AATSR Validation Measurement Protocol

PO-PL-GAD-AT-005 (2)

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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.

This document forms part 2 of the Validation plan. 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 Plan
Measurement Protocol

Contents

1. Introduction

The AATSR Validation plan is divided into three parts: validation definitions and principles, measurement protocol and validation implementation. This document represents the second part, the measurement protocol.

The aim of the document is to provide scientists, wishing to undertake validation activities, with some guidelines as to the measurements that are needed, and the instrumentation, methodology and procedures that should be used. Although it is recognized that methodologies may vary slightly according to individual campaigns and the instrumentation available, it is essential that all measuring equipment must have external, traceable calibration, and all measurements must be fully and reliably documented. Following certain guidelines ensures the maximum exploitation of data obtained from validation campaigns.

The document is divided into three sections, dealing with sea surface temperature measurements, land surface reflectance measurements and land surface thermal measurements.

2. Disclaimer

This document 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.

3. Sea Surface Temperature

This section deals with measurements needed for the validation of the AATSR sea surface temperature data products: the Gridded Sea Surface Temperature (GSST) and the Spatially Averaged Sea Surface Temperature (ASST).

3.1 Temporal and Spatial Sampling

The temporal and spatial variations in sea surface temperature have implications for sea surface temperature measurements. Issues that need to be considered include:

- The spatial separation between satellite and *in situ* measurements: how far away in distance, from the satellite track, should *in situ* measurements be, for reliable validation?
- The temporal separation between satellite and *in situ* measurements: how far away in time, from overpass, should *in situ* measurements be, for reliable validation?
- Sampling frequency
- Size of instrument footprint
- Can spatial variations of sea surface temperature be approximated by a temporal average of a spot measurement?

Ideally, observations should be made precisely at the time of overpass, directly under the satellite track. Observations outside this coincidence, will introduce error into the validation dataset. Minnett (1991), making observations in the southern Norwegian Sea, found that spatial separations of about 10km and time intervals of about 2 hours can introduced rms differences of 0.2K into the error budget of a satellite validation dataset.

As the spatial and temporal separation between satellite and *in situ* measurement increases, the confidence of the validation match up decreases. The exact amount of error introduced by sampling away from overpass will vary according to the local conditions - in frontal regions, the variability could be several degrees over just a few km, whereas in more stable regions, the variability will be much less. Observations away from exact coincidence should be justified by the experimenters, according to the local conditions.

All measurements must be fully and reliably documented. Sampling intervals should be as fast as allowed by the instrument systems - the data can be averaged over longer timescales, at a later date. Crucially, *all data must have a common time stamp.*

3.2 Upwelling infrared radiance from the sea surface and downwelling infrared radiance from the sky

3.2.1 Introduction

Measurements of upwelling and downwelling infrared radiation provide the fundamental validation of the AATSR SST data products. The signal at a surface based radiometer looking at the sea surface is comprised of two components: the radiation emitted from the sea surface and that reflected at the sea surface from the sky. For a self-calibrating radiometer, the brightness temperature of the sea surface can be determined as follows.

The output signal S_W (Thomas et al,. 1995) is given by:

$$S_w = G\left[\varepsilon_w B'(T_w) + (1-\varepsilon_w)B'(T_s)\right] + O\,, \qquad (1)$$

where T_W is the temperature of the water (ie SSST), T_S the sky temperature.

ε_W is the seawater emissivity appropriate to the spectral response of the filter and detector combined and should be calculated e.g. following Sidran (1981) and Downing and Williams (1975).

Following Thomas et al..(1995), it is assumed that the calibration and reference sources are perfect black bodies. *G* is the gain and *O* the offset of the detector and *B'(T)* is radiance integrated over the instrument bandwidth. The gain is given by:

$$G = \frac{S_H - S_C}{B'(T_H) - B'(T_C)} \qquad (2)$$

and the offset by:

$$O = S_C - G\left[B'(T_C)\right], \qquad (3)$$

where S_C and S_H are the output signal when looking at the cold and hot blackbodies respectively. T_C and T_H are the temperatures of the hot and cold black bodies. From these equations, the temperature T_w of the sea surface can be determined.

The upwelling and downwelling signals are measured, using either a single scanning infrared radiometer (best) or two identical radiometers, one looking up, one looking down.

