A Brief Review of Sea Surface Infrared Radiometry as it Relates to the ISAR
(Infrared Sea Surface Temperature Autonomous Radiometer)\textsuperscript{1}

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1 ISAR Measurement Principal

This informal technical memo has been written as an introduction to the basic theory and approximations that are explicit and implicit in the basic equations that are used in estimation of ocean skin temperature by infrared radiometry. The development has been created as much for the edification of the author as it has to serve as a guide to future memos that deal with details related to the ISAR (Infrared Sea Surface Temperature Autonomous Radiometer) instrument and the algorithms it uses.

The ISAR incorporates a specially modified infrared radiometer, the KT1585 made by Heitronics Inc., in storm-proof, ruggedized housing with a special storm shutter that can be closed when weather conditions dictate. The radiometer is protected in a sealed volume with an IR-transparent window that looks onto a 45° window in a rotating scan drum (Figure 1).

![Figure 1: A sketch of the radiometer foreoptics which includes a transparent window, gold mirror and scan drum. The IR detector is positioned in front of the mirror and looks at the 45° gold mirror which is set into the scan drum assembly. The scan drum is rotated under computer control and can be pointed to any angle in the rotation plan to ±0.2°. For normal operation, the drum is pointed at the sea surface, the sky, at an ambient temperature black body and at a heated black body.](image)

The KT1585 is specially designed to have an exceptionally narrow beam width. The radiometer used in the ISAR has focusing optics that reduce the target beam to a 5 mm diameter spot at a focal point 96 mm in front of the detector head (at 98.3 % radiance). The beam width is narrow enough that it accepts radiation through the 5mm hole in the scan drum yet has very low acceptance of stray photons from the edges of the hole or from the edges of the black bodies. The scan drum peep hole is made small in order to minimize any ingress of water droplets.

\textsuperscript{1}File pubs/2007/IsarTheory.tex
The KT1585 has been modified from the normal factory configuration to track brightness temperatures from -100 to 100°C. An important feature of the KT1585 is that the analog output voltage is linearly proportional to received irradiance over an active range corresponding to brightness temperatures from -100°C to 100°C.

2 Basic Theory

There is often confusion between *irradiance* which is a hemispheric integration of all radiant energy incident on a point, and *radiance* which is the radiant energy coming from a specific direction. The IR radiometer analog output is calibrated against irradiance. But, because it is a narrow field-of-view receiver, radiance and irradiance are, in qualitative terms, interchangeable. This section provides some formality of the differences.

**Irradiance.** The rate of energy transfer, from all directions, through an infinitesimal surface is called the *radiant flux*, and has units of energy per unit time (Joules per second or Watts) [Wallace and Hobbs, 1977]. *Irradiance*, $E$, is defined as the radiant flux for an infinitesimal surface divided by the area through which it passes and is expressed in watts per square meter (W m$^{-2}$). In general, $E$ is dependent on the wavelength $\lambda$, and it is desirable to speak of the radiation in an infinitesimal wavelength interval, $d\lambda$. The irradiance per unit wavelength is called the *monochromatic irradiance* $E_\lambda$. Figure 2 gives an example of the monochromatic irradiance as the total flux through the infinitesimal area, $d\omega$.

$$E_\lambda = \frac{dE(\lambda)}{d\lambda}$$

and has units of W m$^{-3}$, or sometimes is written W m$^{-2}$ nm$^{-1}$.

The *wavenumber*, $n \equiv 1/\lambda$, is often used instead of wavelength. By convention, $n$ is expressed in units of cm$^{-1}$ and $\lambda$ is expressed in units of either nm or µm depending on the wavelengths under discussion, and $n(\text{cm}^{-1}) = 10000/\lambda(\mu\text{m})$. In terms of wavenumber, $d\lambda = -\lambda^2dn$ and the monochromatic irradiance, $E_n$, is related to $E_\lambda$ by the relationship $E_n = -\lambda^2E_\lambda$. In the discussions in this document, the expressions will be given in terms of wavelength.

**Radiance.** $L(\omega)$ is the radiant flux passing an infinitesimal area from a particular direction in 3D space. The infinitesimal area is equivalent to an infinitesimal arc of solid angle, $d\omega$, which has units of steradians (sr). $L(\omega)$ is defined as the irradiance per unit solid angle and has units of W m$^{-2}$ sr$^{-1}$. The direction, $\omega$, is defined by the spherical coordinate system angles: the *zenith angle* $\theta$ and the *azimuth angle* $\alpha$:

$$E_\lambda = \int_0^{2\pi} L_\lambda(\omega) d\omega = \int_0^{\pi/2} \int_0^{2\pi} L_\lambda(\alpha, \theta) \cos \theta \sin \alpha d\theta d\alpha$$

where the cosine term, $\cos \theta$, accounts for the oblique angle of the radiant vector to the surface. The *monochromatic radiance* is denoted by the $\lambda$ subscript.
Figure 2: Schematics showing the relationship between irradiance, $E$, and radiance, $L(\omega)$. The same concept applies for monochromatic irradiance and radiance, $E_\lambda$ and $L_\lambda$. $E$ is the total radiant energy passing through an infinitesimal surface, $d\omega$, from all directions. $L$ is the radiant energy passing through the surface from a particular direction, $\omega$. In spherical coordinate systems, $d\omega = \sin \alpha d\alpha d\theta$ where $\alpha$ and $\theta$ are the spherical angles. See for instance Liou [1980, pages 3-4].

