Dual-Band MWIR/LWIR Radiometer for Absolute Temperature Measurements

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ABSTRACT

A Dual-band Radiometer (DBR) has been developed to accurately measure temperature at long ranges. Key to the DBR is a dual-band, quantum well infrared photodetector (QWIP) focal plane array (FPA) that integrates within each pixel both mid-wavelength infrared (MWIR) and long-wavelength infrared (LWIR) spectral sensitivity. A vertically-integrated, two-color FPA eliminates with inter-band optical distortions, temperature-induced alignment errors, and improves radiometric measurement accuracy.

The DBR system is sensitive to human targets, yet minimally sensitive to atmospheric conditions, enabling accuracy over the widest possible range of global conditions by using Two-color Imaging Radiometry (TCIR) to establish a target’s absolute temperature within ±1 °C. The benefits of TCIR for greybody measurements are absolute atmospheric transmission values are not required and uncorrelated shifts in the spectral band transmission cause minimal error.

The system is packaged with an eye-safe laser rangefinder, GPS, and weather station suite, which provides real-time atmospheric measurements. These measurements are input to the USAF MOSART predictive atmospheric codes, which are used for real-time field calibration of the data. The magnification necessary to resolve facial features from 200 m to 750 m range requires a custom designed 6” diameter, f/7 telescope with temperature-stable optical alignment over a wide range of operational temperatures.

Keywords: Radiometer, Two-Color Imaging Radiometry, TCIR, quantum well infrared photodetector, QWIP, thermography, infrared, Active Denial System, ADS, MOSART

1. INTRODUCTION

Accurate long-range temperature measurements are useful for a number of important applications. As example, in countless battlefield and emergence situations, such as those requiring triage, vital physiological parameters, such as skin temperature, must be measured when direct contact is not possible (Figure 1). The requirement driving the design and development is an accurate, long range, imaging radiometer capable of measuring the temperature of human faces within ±1 °C at distances up to 750 m.

One application driving such requirements is the joint service Active Denial System (ADS). The ADS program is a breakthrough non-lethal technology that uses millimeter-wave electromagnetic energy to stop, deter, and turn back an advancing adversary from relatively long range. It is expected to save countless lives by providing a way to stop individuals without causing injury, before a deadly confrontation develops. Non-lethal technologies can be used for protection of Defense resources, peacekeeping, humanitarian missions, and other situations in which the use of lethal force is undesirable. The system is intended to protect military personnel against small-arms fire. The technology was developed by the Air Force Research Laboratory and the Department of Defense’s Joint Non-lethal Weapons Directorate.

Figure 1: 30 meter LWIR QWIP Images w/dual-isothermal thresholding (green Δ1°C above 29 °C and yellow Δ3°C above 27 °C).
To achieve absolute skin temperature measurements, the DBR radiometer was fabricated to achieve +/- 1 °C accuracy at ranges up to 750 m (Table 1). In this context, accuracy is defined as closeness of agreement between the result of a measurement and the true value of the measured quantity. This is inherently different than the intrinsic error parameters such as ‘temperature resolution,’ or ‘noise-equivalent temperature difference’ (NETD), which provide information about ‘precision’ of the repeatability of measurements under a given set of conditions due to the influence of noise on the measurement errors, but do not define absolute error.

Although NETD plays a component in the overall radiometric accuracy, when using a radiometer to measure absolute object temperatures, in addition to a rigorous, NIST-traceable detector system calibration, the temperature-dependent spectral transmission of the complete optical chain, the radiant emission of the optical elements, the electronics stability, the geometry of the engagement scenario, and the measurement spot size must be addressed. Additionally, numerous important factors, including target spectral emittance and atmospheric spectral attenuation characteristics as a function of ambient conditions such as temperature, rain, fog, and background noise, must also be compensated. Difficulties can arise when atmospheric conditions are stressing (e.g., high moisture, heavy aerosol/particulate loading, partial cloud cover, or low sun angle).

### 2. Dual-band (MWIR/LWIR) QWIP Detector Integrated Detector Assembly (IDCA)

Key to Voxel’s DBS system is the 320 x 256 element, spatially-registered, dual-band (MWIR/LWIR) QWIP focal plane array procured from QmagIQ, LLC (Nashua, NH). Of the available detector technologies that can operate effectively in an infrared radiometer, over a wide range of environmental conditions, QWIPs have demonstrated high thermal and spatial resolution, excellent homogeneity, low fixed-pattern noise, low 1/f noise, high pixel functionality, high yield, and moderate cost. This makes them well suited for radiometric measurements.