3.2.2 Accuracy

Any instrument used to validate the AATSR SST data products must match the accuracy of the satellite derived SST, and ideally, should surpass it. The AATSR instrument and ground processing system is required to measure skin SST (SSST) to an accuracy of better than +/-0.3K for a single 1 km sample. The requirement on any validating instrument should measure SSST to an accuracy of at least 0.15K or better and ideally 0.1K or better, over the full range of expected global SSST. Accuracy should be verified using a traceable external calibration source.

3.2.3 Spectral Response

To permit direct validation of the satellite brightness temperature values, the radiometer channels (at the *in situ* operating temperature) should ideally be matched as closely as possible to the AATSR channels (or synthesised, if using a spectrometer). These channels have been chosen to lie in atmospheric windows and (for the thermal channels) in the region of high sea surface emissivity. Different and/or broader spectral windows will not only mismatch the AATSR channels but they will also be more sensitive to emissivity variations with look angle and to atmospheric variations. They should therefore be avoided. If this is not possible, the effects of any mismatch should be minimised by modelling the effect of different passbands on atmospheric absorption, emissivity etc. The effect of any changes of temperature on the spectral response of the radiometer must also be considered.

3.2.4 Choice of radiometer

High accuracy (+/- 0.1K) radiometry is not a trivial task. Several ship-borne radiometers have been designed but are still prototype in nature. Their operation requires experienced personnel and dedicated campaigns. Radiometers should be self-calibrated by two internal black bodies. The two black bodies should be at temperatures, either side of the range of expected sea surface temperature measurements.

3.2.5 Calibration

It is essential that the radiometer is fully calibrated against an external black body source. The calibration should cover the range of expected sea surface temperatures and be made in the range of expected air temperatures. The calibration should be repeated before and after every observation run, and more frequently, if the radiometer gain and offset are found to vary on a shorter timescale. The calibration black body should be a traceable standard, ideally to the AATSR target black bodies by using the AATSR external calibration source. If it is not possible to have regular access to this source, it should be used to provide a one off absolute calibration, and then a secondary source (such as the CASOTS black body) should be used to monitor the calibration in the field.

3.2.6 Installation

Radiometers should be installed in a position that gives an uninterrupted view of clear water (clear of the ship's wake) or of sky emission. They should be at the height needed to give the required footprint at the surface, and be clear of the worst of the sea spray.

The emissivity of a flat sea surface is roughly constant until zenith angles of 40^o - 50^o are reached, when it starts to decrease rapidly. The sea-looking radiometer should, therefore, be installed at a zenith angle ξ large enough to clear the structure of the platform and to avoid any direct reflections but small enough (less than 40^o) to fall in the high emissivity regime. The sky looking radiometer (or the sky sample of a scanning radiometer) should be positioned to measure an area of the sky from which downwelling radiance is expected to reflect into the sea-looking radiometer, ie at a zenith angle of 180-ξ.

Ideally, measurements should also include upwelling radiation at the same look angle as AATSR, i.e. as close to nadir as possible (without seeing direct reflections) and at 53 degrees to nadir.

Note: the use of a single sky temperature measurement is currently under investigation. Evidence suggests that use of a mean value of temperature taken over a wide area of sky is more appropriate given the reflecting properties of the non smooth sea surface.

3.2.7 Roll and Pitch

Inclinometers should be installed to measure roll and pitch, either as an integral part of the radiometer or as stand alone instruments. Possibilities include the use of Acoustic Doppler Current Profilers (ADCP) or dedicated sensors such as those incorporated in some GPS units.

3.2.8 Sea state (including observations of surface slicks)

The minimal requirement is for a visual observation at overpass and typically every 15 minutes either side of overpass. The observation should be more frequent in a variable sea state. It should include a description of the sea corresponding to the Beaufort wind scale and according to the 'Sea Criterion' laid down by the World Meteorological Organisation (see *State of Sea Booklet*, HMSO, Met. 0 688b, ISBN 0 11 400344 0). Features of the sea surface, such as foam, debris and slick material must be noted, with time of observation. If possible, a sea-pointing camera (video or stills) should be deployed to provide an on-going record of sea state. Another possibility is the use of the ship's radar.

3.2.9 Bulk SST (BSST)

At a minimum, bulk temperature should be measured at a fixed depth (0.1m) with a high accuracy temperature sensor (+/- 0.02^oC or better). 0.1m is the depth recommended by CASOTS in the light of the diurnal variability of the upper 1m of the sea surface. Depending upon the deployment, measurements this close to the surface can be difficult to manage. If this is the case, 1m depth bulk temperatures are acceptable. Ideally, measurements will be recorded at a series of depths (0cm, 10cm, 50cm, 1m, 2m) to provide a near-surface temperature profile valuable for heat flux calculations and investigations of the relationship between skin temperature and bulk.

