircraft, measurements between cloud top and 10km can be used to check the measured aerosol loading.

11.3.3 Flight time

Minimum flight time 2 x 6 hours. Desirable to repeat the exercise in different marine situations and overland.

11.4 Cloud free but high aerosol loading over sea

11.4.1 Objective

Determine aerosol optical depth and other possible aerosol products. validate the retrieval of SST through hazy atmospheres.

11.4.2 Measure

As Section 11.2 above but need to seek conditions with aerosol optical depth greater than 0.1. Radiometer needs to measure all AATSR channels.

11.4.3 Flight time

Minimum 3x6 hour flights with different aerosol conditions. Should be repeated over land.

11.5 Measurements of (near surface) land reflectivity

11.5.1 Objective

Validation of satellite retrieval of bi-directional reflectance and build up a more complete description of bi-directional reflectance of site.

11.5.2 Measure

Need an homogeneous area of size at least 5km x 5km.

Make direct measurements in cloud free conditions at the two AATSR view angles of the radiance in all channels at the lowest permitted altitude (75m say) at overpass time. Away from overpass time, make measurements at various viewing and sun geometries of the reflectance.

Conduct profile measurements to characterise the atmosphere up to 10km altitude and directly above that level.

11.5.3 Flight Time

Estimated flight time would be 12 hours in total. Each flight would take about 3 hours on task. Total flight time would depend on the number of sites and the transit time needed to reach them.

11.6 Measurements of (TOA) Land Reflectivity

11.6.1 Objective

Validation of the land surface TOA reflected flux product for the 0.55,0.67, 0.87 and 1.6 micron channels. The TOA reflectance will usually be much higher over the land than over the ocean.

11.6.2 Measure

Need a homogeneous area of size at least 5 km x 5 km.

Make direct measurements in cloud free conditions at the two AATSR view angles of the radiance in all channels at an altitude of at least 3 km above sea level, and preferably at 10 to 20 km. This places the radiometer above almost all of the atmospheric aerosols and water vapour, so that only a simple correction for the residual atmosphere and stratospheric ozone is required. It is essential that the radiometer is accurately calibrated, preferably just before and just after the measurement from the air. Note that pointing off nadir is likely to be more difficult than pointing at nadir.

11.6.3 Flight Time

Minimum 1 hour required. This task could be done on flights to validate TOA brightness temperature over land.

11.7 Radiometer Inter-comparisons

11.7.1 Objective

The aircraft radiometer provides an ideal method of inter-comparing a number of ground/ship based radiometers in their working environment.

11.7.2 Measure

Measurements from a subset of instrumentation mentioned in previous sections to fully characterise the atmosphere in particular a need to extrapolate the effect of the atmosphere from the lowest flight level to the surface.

11.7.3 Flight Time

Probably marginal if aircraft campaign is combined with other surface based campaigns.

11.8 Other Cloud Properties

11.8.1 Objective

Dependent on the development of cloud property algorithms there may be a need to validate newer cloud properties. These may include retrieval of optical depth and particle size for more complicated broken cloud scenes and/or the development of a range of parameters needed to describe ice clouds.

11.8.2 Measure

Depends on problem to be solved. There will be a need for a greater variety of cloud *in situ* probes to fully characterise ice clouds.

11.8.3 Flight time

TBD

11.9 Measurements of Land Thermal Products

11.9.1 Objective

Validation of the AATSR LST product over vegetated surfaces to investigate the use of LST's in mesoscale modelling over land, for climate applications (e.g. surface radiation budget) and for agricultural crop management.

11.9.2 Measure

Measure radiometric brightness temperatures at matching AATSR 11 and 12 micron bands from high altitude over a homogeneous, flat land area of at least 5 km x 5 km. Radiosonde and optical depth measurements are required within 1 hour and 50 km of the land area.

11.9.3 Flight time

Minimum of 4 hours required. It is highly desirable to conduct flights during night and day and in summer and winter.