**Beam Width and Narrow FOV Irradiance.** The radiometric receivers used in temperature measurement have foreoptic lenses that accept energy from a narrow field-of-view (FOV). A typical beam pattern for a narrow FOV optic is shown in Figure 3. In this example we assume the beam pattern is cylindrically symmetrical about a beam axis and is defined by the off-center angle, $\theta$. The beam pattern is defined by the function, $G(\theta)$. As was specified earlier, the radiometer used in the ISAR has focusing optics that reduce the target beam to a 5 mm diameter spot at a focal point 96 mm in front of the detector head, which is equivalent, roughly, to a beam width of 1°. The total irradiance received by this optic system is given by the integration

$$E_\lambda = \int_{-\theta_1}^{\theta_1} \int_0^{2\pi} L_\lambda(\theta, \alpha) G(\theta) \sin \theta \, d\alpha \, d\theta \quad (3)$$

where $\theta_1$ is an angle beyond which any contribution to the total integration is negligible. In the example in Figure 3, $\theta_1 \approx 10^\circ$ where the attenuation is 0.001 (-30 db). The beamwidth, BW, can be defined in any of several ways, but in this example it is taken simply as the spread at the half-power, 3 db, points. That is $G(\theta_{BW}) = 0.5$.

In general, when $\theta_{BW} < 2^\circ$, $L(\theta)$ changes only slightly and the radiance can be moved outside the integral, and with axial symmetry equation 3 becomes

$$E_\lambda(\theta) = L(\theta) 2\pi \int_{\theta_1}^{\theta_1} G(\theta) \sin \theta \, d\theta \quad (4)$$

Therefore, for a narrow FOV optics pointing at any direction, $\omega$ in a spherical coordinate system, the irradiance, $E_\lambda$, and the radiance, $L_\lambda$ are different by a constant multiplier. The ISAR radiometer output in millivolts is proportional to the received irradiance at a particular pointing angle and thus, the analog output voltage is also proportional to the incoming radiance at that angle. There is no need to know $G(\theta)$ precisely, only that $\theta_{BW}$ is small compared to the angular variability of $L_\lambda(\theta)$. 
Black-body Radiance and the Planck Function. The black body is a hypothetical body comprising a sufficient number of molecules absorbing and emitting electromagnetic radiation in all parts of the spectrum so that (a) all incident radiation is completely absorbed and (b) in all wavelength bands and in all directions the maximum possible emission is realized \cite{Wallace and Hobbs, 1977}. The monochromatic radiance for a black body was calculated by Planck using quantum mechanics and is given by the equation \cite{Rees, 1990}:

$$B_\lambda = \frac{2hc^2}{\lambda^5} \left( e^{hc/\lambda kT} - 1 \right)^{-1}$$

(5)

where $h$ is Planck’s constant ($6.626076 \times 10^{-34}$ Js), $c$ is the speed of light ($2.997924580 \times 10^8$ m s$^{-1}$), $k$ is the Boltzmann constant ($1.380658 \times 10^{-23}$ JK$^{-1}$), and $T$ is the absolute temperature, ($^\circ$K). $T({^\circ}$K) = $T({^\circ}$C) + 273.15.

The units of $B_\lambda$ as defined in (5) are W m$^{-3}$. Therefore, $B_\lambda$ is a monochromatic radiance with $2hc^2 = 1.1925 \times 10^{-16}$ and $hc/k = 1.4388 \times 10^{-2}$. A true black body emits uniformly in all directions and thus the black body emitted irradiance, is given as the integral of $B_\lambda$ over a hemisphere: $E^*_\lambda = \pi B_\lambda$.

Radiometric Temperature. Equation 5 states that for any wavelength there is a one-to-one relationship between the temperature of a black body and its radiance, $B_\lambda(T)$. Often a measurement of incoming radiance $L_\lambda$ is expressed in terms of its radiometric temperature or its equivalent black-body temperature which is defined as the temperature a black body would need in order to produce the same measured radiance. Radiometric temperature can be considered as the inverse of the Planck equation:

$$T_\lambda(\theta) = B^{-1} (L_\lambda(\theta))$$

(6)
where $T_\lambda(\theta)$ is the monochromatic black-body temperature that corresponds to the measured radiance, $L_\lambda(\theta)$. It is intuitively more convenient to discuss radiance quantitatively in terms of its equivalent black-body temperature.

**Emissivity.** The radiance emissivity of an emitting surface, $\varepsilon_\lambda$, is defined as the ratio of emitted radiance to the Planck function.

$$L_\lambda(\omega) = \varepsilon_\lambda(\omega) B_\lambda(T)$$

where the emissivity depends on the emitting direction, $\omega$. The actual radiance, thus, is dependent on the measurement angle.