Suitable bulk temperature sensors include the IOS SOAP unit (Kent et al,. 1996), which is designed specifically to trail while underway at a depth of 0.1m or a precision commercially available thermistor chain. For large research vessels, hull mounted thermistors or in line thermosalinograph instruments should be used. For

small vessels moving at low speeds, it is possible to trail a CTD (conductivity, temperature and depth) probe. The CTD can be used in the following modes :
(1) as an in-line thermosalinograph when under way. The CTD is placed into a bucket continually refreshed by sea water pumped from a depth of 1-2m. The system must first be calibrated on station for the effects of any temperature offset in the system.
(2) for deep temperature profiles when on station (at start and end of validation transects).
It is essential that great care is taken in ensuring the accuracy and reliability of any bulk temperature sensors, particularly thermistor chains.

3.2.10 Salinity

Salinity has a small effect on the infrared emissivity of a surface (corresponding top a temperature difference of less than 0.08°K between fresh and sea water (Masuda et al. 1988)). However, knowledge of the vertical and horizontal salinity structure in the region surrounding the validation site provides information on the local hydrography, which is valuable in interpretation of the satellite image. Salinity should be measured at a fixed depth (e.g. 1m) with a sensor of accuracy +/- 0.001S/m or better. Ideally, measurements will be recorded at a series of depths (0cm, 30cm, 50cm, 1m, 2m) to provide a near-surface salinity profile (the surface may be covered for example with fresh water rainfall or run off). A CTD (conductivity, temperature and depth) probe can be used for this measurement (see Bulk SST above). Calibration salinity measurements for the thermosalinograph unit should be made every hour.

3.2.11 Sky state (amount and nature of cloud cover)

The minimal requirement is for a visual observation at overpass and at least every 15 minutes, either side of overpass. The observation should be more frequent in variable weather conditions. It should include the amount (in Octs) and type of cloud cover, as classified by the World Meteorological Office Standards (see *Cloud Types for Observers*, HMSO, Met. 0 716, ISBN 0 11 400334 3). If possible, a sky-pointing wide angle camera (video or stills) should be deployed to provide an on going record of sky state.

3.2.12 Position

Position should be recorded with a GPS (Global Positioning System). This will provide position accurate to 100m (non differential mode) and 25m (differential mode). Non-differential mode is usually adequate. Many vessels will already have a GPS system - it may not however be possible to log the GPS data and an additional system may therefore be necessary. Both the GPS position and time should be recorded.

3.2.13 Meteorological Measurements (Air temperature, Humidity, Pressure, Wind speed, Wind direction, Shortwave Solar Radiation)

The requirement is for a measurement of each of air temperature, humidity, barometric pressure, solar radiation, wind-speed and wind direction at a fixed height above sea surface. 10m is the standard Met. height. If measurements are made at any other heights, they should be corrected for temperature and stability effects to a height of 10m following approved procedures (for example, Smith, 1988). Care must be taken in the positioning of the probes, which should be situated in clean air, away from any influence of the measurement platform (this is particularly important for the wind and temperature measurements). On a boat, the forward mast is often a suitable location. The solar radiation probe (pyranometer) must have a clear, unshaded view over a full hemisphere. The temperature probe should be shielded against the effects of solar heating. Minimum required accuracies are 0.5^{o}C (air temperature), 5% (relative humidity), 1millibar (pressure), 5Wm^{-2} (solar radiation), 10^{o} (wind direction), 1ms^{-1} (wind-speed). Many commercially manufactured Met stations are available.

Ideally, radiosondes should be launched from or close to the platform to provide atmospheric profiles of air temperature, humidity, windspeed at overpass.

3.2.14 Compass direction

The compass heading should be logged, if possible directly from the ship's own system, or else as part of the GPS system (GPS and compass combined) or of the weather station.

3.2.15 Aerosol loading

At the minimum, a record of visibility should be made every 15 minutes or more frequently if changing rapidly. This will give an estimate of the amount of aerosol loading. A sun photometer should be deployed. The instrument should measure both direct beam radiation and sky radiance at a fixed scattering angle and must be located at a stable (land) site nearby. Another possibility is to use an almucantar (Weinman *et al*., and Twitty). Calibration of sun photometers is crucial and must be monitored as often as possible. Given the right site conditions and staffing, they can provide aerosol optical depths to better than 0.002.

