# Investigation of Land Surface Radiation Budgets Using ATSR/ATSR-2 Data


A. J. Prata — CSIRO Division of Atmospheric Research, PMB 1 Aspendale, Victoria, Australia
ajp@dar.csiro.au

R. P. Cechet — CSIRO Division of Atmospheric Research, PMB 1 Aspendale, Victoria, Australia
rpc@dar.csiro.au

I. F. Grant — CSIRO Division of Atmospheric Research, PMB 1 Aspendale, Victoria, Australia
ifg@dar.csiro.au

I. J. Barton — CSIRO Marine Research, Castray Esplanade, Hobart, Australia
ijb@ml.csiro.au


# Abstract


**CSIRO is establishing Australia's Continental Integrated Ground-truth Site Network (CIGSN) for the purpose of calibration and validation (Cal/Val) of current and proposed satellite sensors. Two sites are currently operational. Criteria for selection of the present sites were that they must be flat, on natural terrain, and preferably under an atmosphere with a high probability of clear skies that contain few aerosols and low water vapour loadings. Currently these sites provide surface data at a scale of 1 km, comparable with the field of view of ATSR and AVHRR satellite sensors. The primary site at Uardry (near Hay, NSW) has been providing near-continuous surface measurements since July 1992, in an effort to obtain an accurate long-term series of ground-based measurements of surface temperature, radiative fluxes and albedo for Surface Radiation Budget (SRB) studies.**

**Here we examine two data products from the ATSR satellite instrument; surface temperature and surface leaving shortwave irradiance. We validate these products against the CIGSN ground-based measurements of these quantities. The robustness of coefficients for surface temperature algorithms will be discussed, as will the estimation of shortwave irradiance from 1.5 $\mu$ m radiances. An excellent linear relationship ($r^2 > 0.97$) is found between the surface -leaving irradiance and the raw digital numbers from both the ATSR and ATSR-2 1.6 $\mu$ m channels suggesting that it may be possible to use data from this channel to infer surface-leaving shortwave irradiances at other land regions around the earth.**


# Introduction

Efforts to monitor and understand long-term global changes such as the Greenhouse Effect and desertification increasingly rely on information from earth observing satellites. Global climate models (GCMs) predict an increase in global mean surface temperature of between 2 and 5°C due to a doubling of $CO^2$. This increase in temperature is equivalent to an increase in the global net surface radiation budget (SRB) of between 4 and 10 $Wm^2$. The top-of-the-atmosphere (TOA) radiation balance can be observed using current and proposed satellite instruments, and this balance needs to be related to the SRB in order to determine the absorption in the atmosphere. The net shortwave flux at the surface can be inferred directly from satellite observations of the TOA net shortwave flux. It is difficult to infer the net longwave flux from TOA values because the downward longwave flux at the surface is largely decoupled from satellite observations. Therefore there is a need to complement the satellite observations with high-precision measurements of these fluxes directly at the surface. There are only limited long-term observations of the SRB, and most of these do not have the necessary precision to be able to discern a change in the net flux of 10 $Wm^2$.

The only way at present to monitor the global radiation budget is to observe it from space. The so-called "ground-truth" of this information, which involves both the validation of data products derived from satellite measurements and also the long-term vicarious calibration (i.e. stability) of the satellite instrument radiances, is beginning to receive greater attention from space agencies, researchers and resource managers. In this paper, the Continental Integrated Ground Site Network (CIGSN) will be described and an application of this surface data to the accurate validation of ATSR products (shortwave surface-leaving radiance, and land surface temperature-LST) will be detailed.

# The continental integrated ground site network-CIGSN

Australia's Continental Integrated Ground Site Network (CIGSN) currently has two operational sites - one is 60 km NE of Hay (New South Wales) on the Uardry sheep station, referred to hereafter as the Uardry site, and the other is 100 km WNW of Alice Springs (Northern Territory) on the Amburla brahman cattle stud, referred to hereafter as the Amburla site. The CIGSN is producing accurate and long time series data of surface radiative fluxes and meteorological parameters such as surface temperature, air temperature, relative humidity, wind speed and surface pressure.

The Uardry site has been providing near-continuous surface measurements since July 1992. This site is near the centre of the largest and most uniform plain on the Australian continent. The layout consists of a central data logging and processing site coupled with 8 "satellite" sites which telemeter data via a radio communications link to the central site up to 6 times per minute. The solar powered, low maintenance, autonomous data collection system can handle up to 48 channels of 16-bit resolution data stored onto a computer hard-disk. Upward and downward shortwave and longwave irradiances are monitored. The upwelling irradiances are obtained from instruments mounted on a boom extending from a 15 m tower. Air and ground temperatures are monitored at points across a 1 $km^2$ area. As an example of some of the CIGSN data products, Figure 1 shows the time series of albedo for the Uardry site, illustrating the long-term monitoring of this parameter with respect to the rainfall recorded at the site.

Note that there is a general decrease in rainfall over the length of the CIGSN record, and that the albedo displays a gradual increase over this period in response to the rainfall changes.