QWIPs are based on well-developed III-V materials and processes and offer a superior calibration capability than do alternative technologies, such as uncooled microbolometers (which lack sufficient sensitivity, cold-shielding, and uniformity) and HgCdTe detectors (which lack uniformity, linearity, and are costly). QWIP detectors are ideal for a dual-band system because in manufacturing it can be tuned to almost any spectral region of interest from the MWIR to the VLWIR. And multiple infrared spectral bands can be stacked because the InGaAs substrate is transparent to infrared radiation. There is generally no need for spectral filtering, since QWIPs are inherently narrowband detectors¹, which takes the form of a Lorentzian lineshape with the wavelength of maximum response corresponding to the energy difference between the ground state and the first excited state of the quantum well.²

The QWIP detector is also ideal for radiometric measurements because it has a narrow band spectral response and because in manufacturing it can be tuned to almost any spectral region of interest, from the MWIR to the VLWIR. And, as QWIPs are inherently narrowband detectors, there is generally no need for spectral filtering. QWIP detectors can also be stacked for multi-band sensitivity because the InGaAs substrate is transparent to infrared radiation.

The Voxel DBS system was designed for the ADS’s requirements of global operation under the majority of atmospheric conditions. This drove the selection of a single dual-band MWIR/LWIR detector (Figure 2).

![Figure 2: Schematic of a dual-band QWIP.](image)

**Table 1: DBR Radiometer Specifications.**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Temp Accuracy</td>
<td>+/- 1 °C</td>
</tr>
<tr>
<td>Range</td>
<td>200 m to 750 m</td>
</tr>
<tr>
<td>Optics Diameter</td>
<td>6 inch germanium</td>
</tr>
<tr>
<td>FOV</td>
<td>0.712 degree</td>
</tr>
<tr>
<td>IFOV</td>
<td>40 μrad</td>
</tr>
<tr>
<td>Requisite Focal Length</td>
<td>f/7</td>
</tr>
<tr>
<td>Object Temp Range</td>
<td>22 °C to 60 °C</td>
</tr>
<tr>
<td>Update Rate</td>
<td>60 fps</td>
</tr>
<tr>
<td>Detector Type</td>
<td>MWIR / LWIR QWIP</td>
</tr>
<tr>
<td>Resolution</td>
<td>320x240</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>37 x 37 μm² / 40 x 40 μm²</td>
</tr>
<tr>
<td>Spectral Range</td>
<td>4.4μm-5.1μm / 8μm-9.1μm</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>15% / 19%</td>
</tr>
<tr>
<td>NEP</td>
<td>8x10⁻¹⁰ W/cm² / 7 x10⁻¹⁰ W/cm²</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-20 °C to 55 °C</td>
</tr>
<tr>
<td>Survival Temperature</td>
<td>-55 °C to 65 °C</td>
</tr>
<tr>
<td>Altitude</td>
<td>15,000 ft (4600 m)</td>
</tr>
</tbody>
</table>

²

SPIE Thermosense Conference XXVIII – Pre-release Manuscript 6502-23
Radiant emission from ~310 K humans is peaked in the LWIR, however, notwithstanding the high sensitivities to 310 K BB radiation, and in high humidity conditions, the LWIR tends to be attenuated more than the MWIR due to water absorption, and the LWIR is no panacea for fog.

MWIR imagers provide some significant advantages to LWIR cameras in hot, humid maritime environments. Advantages for MWIR over LWIR are 1) surveillance/reconnaissance requiring long-focal-length telescopes 2) very-long propagation paths having a high gaseous water content (humid, maritime atmosphere), which is absorptive to LWIR. However, in high-scattering conditions, such as smog, fog, smoke, and rain, the MWIR tends to be more attenuated than the LWIR.

Assuming a MWIR channel, the higher water absorption in the LWIR occurs strongly in 10 to 14 μm, leaving the 8 to 9 μm band better correlated with the MWIR.

Another approach, which offers some benefits in cost, would be to use an uncooled microbolometer detector. However, to achieve good sensitivity microbolometers require low F/# optical systems. Using an f/1 optic and a six-inch diameter objective would limit the focal length to 152 mm. For a 25 μm detector, this results in an instantaneous field of view (IFOV) of 164 μradians, which is a factor of four from the required resolution of 40 μradians, and limits the maximum useful range to 250 m or less. The radiometric quality would also be marginal.

Moreover, as dual band uncooled microbolometers are not available, a two focal plane system, including those using other detector material systems would require a split optical path and two spectrally-independent, most likely filtered, detectors. Due to the inherent difficulty in maintaining radiometric accuracy while providing real-time correcting for distortion, registration, and thermal effects between two optical paths, this option was not considered.

Dual-band LWIR/LWIR or LWIR/VLWIR QWIP architectures are available and would also produce a monotonic ratio to the radiation from humans, but for the reasons stated above, modeling showed that alternative bands in the longer wavelengths did not offer any advantage for this application. Alternatively, dual-band HgCdTe detectors could be used. However, dual-band HgCdTe detectors are scarce and, when available, expensive. The material growth and processing technology for III-V QWIP detectors are much more mature for the III-V material systems than for II-VI materials like MCT, allowing for high operability of FPAs with uniform pixel-to-pixel response, which is the principal limitation of the performance of modern IR FPAs.