3.2.16 Campaign Schedule and Satellite Position Prediction

To schedule their validation activities, scientists should obtain up-to-date predictions of times and dates of AATSR overpasses of the validation site. This can be done using the ESOV software (obtainable from ESA).

4. Land Surface Reflectance Measurements

This section deals with measurement protocol for the validation of land surface data products.
The land surface products 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.

Validation of land surface data products differs from sea surface temperature product validation in two main respects:
- The land surface products are based on the reflected channels of AATSR, and therefore the coordinates of the sun must be accounted for.
- The vegetation data product is not a measure of a single physical parameter but a complex of many biophysical parameters. Validation must reflect this indirect relationship.

4.1 Temporal and Spatial Sampling

As with sea surface temperature, land surfaces also show variations in time and space. Similar issues need to be considered:
- The spatial separation between satellite and *in situ* measurements: how far away in distance, from the satellite track, should *in situ* measurements be, for reliable validation?
- The temporal separation between satellite and *in situ* measurements: how far away in time, from overpass, should *in situ* measurements be, for reliable validation?
- Sampling frequency
- Size of instrument footprint

4.2 Spectral Radiance or Reflectance Measurements

A spectrometer with wavelength range spanning the AATSR shortwave bands, or a filtered radiometer with bandpasses of centre wavelength and width closely matching those of AATSR, is needed. If the radiometer is accurately calibrated then it can usefully measure the surface-leaving radiance, although such a measurement provides a more accurate validation when performed from an aircraft above most of the atmosphere’s aerosols and water vapour. More commonly, a laboratory-calibrated reference panel will be used, the surface reflectance will be derived, and absolute calibration of the radiometer will be unnecessary.

4.2.1 Measurement Strategy

Measurements of the surface should be interspersed with nadir measurements of the reference panel every few minutes, noting the times of both surface and panel measurements so that the solar direction at the time can be derived. The effect of the operator or any support structure on the illumination incident on the surface under measurement should be minimised. Avoid disturbances such as trampling to the surface under measurement. This may restrict measurement of the Bi-directional Reflectance Distribution Function (BRDF) to azimuths on one side only of the principal plane. With careful work at a bright target an accuracy of +/- 2% in the reflectance is attainable.

4.2.2 Spatial sampling

Ideally, one should aim to measure the average site reflectance, at the time of overpass. In practice, the reflectance can be measured at several points across the site during the day of the overpass and neighbouring days, taking care to avoid or correct for any effects of solar zenith angle different from that at the time of overpass. The measurements can be made on the ground but more desirable is to make them at low altitude on a light aircraft.

4.2.3 Angular sampling

Very few natural surfaces meet the specifications of a Lambertian surface, and in general, the 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. 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.

For angular sampling, the radiometer attitude (zenith angle and azimuth) should be measured to within a few degrees. The AATSR view directions should be measured during overpass. Alternatively, or in addition, the BRDF can be measured over the whole hemisphere at several locations and interpolated to the AATSR view directions, taking care to account for differences in solar zenith angle for measurements taken at times other than the overpass time.

4.2.4 Radiometer

The spectrometer must have a wavelength range spanning the AATSR bands of interest: ideally at least 0.55 to 1.6 micron, but obviously a smaller range can still validate a subset of the four shortwave bands. The field of view (FOV) should be narrow enough that the surface BRDF does not change significantly across the FOV. This requirement is less stringent for more Lambertian surfaces. The instrument examples quoted below have FOV widths of about 10 degrees. The calibration of the instrument must be stable with, for example, changes in ambient temperature during the measurements.

4.2.5 Reference panel

The reference panel should have a stable, bright, white, spatially uniform and near-Lambertian surface. Typical surfaces are Labsphere Spectralon (TM) and barium sulphate paint. It is essential that the normal spectral reflectance of the reference panel be calibrated in the laboratory over a range of incidence angles spanning the solar zenith angles used in the field measurements.

Example instruments

- The ASD FIELDSPEC FR, high spectral resolution radiometer (0.3 to 2.5 micron) from the NERC equipment pool, used by the University of Nottingham.
- The CCD triple spectrometer (0.2 to 1.0 μm) used by CSIRO.

4.2.6 Aerosol Optical Depth and Size Distribution

Aerosol optical depth is best measured with a sun photometer or an equivalent instrument such as the multi-filter rotating shadowband radiometer (MFRSR). If the atmosphere is clear and not changing in composition during the morning of the overpass, then the Langley analysis method yields the aerosol optical depth for each filter. Otherwise the instrument must be calibrated by the Langley method on neighbouring days with suitable conditions, and the calibration must be stable. An uncertainty of 1% in the instrument calibration produces an absolute error of 0.01 in the optical depth.