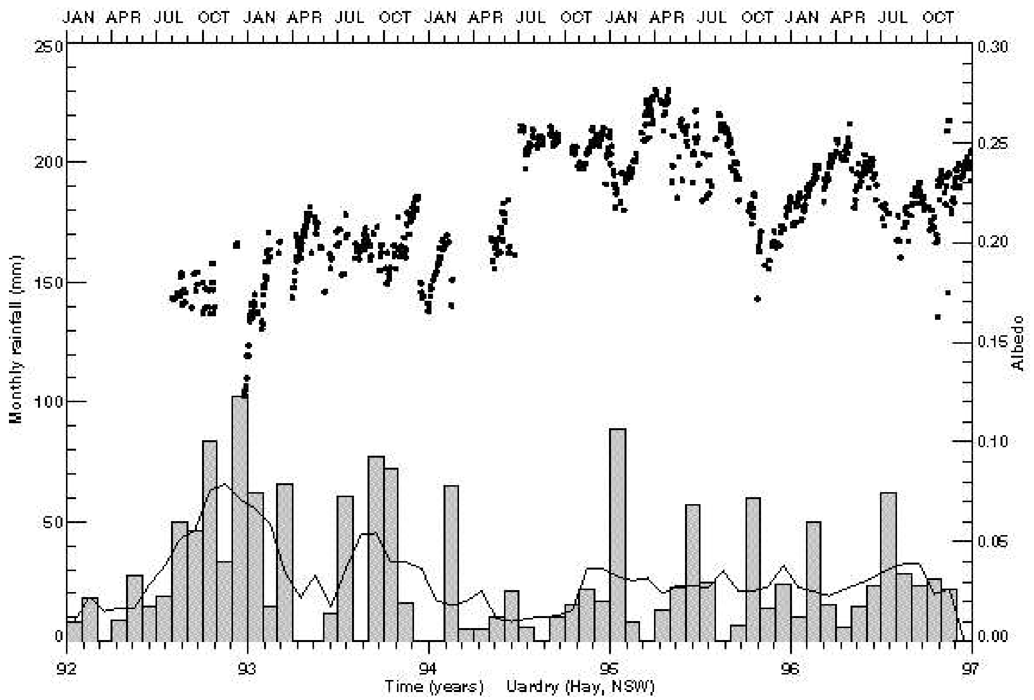


*Figure 1. Albedo measured at the Uardry CIGSN site for the period August 1992 to December 1996 and the recorded monthly rainfall for the period January 1992 to December 1996. The thin line on the rainfall plot is the 3-month moving average of the rainfall.*

The Amburla site has been providing near-continuous surface measurements since March 1995. This instrumentation is on a 12 x 12 km$^2$ plain which is sparsely covered with grass tufts. The layout consists of a central data logging site coupled with 6 "satellite" sites. Electronics, communications and geophysical variables monitored are similar to those at the Uardry site.

For both sites, measurements of the surface irradiances and surface temperature are made at a spatial scale which matches the resolution of satellite imagers such as the Along-Track Scanning Radiometer (ATSR) and the Advanced Very High Resolution Radiometer (AVHRR). Therefore the CIGSN measurements constitute a highly valuable data-set with which to calibrate and validate satellite remote sensing data. The CIGSN data set has greatly assisted our efforts in developing algorithms for land surface temperature (LST) and also surface-leaving shortwave (SW) irradiance from ATSR 1.6 $\mu$ m top-of-the-atmosphere (TOA) radiances.

# ATSR and ATSR-2 data sets

The first Along-Track Scanning Radiometer (ATSR) was launched in July 1991 and continues to operate to the present. The ATSR instrument was specifically designed to provide valuable data related to the earth's oceans. The 1.6 $\mu$ m channel was not calibrated prior to launch and no provision had been made for on-board calibration of this channel. The gain of this channel was adjusted post-launch to provide an adequate dynamic range.

The primary use of the 1.6 $\mu$ m channel was to distinguish between cloud, water, land and ice during the daytime period only, in an effort to assist in the determination of cloud-free pixels for SST measurement.

The ATSR-2 instrument was launched in April 1995 and operated until December 1995 when a problem with the scan mirror mechanism resulted in a long period with no useful data until mid-1996. The ATSR-2 instrument included 3 narrow-band visible channels in the blue, green and red parts of the spectrum (0.55 $\mu$ m, 0.67 $\mu$ m and 0.87 $\mu$ m) as well as all the channels that previously existed on the ATSR instrument. ATSR-2 was designed to provide valuable data related to the earth's land surface as well as the ocean surface.

## ATSR data

A satellite dataset comprising 37 ATSR descending orbit scenes (512 x 512 km) for the Uardry CIGSN site, during the period July 1992 to March 1993, were obtained by courtesy of the European Space Agency and supplied by the Daresbury Rutherford Appleton Laboratory, UK. Descending orbits pass over the CIGSN site at Uardry at approximately 1030LT (Australian eastern standard time.) Details of this dataset and also the surface conditions at the Uardry CIGSN site during the period that these passes were obtained can be found in (Prata *et. al.*, 1996). Of the 37 ATSR passes, only 12 scenes (from 920807 to 930330) were considered. Cloudiness was the main reason for rejecting the other passes.

## ATSR-2 data

During the early part of the ATSR-2 mission (May - December 1995), both of the CIGSN sites were operational. A satellite dataset comprising 48 ATSR-2 descending orbit scenes for the Uardry site and 28 ATSR-2 scenes for the Amburla site were obtained by courtesy of ESA and supplied by RAL, UK. The winter-spring period in the region of the Hay plains received above average rainfall and skies were abnormally cloudy with vigorous cyclonic synoptic activity bringing frequent broken, low, and middle level cloud as well as thin high level cloud associated with the subtropical jet-stream. Of the 48 ATSR-2 scenes, 4 were not considered due to lack of surface data and 37 were rejected due to cloud contamination. Following the presence of a tropical rain depression over the Alice Springs site region in January 1995, where approximately 200 mm of rain was recorded, the site received no further significant rainfall (greater than 10mm) for the remainder of the year. Of the 28 ATSR-2 scenes considered for Amburla, 17 scenes were determined to be cloud free.