Dual-band QWIP detector structures present no serious materials growth issues, because, for the most part, the operating wavelengths are determined by the layer thicknesses, which are easily controlled with molecular-beam epitaxy (MBE) growth. The two-color detector features a MWIR QWIP detector on top of a LWIR QWIP detector with three ohmic contact layers (the first below the MWIR stack, the second between the MWIR and LWIR stacks, and the third above the LWIR stack). Each stack is either a LWIR QWIP realized with quantum wells of GaAs sandwiched between...
AlGaAs barriers, or a MWIR QWIP realized with deeper wells of strained InGaAs sandwiched between AlGaAs barriers; the contact layers consist of doped GaAs. Two etch-stop layers sandwiching a 1 μm layer of undoped GaAs are grown between the substrate and the device layers. QWIP designs similar to the ones used here have been extensively reviewed in the literature.3

The dual-band QWIP FPA process is similar to the single-band process, along with the extra steps required to create and contact via holes to the middle and bottom ohmic contact layers in each pixel, and to run metal lines (on an insulating layer to prevent shorting) from the two vias to the pixel top (Figure 3). The trenches between the pixels are etched deep enough (to the top etch stop layer) to achieve complete electrical isolation between pixels. The bottom etch-stop aids in substrate removal from the backside. The 1 μm thick GaAs layer between the two etch-stops serves to physically hold the array together (in addition to the In bumps and the epoxy); this layer is thin enough that complete optical isolation between the pixels is secured.

The notable features of the QmagiQ dual-band QWIP FPA, integrated in Voxtel’s DBR system, is its high pixel operability (99.5 %) in both the QWIP’s MWIR and LWIR bands. The temporal NETD is less than 40 mK in both bands for operating temperatures below 62 K. The NETD was less than 40 mK for the MWIR channel, alone, for temperatures below 90 K. After two point correction, the standard deviation (σ) of the MWIR and LWIR bands were σ_{MWIR} = 2.1 and σ_{LWIR} = 2.5, respectively (Figure 4).

3. READOUT INTEGRATED CIRCUIT (ROIC)

The dual-band QWIP was integrated with a FLIR Systems/Indigo ISC006 ROIC, which was custom designed by Indigo for dual-band QWIPs and features 320 x 256 pixels for each wavelength band, with both colors colocated inside a 40 μm by 40 μm pitch pixel cell. The ROIC utilizes a direct injection mechanism and provides separate biasing and integrating capabilities for each color detector. To accommodate the range of operational scenarios, the charge well of the ROIC has selectable capacitance (gain) that allows it to achieve approximately equal signal-to-noise (STN) in the two bands. In addition, the ROIC has a bias-dependent responsivity that allows for fine tuning of the response so as to give a balanced output.

4. COLD SHIELD REQUIREMENTS

The DBR’s dual-band QWIP FPA is packaged in a rugged Integrated Dewar Cooler Assembly (IDCA) (Figure 5) and is cooled using a compact ½ W RICOR model K508 Sterling microcooler with a specified MTTF > 8,000 hours.

For accurate temperature measurement, the spot size of the radiometer must be smaller than the target being measured. Should the spot size be larger than the target, error will be introduced into the measurement. The amount of error will be dependent upon a number of factors, none of which can be corrected for by any means including radiometric software.

Limited by the specified six-inch diameter aperture, measurements of facial skin temperature over a range from 250 m to 750 m requires an f/7 optical system to achieve the necessary magnification. With the ~1 m focal length optics, eight cycles can be placed on an average human face at a 250 m range and two cycles at a range of 750 m. This is the absolute minimum necessary for practical operational use.

To accommodate the requisite 1.01 m focal length, the IDCA was custom configured with a custom f/7 cold shield (Figure 6), which was matched to the custom-designed telescope, to reduce stray radiant energy from reaching the FPA and introducing measurement error. Obviously, the relatively ‘slow’ f/7 optical...
system required for such long-range measurements significantly reduces the target’s radiant energy collected at the focal plane, and, therefore, places utmost importance on the optical efficiency, the FPA’s sensitivity, detector uniformity, and careful attention to noise all potential sources of noise.

5. TWO-COLOR RATIO RADIOMETRY

In general, the goal of a radiometer is to produce an electrical signal at the detector output representing the radiation emitted by the object that strikes the detector. The value of this signal carries information about the object temperature, which is determined using a system calibration chart derived from radiometric calculation of the output signal as a function of blackbody temperature. High-quality radiometric measurements are difficult to obtain, and the Voxel’s DBR system’s operational requirement of measuring the propagation of the thermal radiation from the warfighters, through the atmosphere, and into the sensor to within 1 °C accuracy at ranges from 200 to 750 m is a challenging one.

IR thermography exploits the correlation between the temperature of a surface and the IR energy emitted by the surface. This relationship is described by Stefan’s Law:

\[ R(t) = \sigma T^4 \]

where \( \sigma \) is the Stephan-Boltzman constant \((5.67 \times 10^{-8} \text{ W/(m}^2\text{-K}^4))\) and \( T \) is the temperature of the surface.

