1 ISAR Measurement Principal

The ISAR (Infrared Sea Surface Temperature Autonomous Radiometer), shown in Fig.1 incorporates a specially modified infrared radiometer, the KT1585 made by Heitronics Inc., in a 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 (Fig.2).

![ISAR Measurement Principal](image)

Figure 1: Photo of ISAR. The Mini-ORG on the left is a sensitive rain detector as well as a good measure of rain fall. The shutter slot is to the right of center and is open in this photo. The scan drum and the radiometer peep hole are visible in the shutter slot.

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.

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. By incorporating two precision black bodies in the instrument, a direct proportionality between black body irradiance and analog voltage is computed and the radiative temperature of the target is derived without requiring an absolute calibration of the radiometer.

2 Basic Theory

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)
Figure 2: 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.

[Wallace and Hobbs, 1977]. Irradiance, $E$, is defined as the amount of radiant flux passing through 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 3 gives an example of the monochromatic irradiance as the flux from all directions passing through the infinitesimal area, $d\omega$. $E_\lambda$ is the differential of the total irradiance with respect to wavelength:

$$E_\lambda = \frac{dE(\lambda)}{d\lambda}$$  \hspace{1cm} (1)

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 $\mu$m depending on the wavelengths under discussion, and $n(\text{cm}^{-1}) = 10000/\lambda(\mu\text{m})$. In terms of wavenumber, $d\lambda = -\lambda^2 dn$ and the monochromatic irradiance, $E_n$, is related to $E_\lambda$ by the relationship $E_n = -\lambda^2 E_\lambda$. In the discussions in this document, the expressions will be given in terms of wavelength.

**Radiance.** The radiant flux passing an infinitesimal area from a particular direction in 3D space is called the radiance, $L(\omega)$. The infinitesimal area is equivalent to an infinitesimal arc of solid angle, $d\omega$, which has units of steradians (sr). $L(\omega)$ is 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 $\alpha$:

$$E_\lambda = \int_0^{2\pi} L(\omega) d\omega = \int_0^\pi \int_0^{2\pi} L(\lambda(\alpha, \theta)) \cos \theta \sin \alpha d\theta d\alpha$$  \hspace{1cm} (2)

where the cosine term, $\cos \theta$, accounts for the oblique angle of the radiant vector to the level surface. The monochromatic radiance is denoted by the $\lambda$ subscript.
Figure 3: 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 4. In this example 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 a function, $G(\theta - \theta_0)$, where $\theta_0$ is the pointing angle. 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 $1^\circ$. When the narrow FOV optics are pointing in the direction of a unit vector, $\vec{\nu}$, it can be shown that to good accuracy that

$$E_\lambda(\vec{\nu}) \propto L(\vec{\nu})$$

Therefore, for a narrow FOV optics pointing at any direction, $\vec{\nu}$, 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 $\theta_{\text{BW}}$ is small compared to the angular variability of $L_\lambda$.

**Black-body Radiance and the Planck Function.** A 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 [Wallace and Hobbs, 1977]. The monochromatic radiance for a black body was calculated by Planck using quantum mechanics and is given by the equation [Rees, 1990]:

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

where $h$ is Planck’s constant ($6.626076 \times 10^{-34}$ J s), $c$ is the speed of light ($2.997924580 \times 10^8$ m s$^{-1}$), $k$ is the Boltzmann constant ($1.380658 \times 10^{-23}$ J K$^{-1}$), and $T$ is the absolute temperature in degrees Kelvin. $T(\text{°K}) = T(\text{°C}) + 273.15$. 
Figure 4: A typical narrow-field-of-view antenna beam pattern in a rectangular graph. The attenuation curve is normalized so the attenuation is unity, 0 db, at the centerline. The beam width is defined by the half-power points, -3 db. In this example the beamwidth is $3^\circ$ and the first sidelobe occurs at $4^\circ$ and has a value of -18 db, 1.6% of the center.