# Estimating shortwave irradiances from the 1.6 μ m channel

ATSR and ATSR-2 1.6 μ m narrow-band directional radiances have been correlated with the SW surface-leaving broad-band irradiances measured at the two CIGSN sites. The purpose of this is to use the 1.6 μ m radiances to estimate the SW irradiance and ultimately to determine the SW broad-band clear-sky albedo over continental Australia.

As a first approximation it is assumed that the digital numbers (DNs or counts) provided in the raw data stream are linearly related to radiances. CIGSN provides surface shortwave irradiances (upwards and downwards), but no directional radiances at 1.6 μ m are available at the present time. Thus it is only possible to compare the shortwave surface irradiances with the raw DNs at the top of the atmosphere (TOA). Thus we are comparing essentially a surface broad-band irradiance with a directional TOA narrow-band radiance.

Figure 2 shows a scatter plot of the Uardry CIGSN shortwave upward surface irradiance (in units of $Wm^2$) and the ATSR 1.6 μ m DNs for 12 cloud-free coincidences. Figure 3 shows a scatter plot of the Amburla CIGSN shortwave upward surface irradiance and the ATSR-2 1.6 μ m DNs for 17 cloud-free coincidences. The degree of fit ($r^2 > 0.97$) for both cases is remarkably good and the relationship appears to be very linear. It should be noted that a significant increase in the dynamic range of the Amburla ATSR-2 data is expected when we include more recent 1996/97 summer data. This surprisingly good result may be due to the extreme homogeneity of the surface and clarity of the atmosphere found in both the regions surrounding the Uardry and Amburla ground-truth sites.

Atmospheric effects at 1.6 μ m are not expected to be large, as the aerosol extinction is much lower than at visible wavelengths, and gaseous absorption is small (there are some water vapour and carbon dioxide lines, but no other gases contribute). Water vapour loadings are small in the region of the Uardry site (typically about 15 kg $m^{-2}$ column amounts; see inset plot on Figure 2) and also in the region of the Amburla site. The 0.55 μ m aerosol optical depth for inland arid Australia is about 0.05 and relatively small. Most of the effect on the surface-leaving 1.6 μ m radiance must be due to surface effects, through viewing geometry and the unknown bi-directional reflectance distribution function (BRDF).

Prata *et al.* (1996) assessed the effects of the atmosphere and investigated the linearity of the TOA 1.6 μ m directional radiance with broadband irradiance using the Lowtran 7 radiative transfer model. They found that the TOA irradiance is very linear with the surface-leaving irradiance, being related through an atmospheric transmittance factor, and thus confirming the experimental results shown above. These results suggest that the 1.6 μ m channel may be very useful in determining clear-sky land surface albedos.

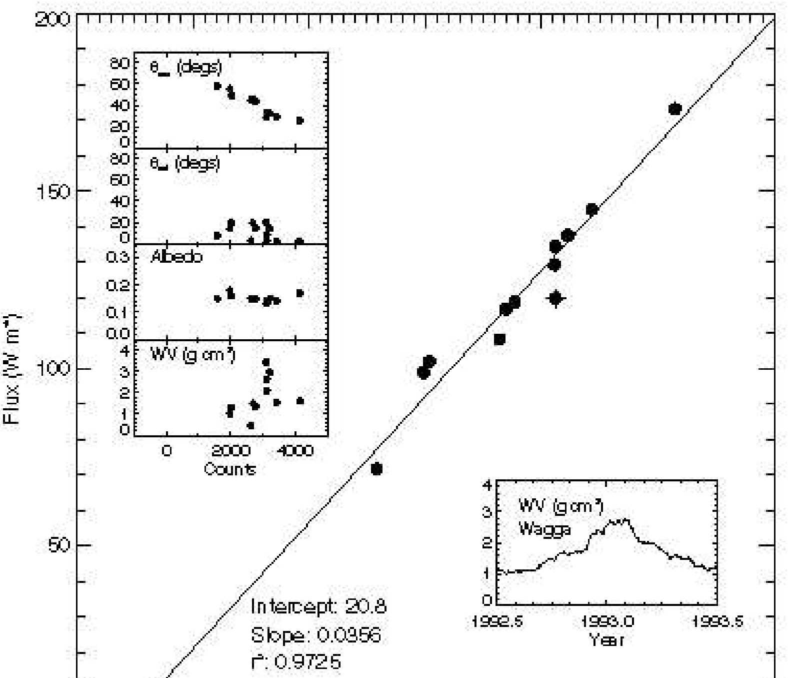


*Figure 2. Surface-leaving shortwave irradiance measured at the Uardry tower (near Hay, NSW) versus the ATSR 1.6 μ m nadir view DNs for the 12 cloud-free overpasses acquired between August 1992 and March 1993. The inset graphs show the variation of the solar zenith angle, satellite view angle, surface broad-band albedo, and precipitable water for the same data-points as on the main plot, and the smoothed variation of precipitable water, estimated from the Wagga-Wagga radiosondes for the same time period.*