The irradiance emissivity is different than the radiance emissivity and is derived from equation 2. In general, the radiance emissivity is dependent on direction.

$$E_\lambda = \int_0^{2\pi} \varepsilon_\lambda(\omega) B_\lambda(\omega) d\omega = \varepsilon^*_{\lambda} E^*_{\lambda}$$

As discussed above, the narrow FOV ISAR instrument output is proportional to received radiance and discussions of emissivity refer to the radiance emissivity, $\varepsilon_\lambda$.

**Reflection and absorption.** The air-ocean interface is the surface between two media with different optical properties. When a beam of radiant energy intersects the surface, some of the beam is absorbed into the surface and the remainder of the energy is reflected away. If the radiance components are normalized by the total radiance, the absorptivity and the reflectivity are defined as

$$a_\lambda + r_\lambda = 1$$

Further, by the Second Law of Thermodynamics, it can be shown that the absorptivity and the emissivity are equal, $a_\lambda = \varepsilon_\lambda$. Thus the reflectivity of the surface is

$$r_\lambda(\omega) = (1 - \varepsilon_\lambda(\omega))$$

The reflected energy can be specular (like a perfect mirror) or diffuse where the reflected radiance depends on all angles, $\omega$. Specular reflection is co-planar. The assumption used in the computation of sea-surface skin temperature by ISAR are that reflections from the sea surface are specular.

**Water-leaving Radiance** Consider the schematic shown in Fig. 4 where a radiant beam, $L_a(\lambda, \theta)$, meets a horizontal surface, the ocean surface, at a zenith angle $\theta$. In the discussion here the spherical direction, $\omega$, is defined by the zenith angle, $\theta$, and the azimuthal angle, $\alpha$.

The reflection can be specular (mirror-like) or diffuse. Donlon et al. [2000] have reviewed the atmospheric correction subject and conclude that specular reflection is the largest contributor to the atmospheric correction and thus we only need be concerned with atmospheric radiance from the zenith angle, $\theta$. We assume reflection is independent of azimuth. While there might be some dependence on azimuth in a directional wave field, the effect is generally considered to be insignificant for the purposes of measuring sea-surface temperature. By (10) the fraction of downward incident radiance that is reflected is $(1 - \varepsilon(\lambda, \theta))$.  

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The surface emits radiant energy and, by (7) and (9), the emitted radiant energy leaving the surface at the zenith angle, $\theta$, is given by

$$L_S(\lambda, \theta) = \varepsilon(\lambda, \theta) B(\lambda, T_S) \quad (11)$$

Figure 4: Measuring water-leaving radiance. The water leaving radiance in a line to the radiometer is composed of the water-emitted radiance, $L_s$, and radiance from the atmosphere that is reflected at the surface. Both diffuse and specular reflection are possible but it is assumed that only the specular reflection is significant. The “zenith angle” is the angle measured from an upward vertical, the zenith. The “nadir angle” is the angle measured up from a downward vertical, the nadir. The “viewing angle” is the pointing angle of the radiometer and is usually relative to a vertical. In the case of specular reflection, the zenith angle of the incident ray equals the nadir angle of the reflected ray.

The upward water-leaving radiance is the sum of the reflected and emitted radiances. A radiometer at some distance above the water surface and pointing at a nadir angle $\theta$, will receive the water leaving radiance after it has travelled the path from water surface to the radiometer.

$$L_d = L_S + (1 - \varepsilon) L_a + L_p \quad (12)$$

where the zenith/nadir angle, $\theta$, and wavelength, $\lambda$, are implicit in all terms, $\varepsilon$ is the emissivity of the sea surface, $L_d$ is the radiance seen by a downward-pointing radiometer, $L_S$ is the black-body radiance emitted from the sea surface, $L_a$ is the atmospheric radiance, and $L_p$ is the path correction for the emitted and absorbed radiance in the path below the level of the radiometer. $L_a$ and $L_S$ will interact with the air along the ray path from the surface to the radiometer and this effect is usually represented by the path correction term, $L_p$. The ISAR radiometer wavelength passband (9.5–11.5 $\mu$m) is in a window region of very low atmospheric emissivity, and therefore, when radiometer-to-surface distance is less than approximately 50 m, $L_p$ can be neglected.

The atmospheric radiance along the $\theta$ vector is the integrated emission-absorption from the atmosphere along the vector path. Most of the weight in the resulting emission comes a distance that depends on wavelength (Fig. 5).

**Skin Temperature.** Within 1 mm on each side of the air-ocean surface, turbulence is suppressed and heat transfer takes place by conduction. This region, with constant temperature slope, is called the thermal conduction sublayer. At the radiometer wavelengths, the water-emitted radiance, $L_S$, comes from a thin layer of 10–20 $\mu$m of the water surface (Fig. 5) and has a complex relationship as discussed by McKeown et al. [1995]. The radiance temperature from
Figure 5: The skin depth of the $T_s$ measurement for different wavelengths.

This layer is well within the thermal conduction sublayer and is approximated by the Planck function in the form

$$L_S = \varepsilon B_\lambda(T_S)$$

which provides a definition of the sea-surface skin temperature, $T_S = B^{-1}(L_S/\varepsilon)$, or

$$T_S = B^{-1}[(L_d - (1 - \varepsilon) L_a) / \varepsilon]$$
3 Instrumentation Details

The above discussion derives expression (12) for water leaving radiance, $L_d(\lambda, \theta)$ for a specific wavelength, $\lambda$ and zenith angle, $\theta$. This section adapts that theory to a practical radiometer with a finite wavelength passband and field of view. A very detailed description of ISAR is provided by Donlon et al. [2007] and the discussion here does not attempt to duplicate that effort. The development here provides a complete description of the operation algorithm for ISAR sampling and a development of the theory to understand the data processing scheme and the resulting computation of sea surface skin temperature.