The spectrum of the infrared light is described by Planck’s blackbody function. Planck’s law states that blackbodies will radiate in a spectral band according to the following formula:

\[
M(\Delta \lambda) = \int_{\lambda_1}^{\lambda_2} \frac{2\pi^2h}{\lambda^5} \left( \frac{hc}{\lambda kT} - 1 \right) d\lambda \quad \text{Wm}^{-2}\text{m}^{-1}
\]

where \( T \) is the temperature (K), \( \lambda \) is the optical wavelength (m), \( c \) is the speed of light (m/s), \( h \) is Planck’s constant (Js), and \( k \) is Boltzmann’s constant (J/K). Often \( 2hc^2 \) is replaced by the constant \( C_1 \), and \( hc/k \) by \( C_2 \).

However, greybody objects are not perfect emitters, so their irradiance will only be a fraction of a black body object at the same temperature. And assuming an object target size, the detector size determines the collection area, and the aperture size sets the solid angle for the radiance calculations. At a given range, the spectrally weighted source power is derived by convolving the detector’s spectral responsivity, with the output of Planck’s equation for a given wavelength interval, and the equation that defines the amount of signal \( S_i \) obtained from a radiometer for a specific spectral waveband is:

\[
S_i = A_i \frac{\varepsilon(\lambda)M_{\text{target}}(\lambda, T) + (1 - \varepsilon(\lambda))M_{\text{ambient}}(\lambda, T)}{\pi} \cdot A_{\text{optics}} \cdot \tau_{\text{optics}}(\lambda) \cdot R(\lambda) d(\lambda) + B_i
\]

where \( A_i \) and \( B_i \) are constants that are obtained from a calibration, \( \varepsilon(\lambda) \) is the target spectral emissivity, \( M_{\text{emitter}} \) (W/cm²-μm) is the spectral radiant emittance from the target, \( M_{\text{ambient}} \) (W/cm²-μm) is the spectral irradiance of the atmosphere, \( A \) is the area of the detector (cm²), \( \Omega \) (mrad) is the solid angle subtended from the emitter to the optics, \( \tau_{\text{optics}}(\lambda) \) is the spectral transmission through the atmosphere, \( \tau_{\text{filter}}(\lambda) \) is the spectral transmission through the filter (if any), \( \tau_{\text{optics}}(\lambda) \) is the spectral transmission through the collection optics, and \( R(\lambda) \) (V/W) is the detector spectral responsivity.

Single-band radiometric systems can be corrected for the case of real objects (non blackbodies), only if their emissivity over the spectral passband is known. Incomplete knowledge of the object’s emissivity is the most common source of bias errors in temperature measurements with single-band radiometers (Figure 7). These systems are

**Figure 7:** One percent change in radiant flux from emissivity (1.0 to 0.99) of a 301 °C blackbody and one percent change in radiant flux from 301 °C blackbody.
additionally vulnerable to such error sources as reflected radiation; limited atmospheric transmittance; attenuation by filters, windows, and optics radiation emitted by optical components; detector noise; and other system internal electronic sources.4,5

Dual-band radiometry measures the ratio of the radiation emitted by a sample in two independently calibrated spectral bands6. By measuring the irradiance at two different wavelengths, one can fit these two points to a Planck curve and derive the temperature of the object under observation. For a dual-band system, using the ratio of LWIR to MWIR the ratio becomes:

\[ \alpha = \frac{S_{\text{MWIR}}}{S_{\text{LWIR}}} \]

where \( S_{\text{MWIR}} \) and \( S_{\text{LWIR}} \) are the calibrated signals from the source in the MWIR and LWIR, respectfully. As the ratio of the power emitted by a greybody at two different wavelengths does not depend on the object emissivity but only on the object temperature, by measuring received power in two separate spectral bands, and assuming a blackbody or greybody curve, the object temperature is determined using a calibration chart that represents a ratio of the emitted power in these two bands as a function of the object temperature. Using the detector’s spectral responsivity curves (such as in Figure 8), we can plot the monotonic ratio response of the two QWIP detector bands versus temperature (Figure 9).

Unlike a single band sensor using ratio radiometry, non-ideal emissivity and atmospheric transmission can change precipitously without affecting the measured temperature – so long as the change is correlated between bands. However, the ratio radiometric measurements are accurate only if the emissivities in both spectral bands are identical (greybody) or if their inter-band ratio is known. Moreover, the ambient radiation must be neglected, whereas, in near room-temperature measurement of a non-blackbody sample, the ambient radiation is usually not negligible.

Thus, although the TCIR can minimize some sources of uncertainty for specific applications, surfaces, and temperature ranges, the method is not a cure-all for ignoring relevant system and environmental factors on a widespread basis. And, as in most operation scenarios for systems, such as ADS systems, ideal conditions do not exist; and, therefore, TCIR, alone, is not adequate to totally eliminate the spectral effects of emissivity, atmosphere, and field of view. Therefore, rigorous analysis and calibration are required to reduce inaccuracies in the temperature measurement. It is the unknown difference in each band that results in an error.

5.1 Radiometric Calibration of TCIR Measurements

Unfortunately, for accurate radiometric measurements, the use of a wavelength dependent detector not only requires assumptions about the functional form of the incident radiation, it also requires more knowledge concerning the physical characteristics of the object and the projected area of the target. A required calibration includes the convolution of the sensor’s wavelength response function with the target’s spectral characteristics to

![Figure 8: Normalized curves showing atmospheric transmission for two conditions, compared to a 300 K BB and MWIR/LWIR QWIP responses.](image)

![Figure 9: MWIR / LWIR Ratio (\( \alpha \)) vs. object Temperature.](image)
form a sensor-dependent quantity. To extract sensor independent quantities from this measurement, a number of lookup
tables, instead of a simple scalar calibration constant, are required.