The units of $B_\lambda$ as defined in (4) 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 4 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:

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

where $T_\lambda(\vec{\nu})$ is the monochromatic black-body temperature that corresponds to the measured radiance, $L_\lambda(\vec{\nu})$ from the direction $\vec{\nu}$ on a spherical coordinate system. 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.

$$L_\lambda(\vec{\nu}) = \varepsilon_\lambda(\vec{\nu}) B_\lambda(T)$$

where the emissivity depends on the emitting direction, $\vec{\nu}$. The actual radiance, thus, is dependent on the measurement angle. The narrow FOV radiometer pointing at a target in a direction, $\vec{\nu}$, has an output that is proportional to $L_\lambda(\vec{\nu})$. If the emissivity is known, the Planck function can be calculated and then the radiometric temperature derived.
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 reflected and absorbed radiance components are normalized by the total incident radiance, the absorptivity and the reflectivity are defined as

$$a_{\lambda} + r_{\lambda} = 1$$  \hspace{1cm} (7)

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

$$r_{\lambda}(\vec{\nu}) = (1 - \varepsilon_{\lambda}(\vec{\nu}))$$  \hspace{1cm} (8)

The reflected energy can be specular (like a perfect mirror) or diffuse where the reflected radiance depends on all directions, $\vec{\nu}$. 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. 5 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 ocean wave field, the effect is generally considered to be insignificant for the purposes of measuring sea-surface temperature. By (8) the fraction of downward incident radiance that is reflected is $(1 - \varepsilon(\lambda, \theta))$.

The surface emits radiant energy and, by (6) and (7), the emitted radiant energy leaving the surface at the zenith angle, $\theta$, is given by

$$L_S(\lambda, \theta) = \varepsilon(\lambda, \theta) B(\lambda, T_S)$$  \hspace{1cm} (9)

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.

$$L_d = L_S + (1 - \varepsilon) L_a + L_p$$  \hspace{1cm} (10)

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 blackbody 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.
Figure 5: 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.

Figure 6: The skin depth of the $T_s$ measurement for different wavelengths. Most emitted energy in the 9–12µm band comes from the top 10–20µm of the surface.

The atmospheric radiance along the $\vec{\nu}$ 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. 6).

**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 10–20µm of the water surface (Fig. 6) and has a complex relationship as discussed by McKeown et al. [1995]. The radiance temperature from this layer is well within the thermal conduction sublayer and is approximated by the Planck function in the form

$$L_s = \varepsilon B_\lambda(T_s)$$  \hspace{1cm} (11)
which provides a definition of the sea-surface skin temperature, \( T_S = B^{-1}(L_S/\varepsilon) \), or

\[
T_S = B^{-1} \left( (L_d - (1 - \varepsilon) L_a) / \varepsilon \right)
\]

(12)

3 Instrumentation Details

The above discussion derives expression (10) 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, \( E_\lambda(\vec{\nu}) \), defined by the incoming radiance field, \( L_\lambda(\vec{\nu}) \), and the field of view function, \( G_\lambda(\theta) \). It is shown in (3) 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. 7). 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

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

(13)

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 7: 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.](image-url)
Figure 7, left panel, shows the bandpass transfer function, $\zeta(\lambda)$, for an infrared radiometer used by ISAR. The black-body radiances for temperatures, from (4), 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 7, right panel, shows the bandpass-filtered Planck irradiance, $\hat{B}_\lambda(T)\hat{}$, using (13) with $B_\lambda(T)$, the Planck function, (4), 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 W m$^{-2}$ over a 10°C range. To achieve an overall uncertainty of 0.1°C the radiance measurement must be at least to 0.02 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 $T_0 = 273.15$K (0°C).

$$\hat{L}(T) = \mathcal{F}(T) = \hat{B}(T)/\hat{B}(T_0)$$ (14)

where the hat ($\hat{}$) defines a passband-filtered variable. The function, $\mathcal{F}(T)$, can be solved using equations (4) and (13). The inverse of this function is the radiometric temperature,

$$T(\hat{L}) = \mathcal{F}^{-1}(\hat{L})$$ (15)

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

$$\hat{L}(T) = a_0 + a_1T + a_2T^2 + a_3T^3 + a_4T^4 + a_5T^5$$ (16)

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 (14), but it is unnecessarily complex and still approximate.