Radiometer Bandpass Filter. For a given viewing angle, the narrow FOV radiometer sees an irradiance, $E_\lambda$, defined by (3) by the incoming radiance field, $L_\lambda(\theta)$, and the field of view function, $G_\lambda(\theta)$. It is shown in (4) that, for the narrow FOV, the received irradiance is linearly proportional to the radiance at the viewing angle, $E_\lambda \propto L_\lambda$.

The radiometer is a narrow bandwidth receiver (Fig. 6). The transfer function as a function of wavelength, $\zeta(\lambda)$, strongly attenuates any wavelengths outside of the 9.5–11.5 $\mu$m band. A general expression for the bandpass-filtered radiance is

$$\hat{L} = \int_{\lambda_1}^{\lambda_2} \zeta(\lambda) L_\lambda d\lambda / \int_{\lambda_1}^{\lambda_2} \zeta(\lambda) d\lambda$$

(15)

where $L_\lambda$ is the incoming radiance for a given view. The radiometer’s analog voltage output at a particular viewing angle is proportional to the bandpass-filtered radiance; $V(\theta) \propto \hat{L}(\theta)$, where the output voltage depends on view angle.

Figure 6: Left: A typical bandpass for the radiometer used by ISAR and the bandpass-filtered Planck function radiance. Right: Relationship between filtered Planck irradiance (W m$^{-2}$) and black-body temperature, °C.

Figure 6, left panel, shows the bandpass transfer function, $\zeta(\lambda)$, for an infrared radiometer used by ISAR. The black-body radiances for temperatures, from (5), from 0–40°C are shown on the same plot as the filter function. We see that over the narrow bandpass, $B_\lambda(T)$ is well behaved and weakly dependent on wavelength.

Figure 6, right panel, shows the bandpass-filtered Planck irradiance, using (15) with $B_\lambda(T)$, the Planck function, (5), inside the integral. The small table in the sketch gives integrated Planck
irradiance for this particular passband function. We note here that the radiance measurements
change by $4 \text{ W m}^{-2}$ over a $10^\circ\text{C}$ range. To achieve an overall uncertainty of $0.1^\circ\text{C}$ the radiance
measurement must be at least to $0.02 \text{ W m}^{-2}$ or better. Errors will be reviewed in more detail
below.

**Normalized Radiance and the Radiance Lookup Table.** For convenience, and with no
loss in generality, we will use a normalized radiance in the final computations. All black-body
and incident radiances are divided by the Planck radiance at $T_0 = 273.15^\circ\text{K (0}^\circ\text{C)}$.

\[ \hat{L}(T) = \mathcal{F}(T) = \frac{B(T)}{B(T_0)} \tag{16} \]

where the hat (') defines a passband-filtered variable. The function, $\mathcal{F}(T)$, can be solved using
equations (5) and (15). The inverse of this function is the radiometric temperature,

\[ T(\hat{L}) = \mathcal{F}^{-1}(\hat{L}) \tag{17} \]

produces the radiometric temperature equivalent to received radiance. Note that from now on
in this discussion, the filtered radiance, $\hat{L}$, is the normalized radiance.

The reciprocal functions, $\mathcal{F}(T)$, and $\mathcal{F}^{-1}(\hat{L})$ are solved by either using high order polynomials or
from a lookup table. A polynomial solution is useful in remote instruments with limited memory
while the lookup table is fast and very accurate as long as the resolution is high enough. Tim
Nightingale, RAL, has provided a polynomial fit in the form

\[ \hat{L}(T) = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + a_5 T^5 \tag{18} \]

where (for unit serial number 4832) $a_0 = -23.2332340, a_1 = 66.124043, a_2 = -82.426267,$
$a_3 = 57.659334, a_4 = -21.432500, a_5 = 3.3086280$. This polynomial fit produces a close fit to
(16), but it unnecessarily complex and still approximate.

**Internal Calibration with Two Black Bodies** The analog output voltage of the ISAR ra-
diometer is proportional to the incoming, bandpass-filtered radiance. The radiometer is located
in a waterproof housing and looks out through a transparent window at a gold mirror (Fig. 1).
The window transmissivity and the mirror reflectivity should be very near zero and one respec-
tively. With time, contamination of the optics will attenuate the incoming radiance and the
received radiance will decrease. Other sources of measurement error are analog-to-digital con-
version calibration drift and radiometer calibration drift. These sources of error are significant
but they have the common characteristic that they change slowly compared to the 5-minute
measurement cycle and, for the narrow radiometer passband, they are wavelength independent.