Additionally, in operation, the environment temperature can vary significantly, and these changes can have a
significant effect on the measurement results, for several reasons. First, the radiation emitted by the optical elements
of the camera depends directly on the temperature of these elements and indirectly on the temperature of the environment.
Second, variation of the environment temperature can change the detector’s temperature and, thus, its sensitivity. Third,
changes of the environment temperature directly change the temperature of the electronic blocks and, thus, indirectly
change their gain and offset. Fourth, the atmospheric conditions change the spectral transmission of the object radiation.

The errors of remote infrared temperature measurement can be generally divided into three basic groups: 1) radiometric errors, 2) electronic errors, and 3) calibration errors. 

The calibration of an infrared radiometer such as the DBR begins with a thorough analysis of all the factors that can
affect the detector output as a result of the internal and external environment. It is then necessary to capture these
changes and to use the data to compensate the detector output – generally using a look-up-table (LUT) to calibrate the
measurement for the given set of external and internal conditions.

Uncertainty due to electronic errors are the errors of output temperature determination resulting from non-perfect
transformation of the radiometric signal(s) into output electrical signal(s), such as due to the standard deviation of the
output temperature dispersion caused by noise of the system, or variations due to the range, in which, the results of the
measurements are located when measurements are repeated in identical measurement conditions, or when the tested
object is located at different places within the field of view of the camera.

The combined standard uncertainty, \( u_{\text{out}} \), of the output temperature, \( T_{\text{out}} \), can be determined as the square root of the
sum of the squares of the partial uncertainty caused by the unknown error of determination of the real object’s effective
emissivity, \( \varepsilon_r \), the partial uncertainty, \( u_T \), due to unknown error of determination of the real effective temperature, \( T_{\text{ba}}(r) \),
of the background, the partial uncertainty, \( u_t \), due to unknown error of determination of the real effective transmittance,
\( \tau_{\text{av}}(r) \), of the atmosphere, and the intrinsic uncertainty, \( u_{\text{in}} \), of the thermal camera:

\[
\begin{align*}
\quad u_{\text{out}}(T_{\text{out}}) &= \sqrt{u_{\varepsilon}^2 + u_T^2 + u_r^2 + u_{\text{in}}^2} \\
&= \sqrt{[c_{\varepsilon}u(\varepsilon)]^2 + [c_Tu(T_{\text{ba}}(r))]^2 + [c_ru(\tau_{\text{av}}(r))]^2 + u_{\text{in}}^2}
\end{align*}
\]

where \( u(\varepsilon) \) is the standard uncertainty of determination of the object effective emissivity \( \varepsilon_r \), \( u(T_{\text{ba}}(r)) \) is the standard
uncertainty of determination of the effective background temperature \( T_{\text{ba}} \), and \( u(\tau_{\text{av}}(r)) \) is the standard uncertainty of
determination of the effective atmospheric transmittance \( \tau_{\text{av}}(r) \). On the right, \( c_{\varepsilon} \), \( c_T \), \( c_r \) are the sensitivity coefficients,
equal to the partial derivatives of the function \( T_{\text{out}}(\varepsilon, T_{\text{ba}}, \tau_{\text{av}}) \). These partial derivatives describe how the output quantity
\( T_{\text{out}} \) varies with changes in the input quantities \( \varepsilon_r, T_{\text{ba}}, \) and \( \tau_{\text{av}} \) for both spectral bands, using the ratio radiometric method of
deriving the temperature.

5.2 Spectral Band Selection for Optimal Global Sensitivity and Minimal Variation

To increase the accuracy of the DBR system's TCIR measurement, we reduced the uncertainties in radiometric
measurements by first optimizing and then calibrating the relationships between the optical radiation emitted by a target
(radiance), and the optical radiation incident on a detector (irradiance) to account for the geometry of the sensor system
and the transport of optical radiation from source to detector through the atmosphere and through conversion of the
optical radiation incident on the detector into photoelectrons, and, ultimately, to produce digital counts that accurately
represent the absolute temperature of the target.

The DBR corrects for the influence of the environment by real-time monitoring and calibration. The DBR is equipped
with hardware and software for that purpose. The temperature of the optics, the detector, the housing, and the analog
signal circuits are monitored in real time, and their contributions to error are corrected for in LUTs. However, even
calibrating for the operating conditions of the radiometers, the emitted energy from the target, in this case, the facial
skin of an adversary, which is transferred to an infrared sensor will always include the reflected energy incident from the
surroundings as a noise.