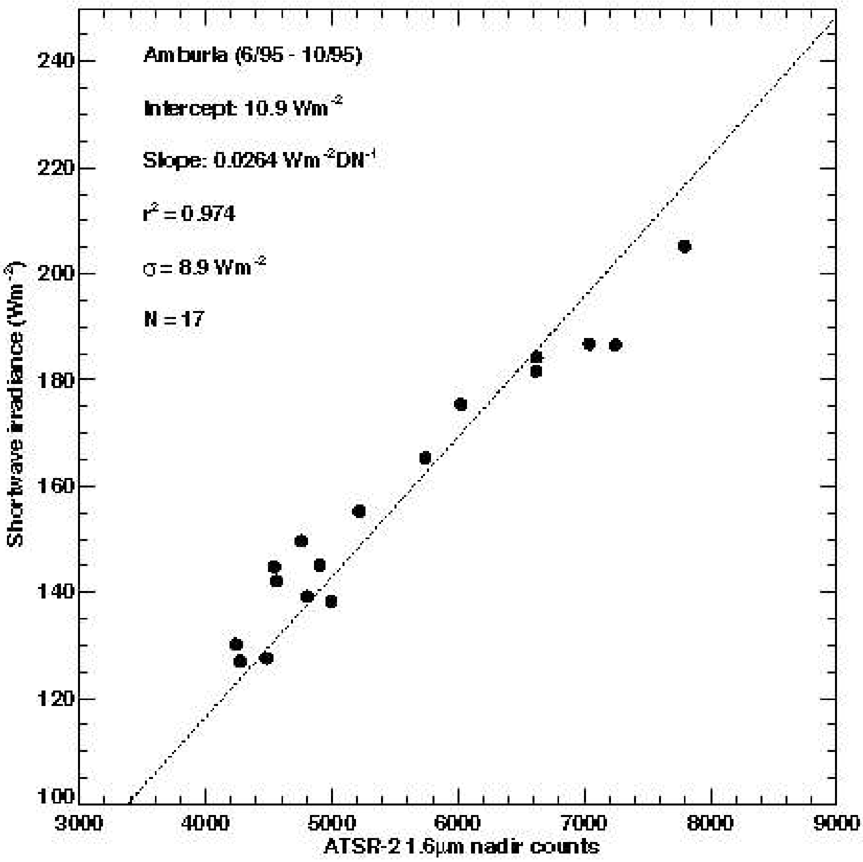


*Figure 3. Surface-leaving shortwave irradiance measured at Amburla versus the ATSR-2 1.6 μ m nadir view DNs for the 17 cloud-free overpasses acquired between June 1995 and October 1995.*

# Land surface temperatures and the longwave surface radiation budget

The longwave surface radiation budget is determined by the two-way exchange of radiation between the surface and atmosphere. Longwave radiation from the clear sky can be estimated using bulk formulas which utilise the surface air temperature from meteorological stations and a measure of the moisture content of the near surface layers of the atmosphere, usually from routine dew-point temperature measurements (see Prata (1996) for examples of these bulk formulas). Since the downwards longwave emission from the atmosphere is almost completely decoupled from the radiation measured by a downward-looking radiometer it is difficult to determine this quantity from a satellite. The longwave emission from the surface is wholly determined by the surface radiant temperature and the longwave (3-100 μ m) surface emissivity. The surface radiant temperature of the land can be readily determined from infrared satellite measurements under clear-sky conditions. Recent research (Becker and Li (1990), Sobrino *et al.* (1991), Ottlé and Vidal-Madjar (1992), Kerr *et al.* (1992), Prata (1993), Li and Becker (1993), Prata *et al.* (1995)) has demonstrated the feasibility of deriving accurate land surface temperatures (LSTs) from the AVHRRs on board the NOAA series of polar orbiting satellites. LST algorithms for the AVHRRs utilise the so-called split-window formulation and accuracies (rms errors) of 1.5-4 K have been obtained when compared to *in situ* ground-truth measurements (Prata (1994a), Sobrino *et al.* (1996)). The ATSR and ATSR-2 have thermal channels which closely match the 11 μ m and 12 μ m channels of the AVHRRs. In addition, the dual angle view of the ATSRs offers interesting possibilities for LST algorithm design. Derivation of accurate surface temperatures over the land is a difficult task for the following reasons:

- land surfaces tend to be very heterogeneous,
- the emissivity of the land can be significantly different from that of a blackbody and does exhibit spectral and angular variations,
- atmospheric absorption and emission effects over the land can be large and complicated because of the presence of near surface inversions,
- wind blown dust, anthropogenically generated particles and other naturally occurring aerosols are prevalent over the land and can affect the transfer of thermal radiation from the surface to the satellite.

These difficulties make validation of LSTs an extremely difficult task and great care must be taken in designing appropriate field measurements for comparison with a satellite-derived LST. Experience has shown that many of the difficulties mentioned above are minimised at night when the atmosphere-surface vertical temperature gradients are smaller, horizontal surface temperature gradients are smaller and the magnitude and spatial variation of the heating rate are diminished. However, the nocturnal inversion and the ability to determine cloud free areas remain as problems for LST determination at night.