ISAR has two precision black bodies mounted outside the sealed compartment at two different
viewing angles. Figure 7 shows a cross-section of one of the two black bodies. These black
bodies were constructed from a design provided by Tim Nightingale of the Rutherford-Appleton
Laboratories [Donlon et al., 2007]. The black body has a re-entrant cone and a partially closed
aperture design which, combined with a high emissivity surface finish (Nextel velvet black) and
Figure 7: ISAR black body. Three precision thermistors are located at the positions marked T1, T2, and T3. In the heated black body, the temperature at T3 is usually several tenths °C from the other two which accounts for a heating gradient in the heated body.

critical internal geometry, ensures that the black body cavities have an emissivity of > 0.999 in the thermal infrared waveband. Three thermistors (having a NIST traceable calibration to 0.05°C) are used to monitor the temperature of each black body. Two thermistors are located in the base cone and provide the primary measurement and a third thermistor is located close to the aperture to detect any thermal gradients when operated in heated mode. Each black body is housed in a plastic shroud leaving a small air gap between the outer wall and the shroud to inhibit convective heat loss and maintain temperature uniformity. Both black bodies are identical and have built-in constant power kapton resistance heating elements wrapped around their outer diameter. Each ISAR black body is designed as a modular component and is easily replaced during maintenance.

The emissivity of the black bodies, \( \varepsilon_B \), is very nearly unity, so the black-body radiance, \( \hat{L} \) is the bandpass-averaged Planck function:

\[
\hat{L}_1 = \mathcal{F}(T_1) \quad \text{and} \quad \hat{L}_2 = \mathcal{F}(T_2)
\]  

(19)

where \( T_1 \) and \( T_2 \) are averages of the three thermistors (T1, T2, T3) in each body. BB1 is passive and its measured temperature, \( T_1 \), drifts with ambient temperature. BB2 is heated with a constant voltage and its temperature, \( T_2 \), usually tracks about 20°C above \( T_1 \).

Figures 1 and 8 (left panel) show the arrangement of the black bodies in the optical path and as part of sampling cycle. In one ISAR measurement scan, the radiometer is pointed at four different view angles. The radiometer signal voltage is digitized and averaged for approximately one minute (60 samples) for each view. The averaged radiometer analog voltages are \( V_1 \), \( V_2 \), \( V_d \), \( V_u \) corresponding to received irradiance for BB1, BB2, looking down at the sea surface, and looking up at the sky.

The points (\( V_1, \hat{L}_1 \)) and (\( V_2, \hat{L}_2 \)) define a straight line which is the ISAR calibration curve. At any other view angle the normalized radiance is computed as

\[
\hat{L} = \hat{L}_1 + (V - V_1) \left( \frac{\hat{L}_2 - \hat{L}_1}{V_2 - V_1} \right)
\]  

(20)

from which the normalized radiances, \( \hat{L}_d \) and \( \hat{L}_u \) are derived.
Figure 8: ISAR measurement scan. A scan consists of four measurements, the downward-looking measurement, $L_d$, the atmosphere measurement, $L_a$, and the two black body calibration measurements $L_1$ and $L_2$. An example calibration curve is shown on the right where measured black body radiances, $L_1$ and $L_2$ are used to make a straight-line fit to correct the downward and atmosphere measurements $L_d$ and $L_a$. The dashed straight line is one form of calibration error and is discussed below.

**ISAR View Angles.** ISAR uses a single radiometer with a rotating scan drum and mirror to measure incoming radiance from four different view directions. The view cycle and time spent on each view is a compromise between averaging accuracy and environmental changes.

The ISAR view angle, $\phi$, is measured from the vertical and outward. For example, a $90^\circ$ view is horizontal, out toward the horizon and a view of $270^\circ$ is horizontal into the instrument. A view angle of $135^\circ$ is toward the ocean with a nadir angle of $45^\circ$.

The black bodies are mounted inside ISAR pointing downward. The downward position minimizes standing water. The un-heated black body, BB1, is positioned at a view angle of $\phi_1 = 280^\circ$ and the heated black body, BB2, is positioned at a view angle $\phi_2 = 325^\circ$. The steep angle of BB2 traps warm air to reduce temperature gradients and to help stabilize the radiance measurement.

The downward, sea view is typically set at $\phi_d = 135^\circ$, which corresponds to a nadir angle $\theta_d = (180 - \phi_d) = 45^\circ$. Choice of $\phi_d$ is crucial. The instrument is mounted on a ship near the bow and the downward view must be an unobstructed view of the un-disturbed ocean surface ahead of the ship bow wake. The ocean emissivity, $\varepsilon_S$ is a function of nadir angle, especially when $\theta > 50^\circ$. A good compromise for ISAR is $\theta_d = 45^\circ$ or $\phi_d = 135^\circ$.

The upward, sky view angle corresponds to the selected downward view for specular reflection at the sea surface. As shown in Fig. 4, most of the reflected sky radiance comes from a zenith angle equal to the downward nadir angle. Therefore, the upward viewing angle $\phi_u = \theta_d$.

Finally, the preferred viewing angle set is $\phi = [\phi_1, \phi_2, \phi_u, \phi_d] = [280, 325, 45, 135]$. It should be noted that ISAR can be programmed to point to up to ten different view angles for special applications. However, the set of four angles defined above make up the basic measurement cycle.