To reduce uncertainty in the field, globally, and over all atmospheric conditions, it is of utmost importance to select
appropriate spectral bands that offer high transmission values that are well-matched to the detectors spectral responsivity,
yet minimally variant to atmospheric changes. For the TCIR measurements, it is also important to select wavelengths
that will provide a monotonic change in ratio as a function of temperature range of human subjects, at or about 310 K,
yet will also offer target sensitivity over global atmospheric conditions. Figure 8, earlier, shows a MODTRAN analysis of atmospheric transmission versus wavelength for a 1 kilometer path length, a temperature of 30 °C and a relative humidity of 90 % and 0 °C and a relative humidity of 10 %.

As can be seen from the figure, significant attenuation takes place between 5 and 8 μm due to water vapor attenuation. There is also another attenuation band between 4.2 and 4.4 μm due to carbon dioxide absorption. Also, wavelengths below 4 μm should be avoided because the solar radiation will dominate the shortwave data and make accurate ratio measurements very difficult.

For the range of ADS relevant temperatures (22 °C to 60 °C), the 4.5 to 5 μm band and the 8 to 12 μm band can provide the desired ratio response. Typically, at MWIR wavelengths, the radiative flux is impacted by the absorption by well-mixed gases such as Ozone (O₃), Oxygen (O₂), Nitrogen (N₂), Methane (CH₄), Nitrous Oxide (N₂O), Nitrogen Dioxide (NO₂) and Carbon Dioxide (CO₂), and the absorption by water vapor.

One moderately transmissive "window" region exists between 3 and 4 μm, with minimum absorption near 3.8 μm for dry atmospheres and 3.9 μm for moist atmospheres, yet this band offers little sensitivity to 300 K radiation. A second transmissive region exists between 4.6 and 5.4 μm with minimum absorption values near 4.6 μm. The higher water absorption in the LWIR occurs strongly in 10 to 14 μm, leaving the 8 to 9 μm band better correlated with the MWIR.

The QmagiQ dual band QWIP array’s spectral response is shown in Figure 10. Due to time and cost constraints, for the first prototype, the dual-band QWIP did not possess the desired MWIR wavelength response, which was peaked slightly past 5 μm, slightly beyond the optimal MWIR transmission window. However otherwise the devices performance was exemplary and excellent DBR system radiometric performance can be achieved with this device.

5.3 Atmospheric Measurement and Predictive Atmospheric Modeling

To predict the robustness of the global and seasonal deployment of the ADS Radiometer accuracy as a function of the variation of atmospheric spectral transmission, we simulated the DBR two color ratio radiometric measurements against the US Navy R384 database. The composition of the R384 database contains several hundred observations, taken globally over a variety of maritime conditions. It is generally recognized that the Maritime environment is most prone to highly variable and fast changing MWIR and LWIR transmission characteristics and may represent a worse case scenario for the possible ADS global operating conditions.

As it corresponds closely to the chosen ADS spectral bands, we chose the Navy’s R384 database’s 3.8 to 4.2 μm MWIR band and 8 to 10 μm LWIR spectral band datasets (which, although convenient, are identical to the QWIP’s spectral wavebands). Using the R384 database MWIR and LWIR data, we statistically tested and quantitatively determined the DBR’s MWIR/LWIR ratio radiometry for the ADS application.

For the entire Navy R384 database, the average difference in the extinction coefficient between the MWIR and LWIR spectral bands was 0.138, with a 0.089 standard deviation. This indicates that the difference in transmission through a 1-kilometer path length is approximately 0.138. For ADS’s short 250 m path length, the standard deviation is only 3.64 %.
Figure 11 shows a graph of the cumulative distribution of the percentage difference in the absolute values of transmission between the MWIR and LWIR for all of the observations in the US Navy R384 database. As verified in Figure 11, for a majority of the R384 inter-band atmospheric observations (~60%), using simple ratio radiometry, would, assuming other elements of the error budget negligible, allow the ADS temperature specifications to be met.

However, to address those atmospheric conditions, such as those shown in the R384 database, where there is sufficiently disproportionate transmission between spectral bands to cause one of the two spectral band conditions to introduce bias error, sufficient to cause an absolute temperature inaccuracy measurement greater than 1 °C, we provide a real-time corrective bias to the TCIR measurement. In the field, to ensure accuracy, the DBR instrument uses a GPS, weather station and laser rangefinder, to collect real-time data about global positioning, temperature, humidity, wind speed, range to target, and the geometry of the point angle relative to the sun angle. Real-time atmospheric data is input to the USAF MOSART atmospheric modeling program, which generates calibration tables of the detector’s response to the atmospheric transmission as a function of wavelength. This data is used to generate correction factors that remove the uncertainties due to the effects of atmospheric transmission. Using the knowledge of the environment to predict the MWIR/LWIR ratio, the ADS +/- 1 °C specification at target ranges from 200 m to 750 m can be met over a statistically significant portion of the global atmospheric conditions.

5.4 Compensating for Skin Emissivity Spectral Variation

Incomplete knowledge of the object’s emissivity is the most common source of bias errors in temperature measurements with radiometers. Emissivity is a measure of the thermal emittance of a surface; it is defined as the fraction of energy being emitted relative to that emitted by a thermally black surface (a blackbody). A blackbody is a material that is a perfect emitter of heat energy and emits all energy it absorbs and, thus, has an emissivity value of one. In contrast, a material with an emissivity value of zero would be considered a perfect thermal mirror and imaging this material would result in readings of reflected energy only and not the actual material. In the real world, there are no perfect "black bodies" and very few perfect infrared mirrors, so most objects have an emissivity between zero and one.