The CIGSN was designed to provide ground-truth temperature data for comparison with satellite-derived LSTs. Results from measurements made at Uardry have been published (Prata, 1994a); these show that during the night accuracies of about 1.5 K can be obtained from fixed-coefficient AVHRR split-window algorithms, while during the day the fixed-coefficient algorithms provide accuracies of 2-3 K. Although many researchers have developed LST algorithms with parametrised coefficients (e.g. Prata, 1993; Sobrino *et at.*, 1991; Coll *et al.*,1994; Ulivieri *et al.*, 1994), it has not yet been demonstrated that these perform any better than fixed-coefficient algorithms. With 4 measurements available (11 μ m and 12 μ m nadir and 11 μ m and 12 μ m forward) for each ATSR pixel it seems likely that improvements over AVHRR algorithms can be obtained. We have investigated the accuracy of some ATSR LST algorithms by utilising our CIGSN data-base. The emphasis here is on the most practical and easy-to-use algorithms, thereby giving users the opportunity to apply the algorithms to their own specific data-sets and applications. Because our algorithms have been validated, users will be able to assess the usefulness of the algorithms against their accuracy requirements.

# ATSR data - Uardry

31 coincidences of ATSR and *in situ* data over the Uardry site are used to investigate the performance of the parametrised dual angle algorithms of Prata (1993). The results are compared with fixed-coefficient split-window algorithms, appropriate for the surface and atmospheric character of the site. The Uardry site is a vegetated site and we anticipate that both the spectral and angular variation of emissivity will be small.

# Dual-angle algorithm

Prata (1993) derived the following parametric dual-angle algorithm for the ATSRs,

$$LST = \frac{T(\nu, \theta_1)}{\varepsilon_0} + \frac{\gamma_\theta}{\varepsilon_0}(T(\nu, \theta_1) - T(\nu, \theta_2)) + \frac{(1-\varepsilon_0)}{\varepsilon_0}\Delta B, \quad (1)$$

$$\gamma_\theta = \frac{1}{\cos\theta_1 / \cos\theta_2 - 1}, \quad (2)$$

$$\Delta B = B[\nu, T(\nu, \theta_1)][\frac{\partial B}{\partial T}]^{-1}.$$

$T(\nu\,\theta)$ is the pixel brightness temperature of a channel with central wavenumber $\nu$ viewed at zenith angle $\theta$ and $\varepsilon_0$ is the surface emissivity, assumed independent of wavenumber and angle. This is a scene-based algorithm requiring no ancillary information other than an assumed surface emissivity. Thus it is a very practical algorithm and mathematically simple - requiring only the coding of the Planck function and its temperature derivative. This algorithm corrects for atmospheric effects by using only the geometry of the observation and for surface effects via the grey-body approximation. For the Uardry site the measured emissivities at 11 $\mu$ m and 12 $\mu$ m are 0.978 and 0.982, respectively (Prata, 1994b). The results of applying (1) to the Uardry ATSR validation data are shown in Figure 4(a) for the 11 $\mu$ m dual-angle algorithm and in Fig. 4(b) for the 12 $\mu$ m algorithm. The rms error and bias ($T_s$-LST) are 1.30 K and -0.07 K for the 11 $\mu$ m algorithm and 1.35 K and +0.45 K for the 12 $\mu$ m algorithm. The surface data temperature ranges from about 273 K to about 325 K, and include both nighttime and daytime measurements. It appears that the dual-angle algorithms work extremely well for this surface and atmosphere for a wide range of temperatures.

The split-window algorithm has the form,

$$LST = \alpha_0 + b_0 T_{11} + c_0 T_{12}, \quad (3)$$

where the subscripts 11 and 12 correspond to the 11 $\mu$ m and 12 $\mu$ m channels, respectively. The coefficients have the values $\alpha_0$ = 3.172, $b_0$ = 3.559, and $c_0$ = -2.542 (Prata (1994a), Table 5 column 1, panel 2). The split-window algorithm with these fixed coefficients gives a bias=0.00 K and an rms error = 1.83 K (see Fig. 4(c)). Thus the split-window algorithm has a slightly worse rms error but is remarkably accurate given that the coefficients were derived from AVHRR data and no explicit account is taken of the changing surface and atmospheric conditions.

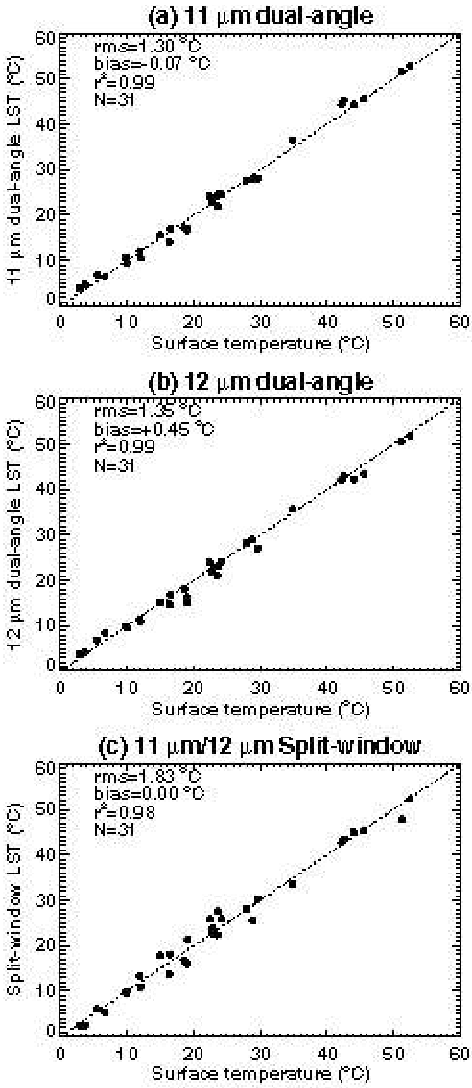


*Figure 4. Comparison of ATSR dual-angle LSTs with in situ data for the CIGSN Uardry site. (a) 11 μ m algorithm, (b) 12 μ m algorithm, (c) fixed coeffcient split-window algorithm.*

It is worth noting here that the dual-angle algorithm has a particularly great advantage over the split-window algorithm in the case of ATSR brightness temperatures in hot conditions. The digitisation of the 11 μ m ATSR channel causes this channel to saturate at around 320 K whereas absorption effects and 12 bit digitisation prevent saturation of the 12 μ m channel.