**Analog-to-Digital Converters** Precision analog measurements are made with an Adam-4017 eight-channel analog-to-digital converter (ADC). This ADC has a precision of 0.0001 V from -5 to 5 V input. We have evaluated temperature drift and sensitivity to supply voltage and
found that for ambient temperatures from -20 to 50°C and for a wide range of supply voltages, the measurements changed by no more than ±0.1 mv. The eight channels of the precision ADC were assigned to the six black body thermistors, the KT15 radiometer output, and the optical rain gauge.

The 12-bit ADC is used to measure voltages on four thermistors located around the instrument (system temperatures are described below), the supply voltage, and the reference voltage for the black body thermistors (also described below).

**Pitch and Roll** The mean tilt of ISAR is monitored with a pitch and roll sensor which is incorporated into a flux-gate compass.

**GPS** The location of the system is recorded by a GPS that is intrinsic to the ISAR.
4 Sample Averaging and Uncertainty

The measurement cycle. The basic measurement cycle involves rotating the scan drum to each of the four proscribed view angles and taking a series of samples. Each raw sample set requires approximately 1.5 seconds and includes (1) The eight-channel precision ADC, (2) The eight-channel 12-bit ADC, (3) The digital flux-gate compass with pitch and roll, (4) The digital GPS for latitude and longitude. and (5) The KT15 digital output, case and target temperatures.

A major source of uncertainty in the ISAR measurement is noise uncertainty from the KT15 radiometer. Noise in the KT15 analog voltage was equivalent to $0.1^\circ C$ and thus some signal averaging was necessary. A compromise between the time required to pause at the four view angles for averaging and the time scale for changing environmental conditions was necessary. The following sampling plan has been adapted:

<table>
<thead>
<tr>
<th>Name</th>
<th>View Angle</th>
<th># Secs</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB1</td>
<td>$\phi_1$</td>
<td>280</td>
</tr>
<tr>
<td>BB2</td>
<td>$\phi_1$</td>
<td>325</td>
</tr>
<tr>
<td>Sky</td>
<td>$\phi_d$</td>
<td>45</td>
</tr>
<tr>
<td>Sea</td>
<td>$\phi_u$</td>
<td>135</td>
</tr>
</tbody>
</table>

This cycle requires approximately 180 sec to complete all four views including the time required to rotate the scan drum to a new position. The cycle continues without pause, unless it is interrupted by precipitation at which time it closes up and waits for the next opportunity to re-open and continue sampling.

System Temperatures Several thermistors are located around the ISAR to track system changes. These thermistors are all YSI44006 (10K ohms at $25^\circ C$) beads in a voltage divider circuit with the reference resistance to analog ground. The thermistor voltage is recorded by the 12-bit ADC so that

$$v_t = V_R \left( c/4095 \right)$$

$$r_t = R_R \left( v_t / (V_R - v_t) \right)$$

and the temperature is read by linear interpolation from an R-T table supplied from YSI, Inc. The 12-bit ADC is read and recorded for each ISAR sample, at a rate of 1.5 sec. The thermistor beads are located in tiny holes in the housing and are packed with thermally conductive grease. The holes are located as follows:

- Window: Adjacent to the the window
- Aperature 1: Between BB1 and the case.
- Aperature 2: Between BB1 and BB2
- Aperature 1: Between BB2 and the case.

Other temperatures, also sampled each raw sample, are

- KT-15: Radiometer case temperature, from KT15 digital interface
- PNI: On-board temperature for the pitch-roll flux-gate sensor
- TT8: On board temperature of the TT8 microprocessor
5 Calculation of Sea Surface Skin Temperature

The ISAR Sampling Algorithm The calculation of skin temperature proceeds by the following steps.

1. Cycle through the four view angles, $\theta_1, \theta_2, \theta_d, \theta_u$. Make approximately 40 samples of all temperatures and the radiometer voltage at each view.

2. At the end of the averaging period, typically 10 minutes, compute averages of the following measurements: $T_1$ is the mean temperature for the three thermistors in black body 1. $T_2$ is same for black body 2. $V_1$ is the mean radiometer voltage during view 1. $V_2$ is the mean radiometer voltage during view 2. $V_d$ is the mean radiometer voltage during the downward, sea view. $V_u$ is the mean radiometer voltage during the upward, sky view.

3. Compute $\hat{L}_1$ and $\hat{L}_2$ from (19).

4. Compute the calibration slope from (20)
\[
m = (\hat{L}_2 - \hat{L}_1) / (V_2 - V_1)
\] (23)

5. Apply the slope correction term (described below), $m' = \alpha m$.

6. Compute up and down view radiances from (20).
\[
\hat{L}_d = \hat{L}_1 + m' (V_d - V_1)
\]
\[
\hat{L}_u = \hat{L}_1 + m' (V_u - V_1)
\]

7. Given $\hat{L}_d$ and $\hat{L}_u$, estimate the sea surface emissivity, $\varepsilon_S$ and use (14) to compute the normalized radiance emitted by the sea surface
\[
\hat{L}_S = \frac{(\hat{L}_d - (1 - \varepsilon_S) \hat{L}_u)}{\varepsilon_S}
\] (24)