In conventional infrared thermography, the temperature is often estimated using a presumed emissivity. Variations in the spectral emissivity of different materials, as a function of temperature, wavelength, and viewing angle, make it difficult to obtain exact temperature readings. It is particularly difficult to apply infrared thermography to low emissivity targets, where the influence of the reflected energy becomes severe and the measurement error becomes large and distinguishing the signal for determining temperature quantitatively from the signal detected with the infrared sensor is difficult.

Published values for MWIR and LWIR infrared human skin emissivity vary from 0.96 to 0.99. As water has an emissivity of 0.96, and skin is a mixture of water, fats, and proteins, we compared measured data to a 70 % water solution to model skin. As can be seen in the reflectance curve of water in Figure 12, the emissivity of salt water varies as a
function of wavelength, so the implications of this assumption, as it relates to the DBR system errors, must be revisited when the spectral responsivity characteristics of the sensor are determined.

Questioning the test conditions of published data, we performed simple bidirectional reflectance distribution function (BRDF) measurements of a small sample of human skin over a variety of conditions and types (e.g., hair, lotion, sex, etc.) and determined an $\varepsilon_{\text{MWIR}} = 0.99$ and an $\varepsilon_{\text{LWIR}} = 0.87$ (Figure 13). Our skin emissivity data in the LWIR is lower than previously published data. We use these values to further reduce uncertainty in the DBR’s absolute temperature measurements.

### 5.5 Radiometer Electronics and Calibration

Because the detector not only receives infrared radiation from the target but also from the internal surfaces of the radiometer, it is important to measure the temperature of the internal surfaces of the radiometer. Each surface has a different contribution to the total energy impinging on the detector. Therefore, the use of several sensors on critical surfaces is important. Critical surfaces can be found by extensive stray light analysis; however, experience has shown that the housing area around the front objective and the housing around the reimaging lens are the most critical. For the dual-band radiometer, we actually use four temperature sensors: one mounted near the front objective, one mounted on the first fold mirror, one mounted on the relay optics housing, and one mounted on the system housing. Internal housing surfaces are coated with high emissivity paint and are baffled to minimize external energy from impinging on the detector.

The important sources of the electronic errors include: noise, non-linearity, non-uniformity of the detector, limited stability of the detector cooling system, variation of the preamplifier gain and offset, and limited resolution and limited linearity of the analogue/digital converter.

Measurement of the uncertainty of electronics errors give information about the ranges around the output temperature $T_{\text{out}}$ in which the true temperature, $T_{\text{ob}}$, due to different sources of errors like: noise in the analog channel of the thermal camera, limited resolution of the digital channel of the thermal camera, changes of temperature of environment, changes of camera parameters with time, changes of camera parameters within its field of view, and all other sources that exist in calibration conditions.

The ADS electronics use a Atmel AVR Atmega162 microcontroller to setup the radiometer functions to cause the camera component temperature measurements to be measured and to cause the atmospheric measurements to be
collected (Figure 14). Each of the two signal channels is digitized by a 14-bit, 10MHz ADC LTC2245 analog-to-digital converter (ADC). A XC3S400 FPGA is used to perform the TCIR temperature measurement, to compensate, in real time, for the atmospheric conditions, the range of the subject, the temperature of the detector, the optics, and the housing, and to perform a two-point calibration on each of the detector pixels. Additionally, the FPGA provides the FLIR/Indigo ISC0006 ROIC the necessary clocking and biasing signals. I/O is performed using two CameraLink channels.

6. OPTICAL DESIGN

The optical design of the DBR was derived from an analysis of the range requirements of the ADS program as summarized earlier in Table 1. The requirement to identify a human at 250 m translated into a 40 μrad IFOV using a conservative six cycle criteria. With a detector size of 40 μm and a maximum 6" (152 mm) aperture for the telescope, a 1.01-m focal length telescope is required (~F/6.6). One problem with this approach is that the diffraction limit of the telescope in the LWIR is:

\[ 2.44 \times \frac{F}{f} \times \lambda = 2.44 \times 6.6 \times 8.5 = 136 \, \mu m. \]

While this provides only 20% modulation at the desired resolution, because there will be up to 10 IFOV’s across the human face, we believe that there will be sufficient resolution to perform the temperature measurement function. In the MWIR, the diffraction limit is 80 μm. This will provide 50% modulation at the IFOV and can be used as the primary viewing image, or can be overlaid with the boresighted visible camera.

The use of a colocated dual-band FPA results in a simplified optical design. No beamsplitters are required, nor are dual optical paths or the sacrifice of resolution due to image splitting. The front objective consists of a germanium plano-convex element and a zinc selenide plano-concave color corrector. A reimaging optical group (Figure 15) is used to focus the system and to provide an aperture stop at the detector cold shield. To minimize vignetting, the telescope reimaging design uses the cold shield as the aperture stop of the optical system.