# ATSR-2 data - Amburla

The second CIGSN site was chosen to test the ATSR LST algorithms for a surface with different character (largely bare sandy soil) and with a drier, hotter atmosphere. Arguably these conditions are the most difficult test of the linearised LST algorithms suggested by numerous researchers. Unlike Uardry, no measurements of the surface emissivity exist for the Amburla site. Instead we infer the emissivities (spectral and angular) from campaign data obtained during an ATSR-2 overpass when radiosonde and infrared radiometer measurements were simultaneously available. Using a radiosonde profile obtained at the Amburla site coincident with the ATSR-2 overpass and a high spectral resolution radiative transfer model (Modtran 3 at 1 $cm^{-1}$ resolution), the directional atmospheric radiances (downward and upward) and atmospheric transmittances were convolved with the ATSR-2 filter functions. The "at satellite" radiances (or brightness temperatures) in each channel for various zenith viewing angles and surface emissivitiy configurations were calculated for the pixel matching the location of the Amburla field site.

Figure 5 shows the variation of brightness temperature with zenith viewing angle for the ATSR-2 11 μ m channel (Fig. 5a) and the 12 μ m channel (Fig. 5b) and five hypothesised surface emissivity values. These curves show how the atmosphere attenuates the surface-leaving radiance. No correction for any angular variation of emissivity has been used. The actual value of the brightness temperature measured by the ATSR-2 is also shown on each plot (closed circles). For the 11 μ m nadir channel, the point shown is a lower limit estimated by assuming that the 11 μ m channel is saturated at 319.5 K. This assumption was necessary because the 11 μ m channel was saturated at the location (and in several nearby pixels) of the field site. A value of 321.1 K is suggested by a linear extrapolation of the relationship between the 11 μ m nadir and 12 μ m nadir brightness temperatures for unsaturated pixels. The ground-based infrared radiometers were measuring surface temperatures of between 50 and 55° C during the overpass. The surface temperature was also varied for these calculations - the value used in Fig. 5 was the average value determined from a set of *in situ* contact temperature transducers, at the time the pixel was scanned. These validation measurements are considered to be reliable and accurate.

From Fig. 5 it is possible to infer a surface emissivity value for the 11 μ m and 12 μ m channels and also estimate the angular variation. The plots suggest that the 11 μ m nadir emissivity is no lower than about 0.960 and the 11 μ m 55° emissivity is about 0.945. The 12 μ m nadir emissivity is estimated to be about 0.965 and the 12 μ m 55° emissivity to be 0.925. It is clear from the analysis of the campaign data that there is a strong variation of emissivity with angle for the Amburla site. Thus the simple model (1) will not be adequate for estimating accurate LSTs for this surface. Instead we utilise the radiance form of the dual angle algorithm given by Prata (1993) (Eq. 33).

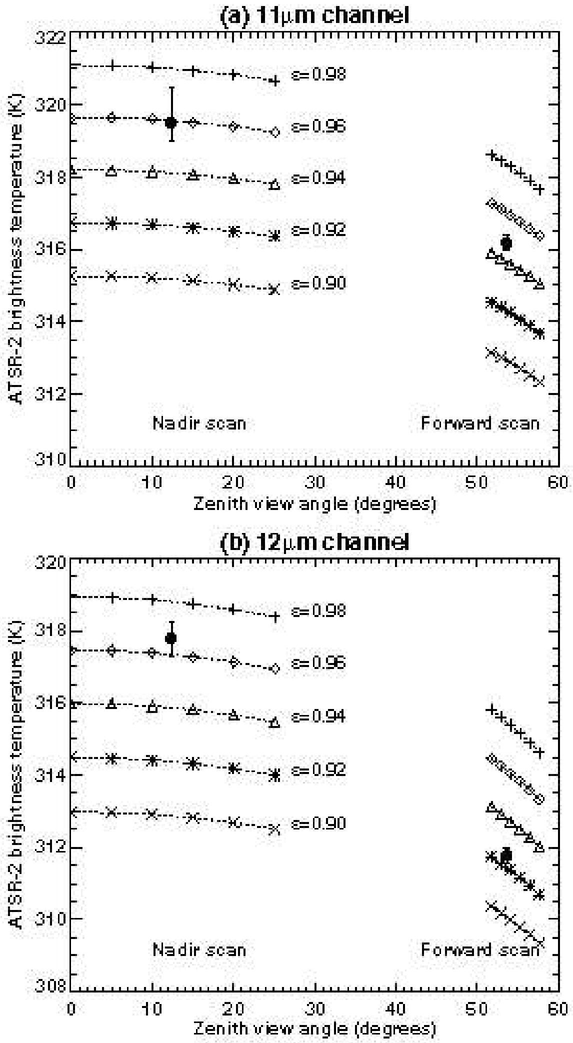


*Figure 5. Variation of calculated ATSR-2 brightness temperatures with zenith view angle for 5 different surface emissivities. (a) 11 μ m channel, (b) 12 μ m channel. Solid circles indicate the actual ATSR-2 measurements and the standard deviations about a 3x3 pixel mean. The 11 μ m nadir measurement is a lower-bound estimate.*