To estimate the aerosol size distribution, the sun photometer should measure the direct solar beam in at least two narrow bands at wavelengths suitable for sun photometry, spanning at least the range 0.4 to 0.8 micron.

4.2.7 Column Ozone Amount

A sun photometer (or MFRSR), which includes a filter near the middle of the ozone Chappuis absorption band (0.6 micron), in addition to the filters for the aerosols mentioned above, can retrieve both column ozone amount and aerosol optical depth by an iterative algorithm.

4.2.8 Column Water Vapour Amount

Because the AATSR bands have been selected to largely avoid wavelengths affected by water vapour absorption, high accuracy in the measurement of the water vapour column amount is unnecessary. A sun photometer (or MFRSR) which includes a filter in a water vapour absorption band, such as the band at 0.94 micron, can retrieve column water vapour amount. Alternatively a radiosonde profile over the site for the time of the overpass can be integrated.

4.2.9 Surface Air Pressure

The surface air pressure is required to specify the Rayleigh component of the atmospheric correction and the column amount of carbon dioxide. High accuracy is not required. A barometer should be read at the time of the overpass.

4.2.10 Sky State

At least a visual observation of the cloudiness of the sky at the overpass time should be recorded. Images from an all-sky camera at and around the overpass times would be better.

4.2.11 Additional measurements

These additional measurements make a comprehensive set permitting the analysis of discrepancies:

4.2.11.1 Aerosol Single-Scattering Albedo

The single-scattering albedo of the aerosol particles, determined by their composition, determines the fraction of radiation which is absorbed rather than scattered by the aerosol and hence influences the atmospheric correction. The single-scattering albedo, or equivalently the imaginary part of the aerosol refractive index, can be inferred from the composition of the aerosol, if known, or retrieved from the ratio of direct-to-diffuse irradiance.

4.2.11.2 Diffuse-to-global Irradiance Ratio

Direct, diffuse and global spectral irradiance can be measured with a spectroradiometer such as the one made by LiCor or the MFRSR. This measurement provides a diagnostic check on the radiative transfer calculation, acts as a backup to the sun photometers, and can be used to retrieve the aerosol single-scattering albedo.

4.2.11.3 Solar Radiation (broadband Irradiance)

The downwelling irradiance is a monitor of the steadiness of the atmospheric conditions around the overpass time.

5. AATSR Land Thermal Products

This section deals with measurement protocol for the validation of land thermal products. The land thermal products are:

- ToA level 1b gridded data at 11 and 12µm, in both the forward and the nadir views. Procedures for using the 3.7µm channel over land are not well advanced and this channel is excluded from the land validation plan.
- A land surface temperature product (LST). This is a level 2 geophysical product

An 'at surface' brightness temperature product is not currently proposed but the validation procedures outlined do permit some limited validation of this quantity.

In many respects the radiometric requirements for LST measurement protocol are the same as those for SST. Radiometers used for land surface temperature validation should be scrutinised to the same degree as those used for SST.

5.1 TOA Brightness Temperature

Validation of the AATSR TOA brightness temperature must be performed over uniform land areas (5 km x 5 km) using aircraft mounted radiometers. It is imperative to conduct these measurements as close as possible to the overpass time because of the significant temporal variability associated with land surface temperatures. This protocol requires accurate, well-calibrated radiometers with bandpasses that match AATSR. In many respects the radiometric requirements for this measurement protocol are the same as those for SST. Radiometers used for land surface temperature validation should be scrutinised to the same degree as those used for SST. It is possible that this product could be validated over the ocean, but it is desirable to conduct validation over the land for two reasons:

(i) Measurements are required during both ascending and descending orbits, for dry and humid atmospheres, but there is no particular preference for hemisphere.

(ii) Measurements are required over spectrally variable high temperature targets to check on the temperature linearity of the AATSR IR detectors for high radiance sources.

5.2 'At Surface' brightness temperature

Validation protocol for this measurement is the same as the TOA brightness temperature. Ancillary radiosonde and spatially averaged surface temperatures are required. Radiosonde and surface data will be fed into an RT model and used to determine the directional brightness temperature at 11 and 12 microns. The 'at surface' brightness temperatures will be computed and compared with the ground-based radiometer measurements. Temporal and spatial coincidence to 1 minute and 500 m over very uniform, flat land targets are required.

5.3 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 temporal sampling by the surface-based radiometers and contact devices are as short as 1 s.