A temperature stabilized shutter is used to provide Non Uniformity Correction (NUC) and temperature calibration. To minimize the complexity of the shutter, it is stowed in a temperature controlled oven. The short duration of the NUC process results in minimal thermal loss to the shutter. A thermal analysis on the optical system -20 to +55 °C temperature range concluded that no defocus occurs. The optics design was performed by Joel Johnson of Optical Subassemblies (Portland, OR).

7. MECHANICAL PACKAGING

The telescope, detector, and associated electronics are housed in a 0.5 m x 0.5 m x 0.16 m container. The front objective includes an integral heater to prevent fogging. The optics design is folded (Figure 16) using four mirrors to provide a compact package. The detector is mounted to a precision linear slide and driven by a stepper motor to provide focus.

Temperature sensors are located at the front objective and at the first fold mirror as well as on the reimaging optics. The temperature sensors provide feedback to the calibration and focusing system. The housing also includes power supplies to operate the electronics and a fan to provide cooling and thermal stabilization.
8. INFRARED RADIOMETER CALIBRATION

Once the temperature sensors have been located and calibrated, and the system integration is completed, laboratory calibration can be performed. The first step is to view a blackbody source and to vary the blackbody temperature to generate a detector output versus temperature curve.

To compare pixels across different subframes and to generate a radiometric image, the camera must be calibrated by using standards of known in-band radiance. This is done by using NIST-traceable laboratory blackbodies. This is the baseline calibration. One must take into consideration the spectral emissivity characteristics of the blackbody, itself, which changes as a function of temperature, and which also ages. Calibration errors are result from output temperature determination caused by limited accuracy of standard radiation sources used during calibration of the thermometer. They are typically generated due to the limited accuracy of the blackbodies used during the calibration process and by the fact that the emissivity of blackbodies is spectrally dependent (Figure 17). These errors contribute to the overall absolute temperature error budget.

Because the radiometer is required to operate over a wide range of ambient temperatures, it is necessary to observe what effect varying the radiometer temperature has on the output tables. This is done by viewing a constant temperature source with the radiometer and then changing the radiometer’s operating temperature over the full range of ambient temperatures, recording the detector output and each temperature sensor’s output, taking into account the calibration errors, including the cumulative uncertainty due to the emissivity of the calibration equipment. At the completion of the test, the change in output voltage of the detector is compared to the change in each of the temperature sensors and a correction table is generated that is the weighted sum of each of the temperature sensors. This table is then used as an offset correction table for each of the detector outputs.

The next steps are to choose 8 to 10 temperatures for the target, choose 8 to 10 ambient temperatures, and record the output voltage from each of the detectors using the correction tables. Once this process is complete, the tables can be adjusted to fine tune the calibration.

The final step is to place the target at several points in the field, under variable atmospheric conditions, and to repeat the tests to determine if a field correction table is required. If a field correction table is necessary, it is constructed from the offset table generated above and adjusted for field position.

Using this approach, we have developed a radiometer that will provide the required +/-1 °C temperature measurement accuracy for the specified range of environments.

9. SUMMARY

The Voxel Dual-Band Radiometer has been designed for military operation. The telescope, detector, and associated electronics are housed in a 0.5 m x 0.5 m x 0.16 m container (Figure 18). The front objective includes an integral heater to prevent fogging. The optics design is folded using four mirrors to provide a compact package. The detector is mounted to a precision linear slide and driven by a stepper motor to provide focus. For radiometric accuracy, temperature sensors are located at the front objective and at the first fold mirror, as well as on the reimaging optics. The temperature sensors provide feedback to the calibration and focusing system. The housing also includes power supplies to operate the electronics and a fan to provide cooling and thermal stabilization.

Besides these operational issues for radiometers, the cost of ownership has been considered, and the design has included all lifecycle costs. Instrument characteristics change over time and use, and a radiometer’s calibration is never concluded once and for all. Calibration must be viewed as an iterative process as long as an instrument is in use. This requires that reliable standards be used and maintained, against which periodic recalibration may be
performed. The design and optimization of the operational calibration plan and calibration equipment is an essential and very important part of the radiometer design and plays a significant role in the absolute accuracy of the system. The DBR system design has taken these considerations into account.

The next phase of the program is to demonstrate the Technology Readiness Level (TRL) of the Dual-Band Radiometer through operational field tests, under a variety of atmospheric conductions, and verify accuracy through ground-truths measured using contact thermographic measurements of the target.

ACKNOWLEDGMENTS

This research is being conducted under an SBIR Phase II contract funded by the U.S. Marine Corps Systems Command. Technical Monitors: Mr. Carlton Land, Joint Non-Lethal Weapons Directorate, Quantico, VA and Dr. Patrick A. Mason, Air Force Research Laboratory, AFRL/HEDR, Brooks AFB, TX. This SBIR was funded to develop the thermographer as a feedback mechanism for Directed Energy non-lethal weapons, where the goal is to make an accurate and absolute skin temperature measurement at the standoff ranges described in this paper.

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