Microbolometer Arrays for Airborne Fire Measurements

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January 6, 2014

1 Introduction

For airborne data collection of fire images, microbolometer cameras are attractive owing to their light weight (often $\leq$ 100g), easy computer interfacing (typically USB or CameraLink), low power ($\leq$ 1 watt), and reasonable price. An example of the current crop of these is the DRS "Tamarisk 320" family of devices with a variety of thermal infrared lenses available. With a lens focal length of 35mm and a 9 degree field width, its 320 x 240 pixels yields a target sampling distance of 0.5m per kilometer of range. Here I explore the microbolometer imager in further detail.

Figure 1: Tamarisk320 camera and 35mm lens. Length 49mm; weight 64g.

2 Planck Power Flux

For microbolometer arrays, the exterior scene pattern warms the thermistors and produces an image as a pattern of thermistor temperatures. Here we assume that this heat flow is uniform over each pixel, determined by the scene temperature T_{scene} averaged over each pixel/thermistor. We begin with the Planck scene brightness B in a given wavebandband

$\Delta\lambda$, in $W/m^2 ster$:

$$B = \int_{band} \frac{2hc^2 d\lambda}{\lambda^5 \cdot (exp(hc/\lambda k T_{scene}) - 1)} \tag{1}$$

We shall also need the derivative of B with respect to scene temperature. Here we are interested in the thermal band 8 to 14 μm and the fire band 3 to 5 μm:

Table 1: Brightnesses, $W/m^2 ster$

Band	$B, 300K$	$dB/dT, 300K$	$B, 1000K$	$dB/dT, 1000K$
8-14μm	55.0	0.84	1913	3.63
3-5μm	1.78	0.067	10397	47.4

3 Pixels

The scene power (watts) onto pixel area A, via optical solid angle Ω is:

$$P = \eta \cdot A \cdot \Omega \cdot B \tag{2}$$

$$dP/dT_{scene} = \eta \cdot A \cdot \Omega \cdot dB/dT \tag{3}$$

Here the optical solid angle $\Omega = \pi/(4F^2)$ where F is the f/number of the optical system that illuminates the pixel. Here I roll up the many inefficiency factors (filter and lens transmissions; thermistor area fraction; absorbance; etc) into an overall efficiency factor η. With the popular 17 μm pixel size, $\eta \approx 0.5$, A $\approx 3 \times 10^{-10} m^2$, and $\Omega = 0.8$ steradians for an f/1 lens, making $\eta A \Omega \approx 1.2 \times 10^{-10} m^2 ster$ and, for the 8-14 μm thermal band, $dP/dT_{scene} \approx 1 \times 10^{-10} W/K$.

4 Responsivity

The scene responsivity $\mathcal{R}$ of a pixel is the slope of its output voltage with respect to scene temperature. This can be factored as follows:

$$\mathcal{R} \equiv \frac{dV}{dT_{scene}} = \frac{dT_{thermistor}}{dT_{scene}} \cdot \frac{dV}{dT_{thermistor}} \tag{4}$$

$$= \frac{dP}{dT_{scene}} R_{thermal} \cdot \alpha V_{bias} \tag{5}$$

The first factor here is the ratio of thermistor to scene temperatures; it is given by the power-to-scene ratio derived above, multiplied by the thermal resistivity of the thermistor. For highest sensitivity applications, thermistor arrays use vacuum packages and very fine lithography and can deliver $R_{thermal} \approx 1 \times 10^8 K/W$. See for example Becker et al Proc SPIE 8541 (2012). This gives a temperature coupling ratio $\approx 10^{-2}$.

The second factor here is the voltage response to this chip temperature rise. This response has two contributing factors: the relative voltage temperature coefficient $\alpha = (1/V_{dc}) \cdot dV/dT$ which is typically 0.03 per degK, and the DC bias voltage V_{bias} which is typically 2 volts. Together these give $dV/dT_{thermistor} \approx 0.06 V/K$, in reasonable agreement with industry findings (see for example Li et al Opt.Eng. v.50 no.6 2011 Fig 10.)

These two factors give our scene responsivity $\mathcal{R} \approx 600 \mu V/K$.

5 Noise

Voltage measurements on the thermistors suffer from a variety of measurement errors: 1/f noise, thermal noise, quantization noise, etc. This voltage error is the order of a few tens of microvolts RMS. We can relate this RMS voltage error V_{rms} to the scene temperature errors T_{rms} using the pixel responsivity derived above. In the literature, T_{rms} is named $NE\Delta T$ standing for Noise Equivalent Delta Temperature:

$$T_{rms} \equiv NE\Delta T = \frac{V_{rms}}{\mathcal{R}} = \frac{V_{rms}}{dP/dT_{scene} \cdot R_{thermal} \cdot \alpha V_{bias}} \tag{6}$$

In the thermal 8-14 μm band, we see that 30 μV and $1 \times 10^8 K/W$ combine to suggest $T_{rms} \approx 0.05K$; a value that many manufacturers apparently achieve (see for example Robert et al Proc SPIE 8353 2012 Fig 6; Li et al Opt.Eng. v.50 no.6 2011 Fig 9; Becker et al Proc SPIE 8541 (2012) report $T_{rms} = 0.054K$.)

6 Dynamic Range in the 8-14 μm Band

Could a thermal-band microbolometer remain in its linear range while viewing a fire? If run at full sensitivity with an f/1 lens, the 1000K brightness of $1900 W/m^2 ster$ (from Table 1) combined with the $\eta A \Omega$ factors deliver about $0.23 \mu W$ to each thermistor, giving a temperature rise of 23K and a voltage rise of 1.3 V. This swing exceeds the dynamic range of most on-chip multiplexers (see for example Pochic etal Proc SPIE 7481 2009 Fig 9.) Indeed, Pochic et al note that their 2V full scale digitizing range corresponds to a scene dynamic range of 400 degC suggesting that they have adopted a higher-than-usual thermal resistance. Durand et al Proc SPIE 8012 2012 Fig 7 show a dynamic range extending to 490K.

These fire signatures are easily attenuated to bring the image dynamic range into the linear regime. The lens could be stopped down (but that worsens the diffraction patter size.) Better, a 4:1 attenuating filter could be fitted to the front of the lens.

7 Microbolometers for the 3-5 μm Band

Several manufacturers have announced "broadband" microbolometer array sensors that span a remarkably wide range of infrared wavelengths, often 2-16 μm (see for example Li et al (DRS) "Umbrella" Proc SPIE v.6542 2007 Fig 5; Li et al 2011 Fig 17; Fieque et al (ULIS) IR Phys. and Tech. v.49 2007 Fig 2.) Even without these advances, however, it appears likely that fire-viewing will deliver too much signal in the common f/1 optical system.

In this band, the nominal 300K sensitivity will be an order of magnitude smaller than for the 8-14 μm band owing to the shape of the Planck spectrum (see Table 1) so the NEDT's here will be an order of magnitude worse than for the thermal band. However at higher temperatures 500-1000K characteristic of fires, the 3-5 μm power flux and derivative are much increased, as shown in Table 1. So the practical problem will be to attenuate the native efficiency of the camera system, again by supplying an attenuating filter in front of the lens.