Program ISARAVG computes a lookup table using (14) directly with no approximations. The table is used during $T_S$ computations as long as the program is active. The table of $T(\hat{L})$ vs. $\hat{L}(T)$ from -80 to 60°C in steps of 0.1°C provides sufficient accuracy and range for all ISAR situations. A lookup table has the advantage that, once computed, it is fast to use and the same table can be used in both directions between $\hat{L}$ and $T$.

### Internal Calibration with Two Black Bodies

The analog output voltage of the ISAR radiometer 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. 2). The window transmissivity and the mirror reflectivity should be very near zero and one respectively. 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 conversion calibration drift and radiometer calibration drift. These sources of error are significant
Figure 8: 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.

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 8 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 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:

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

(17)

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 $T_1$. The time constant of the black bodies is very large compared to the scan drum sampling cycle of five minutes.

Figures 2 and 9 (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.

![Diagram of ISAR measurement scan](image)

Figure 9: 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.

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

$$\hat{L} = \hat{L}_1 + (V - V_1) \frac{(\hat{L}_2 - \hat{L}_1)}{(V_2 - V_1)}$$  \hspace{1cm} (18)

from which the normalized radiances, $\hat{L}_d$ and $\hat{L}_u$ are derived.

**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. 5, 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. The emissivity is a function of the view. ISARAVG computes the emissivity based on the mean tilt of the ISAR as defined in the instrument configuration and corrected for the roll angle.

**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>30</td>
</tr>
<tr>
<td>BB2</td>
<td>$\phi_1$</td>
<td>30</td>
</tr>
<tr>
<td>Sky</td>
<td>$\phi_d$</td>
<td>10</td>
</tr>
<tr>
<td>Sea</td>
<td>$\phi_u$</td>
<td>40</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°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

\[ v_t = V_R \left( \frac{c}{4095} \right) \]  
\[ r_t = R_R \left( \frac{v_t}{V_R - v_t} \right) \]

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. A complete cycle takes approximately five minutes.

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 (17).

4. Compute the calibration slope from (18)

\[ m = \frac{(\hat{L}_2 - \hat{L}_1)}{(V_2 - V_1)} \]

5. Apply the slope correction term (described below), \( m' = \alpha m \).
6. Compute up and down view radiances from (18).
\[ \hat{L}_d = \hat{L}_1 + m'(V_d - V_1) \]
\[ \hat{L}_u = \hat{L}_1 + m'(V_u - V_1) \]

7. Given \( \hat{L}_d \) and \( \hat{L}_u \), estimate the sea surface emissivity, \( \varepsilon_S \), with corrections for ship roll, and use (12) to compute the normalized radiance emitted by the sea surface
\[ \hat{B}_S = \frac{(\hat{L}_d - (1 - \varepsilon_S) \hat{L}_u)}{\varepsilon_S} \quad (22) \]

8. Use the lookup table or the polynomial fit \( F^{-1}(\hat{B}_S) \) 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 less than 0.1°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°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>Emissivity, ( \varepsilon )</td>
</tr>
<tr>
<td>ADC gain and offset</td>
<td>A big problem</td>
</tr>
<tr>
<td>Mfr's Calibration</td>
<td>ADC drift</td>
</tr>
<tr>
<td>Contamination of the optics</td>
<td>Lab tests show this is minimal.</td>
</tr>
</tbody>
</table>

Epistemic 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 ±10° 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°. We will neglect the dependence of \( \varepsilon \) on \( \alpha \).
Figure 10: A plot of $\hat{L} \text{ vs. } T$ for two different values of $\varepsilon$.

Figure 11: 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 $\varepsilon$ 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.
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 ε 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 11 shows the variation of emissivity for a planar sea surface at different zenith angles and different wavelengths. Masuda provided data for ε 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°. The inset shows the uncertainty in ε 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°.

7 Conclusions

The program ISARAVG is designed to process raw samples from ISAR and compute the mean sea surface temperature, SSST. The program has been adapted to operate on raw samples stored in a computer file, as collected be a data acquisition program such as SCS, or in a real-time mode when the samples come directly from ISAR.

ISARAVG has been tested in many field programs, M-AERI ISAR comparisons, and calibrations and is considered to be operational.

References