8. Use the lookup table or the polynomial fit $\mathcal{F}^{-1}(\hat{L}_S)$ to compute the radiometric temperature of the sea surface, $T_S$. This is the sea surface skin temperature.
6 Measurement Uncertainty

In the proceeding discussion it has become apparent that a measurement of SSST with an uncertainty of $< 0.1^{\circ}C$ requires extreme care and attention to detail. Several important factors enter into the uncertainty of the measurement of $T_s$ and these need to be considered in order to validate the measurement goal of $0.1^{\circ}C$. In order of importance, these are:

<table>
<thead>
<tr>
<th>MINIMIZED BY SELF-CALIBRATION</th>
<th>PRIMARY TO UNCERTAINTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical alignment</td>
<td>Determined in NIST calibrations.</td>
</tr>
<tr>
<td>ADC gain and offset</td>
<td>Must be stable over the measurement cycle, 30 sec.</td>
</tr>
<tr>
<td>Mfgr’s Calibration</td>
<td>Must be stable over the measurement cycle.</td>
</tr>
<tr>
<td>Contamination of the optics</td>
<td>optics contamination, especially spectral changes.</td>
</tr>
<tr>
<td>Emissivity, $\varepsilon$</td>
<td>A big problem</td>
</tr>
<tr>
<td>ADC drift</td>
<td>Lab tests show this is minimal.</td>
</tr>
<tr>
<td>ADC noise</td>
<td>Requires low noise conversion and multiple sampling.</td>
</tr>
<tr>
<td>BB Emissivity</td>
<td>Keep contamination minimal.</td>
</tr>
<tr>
<td>BB Thermistor</td>
<td>Laboratory testing and calibration required.</td>
</tr>
<tr>
<td>Atmos Correction</td>
<td>Diffuse reflection on a wavy surface.</td>
</tr>
<tr>
<td>Intervening air</td>
<td>needs some thought, high RH, spray</td>
</tr>
<tr>
<td>Temp Drift</td>
<td>The black body radiance and temperature measurements should be synchronous. Are there temperature dependencies from the mirror and the window? Are these a problem?</td>
</tr>
</tbody>
</table>
Measurements of $L_d$ and $L_a$ must be taken at the same zenith and nadir angles respectively. On a rolling ship, when many seconds pass between measurements, the difference in $\theta$ between sky and downward angles can lead to error, especially in certain conditions [Donlon et al., 1999]. The atmospheric correction is small during periods of clear sky, and $L_a$ is approximately isotropic during overcast and high-humidity conditions. In these cases, differences between the sea and sky angles can be as much as $\pm 10^\circ$ without leading to significant uncertainty. During partly cloudy conditions in dry air, such as in the trade Cumulus areas of the oceans, more care must be exercised. It is for this reason that the best measurements must be made from larger volunteer or research ships when the pitch and roll angles seldom exceed 1–3$^\circ$. We will neglect the dependence of $\varepsilon$ on $\alpha$.

With the above caveats and assumptions, a working equation for the skin temperature, $T_s$ is

$$B_\lambda(T_s) = \frac{L_d(\lambda, \theta) - (1 - \varepsilon) L_a(\lambda, \theta)}{\varepsilon}$$

(25)

where $\varepsilon = \varepsilon(\lambda, \theta)$. and the Planck function (5) is inverted to determine $T_s$.

**Emissivity** We will see below that an uncertainty in emissivity of 0.01 will result in an uncertainty in temperature of 0.66°C. Thus it is essential to know $\varepsilon$ as accurately as possible. The variation of emissivity is discussed by Donlon et al. [2000] who use the results from Masuda et al. [1988] and Watts et al. [1996]. Figure ?? shows the variation of emissivity for a planar sea surface at different zenith angles and different wavelengths. Masuda provided data for $\varepsilon$ as a function of wind speed and surface roughness, but Donlon et al. [2000] concluded that these effects are secondary when the viewing angle, from nadir, is less than 40$^\circ$. The inset shows the uncertainty in $\varepsilon$ that leads to an 0.2°C uncertainty in the SSST measurement. A bold line shows the desired operating region inside the radiometer passband and at zenith angles of approximately 40$^\circ$.

In the case of the atmospheric correction, (29), emissivity can be taken as a constant, $\varepsilon \approx 0.988$ for the operating region specified in Fig. ?? . The atmospheric correction is secondary and any differences from a slightly varying emissivity are well within the uncertainty noise. Therefore,
approximately,

\[ S_u(\theta) = (1 - \varepsilon) S_u(\theta) \]

and we can compute the filtered water radiance as

\[
\int_0^\infty \varepsilon(\lambda, \theta) B(\lambda; T_s) = S_s = S_d(\theta) - S_u(\theta)
\]
Figure 10: Emissivity of seawater over the wavelengths of the isar radiometer for different zenith angles. The figure is taken from Donlon et al. [2000] who used data from Masuda et al. [1988]. The inset box shows the uncertainty in ε that will result in 0.2°C uncertainty in measured SSST. The vertical dashed lines show the passband of the IR radiometer and the bold area shows the approximate operating region in viewing angle and wavelength.

The sketch below shows the radianse from a black body at different temperatures. The plots are shown for those wavelengths inside the radiometer passband. The radiometer passband curve is laid over the Planck spectra and the filtered radiances are shown.