The algorithm is,

$$B_s[\nu, T_s] = \frac{(1+\gamma_\theta)I_{\nu,\theta_1}}{\varepsilon_{\theta_1} + \gamma_\theta(1-k_\nu w \sec\theta_2)\Delta\varepsilon} - \frac{\gamma_\theta I_{\nu,\theta_2}}{\varepsilon_{\theta_2} + (1+\gamma_\theta)(1-k_\nu w \sec\theta_1)\Delta\varepsilon}, \tag{4}$$

where $T_s$ is the surface temperature, $I_{\nu,\theta}$ is the radiance at wavenumber $\nu$ and zenith view angle $\theta$ , $\varepsilon$ is emissivity, $\Delta\varepsilon$ is the difference in emissivity when viewing the surface in the nadir and forward scans, $k_\nu$ is the absorption coefficient (in $cm^{-1}$) at wavenumber $\nu$ , $w$ is the precipitable water amount (in cm), and $\gamma_\theta$ is defined as before (Eq. 2). Most of the quantities given in (4) are easily obtained from the data. However, the atmospheric parameters $\nu$ and $w$ must be obtained from independent data - usually a radiosonde profile.

A set of 16 cloud-free daytime ATSR-2 validation data are available for the Amburla site. In these data the nadir view angle varies from 0 to 22 degrees while the forward view angle varies from 51 to 55 degrees. An expression for the angular variation of emissivity has been developed by Prata (1994c), viz.

$$\varepsilon = \varepsilon_0 \frac{[1-\exp\{-d_0\cos(\theta/d_1)\}]}{[1-\exp\{-d_0\}]} \tag{5}$$

where $d_0$ and $d_1$ are empirical adjustable parameters and $\theta$ is the zenith view angle. Values of $d_0$ = 5.0 and $d_1$ = 1.35 were suggested by Prata (1994c). For these data values of $d_0$ = 3.5 and $d_1$ = 1.35 give a good fit for both channels. Constraining the angular emissivity dependence to be the same for both channels suggests that the nadir 11 μ m emissivity is 0.970. Thus we utilise the angular emissivity model (5) with $\varepsilon_0$ = 0.970, $d_0$ = 3.5, $d_1$ = 1.35 for the 11 μ m channel, and with $\varepsilon_0$ = 0.965, $d_0$ = 3.5 and $d_1$ = 1.35 for the 12 μ m channel. Atmospheric parameters are not readily available for these validation data, however the atmospheric parameters appearing in (4) occur only in terms associated with $\Delta\varepsilon$ , which has a maximum variation of less than 0.1. We use a climatological value for $k_\nu w$ of 0.20 at 12 μ m and 0.15 at 11 μ m, and justify this by asserting that the impact of errors in the choice of these parameters is small on the final LST estimate. Having determined all of the parameters appearing in (4) from the data and from climatology, inversion of (4) using the Planck function at 11 μ m and 12 μ m provides two independent estimates of the LST. As before, we compare these and the LST from a fixed-coefficient split-window algorithm with coefficients $a_0$ = 4.151, $b_0$ = 3.297, and $c_0$ = -2.433 (Prata, 1994, Table 2, column 2, panel 2), with the ground-based surface temperature measurements. The split-window coefficients were determined for daytime measurements over a bare soil surface which has a similar soil type to that found at Amburla. Results of the analyses for the 16 daytime cloud free coincidences are given in Table 1

| Algorithm | Bias (K) | rms error (K) |
|---|---:|---:|
| Split-window | -0.49 | 1.73 |
| 11 $\mu$ m dual-angle | +0.23 | 2.32 |
| 12 $\mu$ m dual-angle | +0.35 | 1.79 |

*Table 1: Biases and rms errors ($T_s$-LST) for the split-window and dual-angle algorithms used with ATSR-2 validation data at the Ambula site.*

The results are worse than those for the Uardry site, but we note that these data contain only daytime values for which we expect lower accuracy. Surprisingly, the split-window algorithm has the lowest rms error, although this is marginal when compared to the 12 $\mu$ m dual-angle algorithm. The presence of non-zero bias is caused by incorrect coefficients in the case of the split-window formulation, and primarily due to inadequacies in the emissivity model used and the choice of atmospheric parameters in the case of the dual-angle algorithms. Further research is required to refine the LST ATSR algorithms but it is clearly extremely useful to have 4 measurements and the dual-angle capability. For the homogeneous surfaces used here the different spatial sampling of the nadir and forward views is not contributing much error, however for less uniform terrain this could be a major source of error when utilising data from the two views.

# Conclusions

The excellent linearity of the relationship between the surface-leaving shortwave irradiance and the directional ATSR 1.6 $\mu$ m (uncalibrated) DNs implies that these satellite data can be used in a quantitative manner. A similar relationship with the ATSR-2 1.6 $\mu$ m (calibrated) DN's confirms the usefulness of these data. It is anticipated that the slope and intercept will change from region to region, depending on the clarity of the atmosphere and more crucially on surface conditions (i.e. vegetation cover, moisture status etc.). If the linearity proves to be robust, then it would be feasible to parametrise the effect of albedo change (using a model) on the linear coefficients so that continental surface-leaving shortwave irradiances can be estimated from the 1.6 $\mu$ m channel. Further work is in progress to evaluate this possibility.