The KT15 radiometer output is a 0–1000 mV analog voltage over a -25 to 200°C range so that 4.44 mV correspondes to 1°C. The manufacturer provides a calibration lookup table to convert measured temperature to the corresponding values of S (see typical plot above). A plot of radianse vs. measured temperature in the range of sea surface temperatures is a smoothly varying curve, and a simple lookup table and interpolation routine will easily allow one to move between the two terms.

The analog output must be measured with great care. To achieve an overall uncertainty of 0.1°C, the radiometer temperature measurement should be at least to an accuracy of 0.02°C which means we need to measure the output voltage to an accuracy of ±0.09 mV. The analog-to-digital converter used in ISAR is an Advantech Model Adam-4017 16-bit, 8-channel converter. At the 250 mV full scale setting, one bit represents 0.008 mV. The specified instrument accuracy is ±0.1% (32 bits) and at a full-scale setting of 250 mV this translated to a single-measurement uncertainty of 0.25 mV. Careful testing of the Adam-4017 shows that over a temperature range of -20 to 60°C, and over a wide range of input voltage, the accuracy is better than ±0.01 mV and the overall temperature drift was < 1 bits (0.008 mV). To further improve the analog-to-digital converter measurement, a mean voltage measurement is computed from (??) individual samples. In the algorithm, the maximum and minimum samples are excluded from the mean.
Radiometer Measurements of Water-Leaving Radiance  The radiometer looks downward at a set nadir angle, $\theta$, and measures the bandpass-filtered radiance

$$S_d(\theta) = S_a + S_s$$  

where

$$S_a(\theta) = \int_0^\infty \zeta(\lambda) \left(1 - \varepsilon(\lambda, \theta)\right) L_a(\lambda, \theta) d\lambda / \int_0^\infty \zeta(\lambda) d\lambda$$  

and

$$S_s(\theta) = \int_0^\infty \zeta(\lambda) \varepsilon(\lambda, \theta) B(\lambda, T_a) d\lambda / \int_0^\infty \zeta(\lambda) d\lambda$$

The atmospheric effect is estimated by pointing the radiometer to a zenith angle $\theta$ identical to the angle used for looking at the sea surface and measuring $S_u(\theta)$, the upward-looking measurement.
section Calibration

An ISAR scan includes measurement of four different radiances (see sketch below), $L_d$ the downward view to the sea surface, $L_u$ the upward view to the atmosphere at a zenith angle corresponding to the angle of the downward view, $L_1$ and $L_2$ the black body views.

The corresponding measurements from the radiometer are $S'_d$, $S'_u$, $S'_1$, and $S'_2$. The primed variables indicate uncalibrated measurements of the bandpass-filtered radiances using the manufacturer’s lookup table (figure ??). The temperature of the black bodies, $T_1$ and $T_2$ are measured at the same instant as the radiances. One of the blackbodies is heated and the other remains at ambient temperature.

The actual radiance from each black body is computed from the Planck function assuming an emissivity of 1 and measured temperature, $T_1$ and $T_2$.

$$S_1(T_1) = \int_0^\infty \zeta(\lambda) B(\lambda; T_1) \, d\lambda / \int_0^\infty \zeta(\lambda) \, d\lambda$$  

(31)

with a similar relationship for $S_2$. We define a correction relationship based on a straight-line fit to the black body equations (figure ??):

$$S = mS' + b$$  

(32)

where $m = (S_2 - S_1) / (S'_2 - S'_1)$, and $b = S_1 - mS'_1$. Using the calibration equation, the corrected, filtered radiances $S'_d$ and $S'_u$ can be estimated and using (9) and (10) the bandpass-filtered Planck function.

The algorithm: The above mathematics are incorporated into the algorithm for the computation of the skin temperature $T_s$. The radiometer outputs, in °C, are converted to measured bandpass-filtered radiances ($S'_u$, $S'_d$, $S'_1$, $S'_2$) using the manufacturer’s lookup table. These are combined with the measured black body temperatures, ($T_1$, $T_2$), and corrected using the bandpass-filtered Planck black-body relationship. The corrected $S_u$ and the empirical relationship for $\varepsilon$ are combined (equation 26) to compute the reflected atmospheric radiance term $S_a$. Then (27) is used to relate $S_d$ and $S_a$ to $T_s$ through the integral relationship.

In practice, several different view angle pairs, $\theta$, are taken, e.g. $\theta = [40, 43, 45]$ and the results compared. The most stable view angle with the most consistent results is $\theta = 43^\circ$. This is the angle used for operation skin SST measurements. [HOW IS THIS DONE OPERATIONALLY?]

Equation (27) is most effectively solved in the ISAR computer by incorporating a lookup table of $S_s$ vs $T_s$ and using that with an interpolation algorithm. An alternate method would be to use a piecewise-quadratic fit method. Figure ?? shows the relationship of equation (27) for two different constant emissivities. The importance of emissivity is apparent in this plot where a difference from 0.98 to 0.99 produces a typical temperature error of -0.66°C (at 25°C). Thus we need to know $\varepsilon$ to an accuracy of better than 0.001 to achieve the needed accuracy. The importance of emissivity is discussed below.
References