The magnitude of the emission of longwave radiation from the land surface can be estimated through satellite-derived LSTs. The impact of LST errors on estimating the longwave emission from the surface is significant because the irradiance is proportional to $T_s^4$. Consequently, accurate and carefully validated algorithms are required. It appears that the ATSR and ATSR-2 can provide accuracies of 1-3 K which are comparable to or better than the accuracies obtained from AVHRR data. The use of satellite-derived LSTs is perhaps the only methodology available to estimate the longwave emission from the surface at continental to global scales.

# Acknowledgments

It is a pleasure to acknowledge the work of the ATSR team at the RAL, UK, who have provided us with the processed ATSR images. Dr Chris Mutlow and Dr David Llewellyn-Jones are particularly thanked for their help and advice with the data. The European Space Agency supplied the raw ATSR data to the UK/Australia/France ATSR Consortium.

# References

Becker, F., and Z.-L. Li, 1990:Towards a local split window method over land surfaces, *Int. J. Remote Sens.*, **3**, 369--393.

Coll, C., V. Caselles, J. A. Sobrino, and E. Valor, 1994:On the atmospheric dependence of the split-window equation for land surface temperature, *Int. J. Remote Sens.*, **15** (1), 105--122.

Li, Z.-L., and F. Becker, 1993:Feasibility of land surface temperature and emissivity determination from AVHRR data, *Remote Sens. Environ.*, **43**, 67--85.

Kimes, D. S., and P. J. Sellers, 1985:Inferring hemispherical reflectance of the earth's surface for global energy budgets from remotely sensed nadir or directional radiance values, *Remote Sens. Environ.*, **18**, 205--223.

Kerr, Y. H., J. P. Lagouarde, and J. Imbernon, 1992:Accurate land surface temperature retrieval from AVHRR data with use of an improved split window algorithm, *Remote Sens. Environ.*, **41**, 197--209.

Ottlé, C., and D. Vidal-Madjar, 1992:Estimation of land surface temperature with NOAA9 data, *Remote Sens. Environ.*, **40**, 27--41.

Prata, A. J., 1993:Land surface temperatures derived from the AVHRR and ATSR I: Theory, *J. Geophys. Res.*, **98**}, 16,689--16,702.

Prata, A. J. 1994a:Land surface temperatures derived from AVHRR and ATSR. II: Experimental results and validation of AVHRR algorithms, *J. Geophys. Res.*, **99**, 13,025--13,058.

Prata, A. J., 1994b:Validation data for land surface temperature determination, CSIRO, Technical Paper no. 33, CSIRO, Division of Atmospheric Research, Aspendale, Victoria, Australia, 36pp.

Prata, A. J., 1994c:Infrared measurements of land surface temperature from space and the effects of viewing geometry, Proc. of the 6th Symposium on Physical Measurements and Signatures in Remote Sensing, Val d'Isére, France, 17-21 January, 1994.

Prata, A. J., V. Caselles, C. Coll, J. Sobrino, and C. Ottlé, 1995:Thermal remote sensing of land surface temperature from satellite: Current status and future prospects, *Remote Sens. Rev.*, **12**, 175--224.

Prata, A. J., 1996:A new longwave formula for estimating downward clear-sky radiation at the surface, *Quart. J. Roy. Meteorol. Soc.*, **122**, 1127--1151.

Prata, A.J., R. P. Cechet, and I.F. Grant, 1996:Validation of ATSR retrieved surface reflectance for Hay, NSW, using in-situ data, Proceedings of the First Australian ERS Symposium, Hobart, Editor: J. Kingwell, COSSA publication 37, 94--101.

Sobrino, J. A., C. Coll, and V. Caselles, 1991:Atmospheric correction for land surface temperature using NOAA-11 AVHRR channels 4 and 5, *Remote Sens. Environ.*, **38**, 19--34.

Sobrino, J. A., Z-L. Li, M. P. Stoll, and F. Becker, 1996:Multi-channel amd multi-angle algorithms for estimating sea and land surface temperature with ATSR data, *Int. J. Remote Sens*., **17**, 2089--2114.

Suits, G., 1972:The calculation of directional reflectance of a vegetative canopy, *Rem. Sens. Environ.*, **2**, 117--125.

Ulivieri, C., M. Castronuovo, R. Francioni, and A. Cardillo, 1994:A split-window algorithm for estimating land surface temperature from satellite, *Adv. Space Res.*, **14**, 59--65.

Gartner, Jochen, 1995a:Another Sample for the Bibliography. *Journal of Sample Research*, **56**, pp. 165-169.

Gartner, Jochen, 1995b:Discontinued Samples. *Technical Report N2345*, Laboratory of Research New York, p. 342.

Severin, Priska, Muller, Rudolf, 1994:*The Sample Project, Results and Comments*. The Olsen publishing company, Inc., Toronto, 213 pages.

Keywords: ESA European Space Agency - Agence spatiale europeenne, observation de la terre, earth observation, satellite remote sensing, teledetection, geophysique, altimetrie, radar, chimique atmospherique, geophysics, altimetry, radar, atmospheric chemistry