NIRST, a satellite based IR instrument for fire and sea surface temperature measurement

Hugo Marraco[*a] and Linh Ngo Phong[b]
[a] Comisión Nacional de Actividades Espaciales, Paseo Colón 751, C1063ACH Buenos Aires, Argentina
[b] Canadian Space Agency, 6767 route de l´Aeroport, Saint-Hubert, QC J3Y 8Y9, Canada

ABSTRACT

NIRST is a pushbroom scanning infrared radiometer that makes use of 512×2 arrays of resistive microbolometers. This instrument comprises mainly two cameras, one operating in the spectral band of 3.4-4.2 µm (band 1) and the other in the bands of 10.4-11.3 (band 2) and 11.4-12.3 µm (band 3). It is intended for the retrievals of forest fire and sea surface temperatures in the Aquarius / SAC-D mission. In this mission the satellite will be launched into a Sun Synchronous polar orbit with an ascending node at 6 PM. This orbit suits the need of discriminating forest fires from solar reflections. NIRST is designed to achieve a spatial resolution of 350 m and a swath width of 180 km at nadir. Its field of view can be steered across track up to 500 km on each side to shorten the revisit time.
To measure fire intensity temperatures NIRST will perform multispectral scans of ground area in bands 1 and 2 and the acquired data will be analyzed using a double band algorithm . The microbolometer detectors have been designed to exhibit useful dynamic range for this application. It is projected that the detector response in band 1 saturates only when NIRST scans a 350 m ground pixel of average temperature of 700 K. The use of the data acquired in bands 2 and 3 allows for the retrieval of sea surface temperature by means of the split algorithm technique.

Keywords: remote sensing, uncooled microbolometer, infrared camera, space mission.

1. INTRODUCTION

NIRST (New IR Sensor Technology) is an infrared radiometer based on uncooled microbolometer detectors. It is one of eight instruments scheduled for launch in 2009 on board of Argentina's SAC-D satellite. The main instrument to be flown on the SAC-D, Aquarius, is a NASA-contributed radiometer-scatterometer designed to achieve monthly global measurement of sea salinity. To this end the SAC-D satellite will be launched into a circular heliosynchronic orbit at 657 km altitude with an ascending node located over the equator zone at 6 PM local time. The SAC-D satellite will therefore evolve on the sunset side of the earth during most of its time. Such an orbit makes it easier to discriminate forest fire from solar reflection, which suits the purposes of NIRST. In effect, NIRST is a technology demonstration instrument that aims to meet the needs of scientific communities of Argentina and Canada in forest fire and sea surface temperature retrieval. It is to be built under an Agreement between the Comision Nacional de Actividades Espaciales (CONAE) of Argentina and the Canadian Space Agency (CSA). Under this collaboration, the CSA is providing microbolometer detectors and camera electronics technology for CONAE's radiometer. The latter comprises mainly two cameras, one operating in the mid-wave infrared (MWIR) and the other in the long-wave infrared (LWIR) atmospheric window. Each camera will make use of one 512×2 array of uncooled microbolometers to pushbroom scan the ground . The combination of the MWIR and LWIR bands allows for the retrieval of fire temperatures using the double band algorithm. Conversely the use of two LWIR bands enables sea surface temperature measurement by means of the split algorithm technique.
In the following the technical details of the NIRST instrument and its microbolometer detectors will be reported.

[*] hmarraco@conae.gov.ar; Phone +54-11-4331-0074 x314

2. DESCRIPTION OF NIRST INSTRUMENT

The NIRST instrument is housed in a 35×40×50 cm^3 Al compartment which is mounted on the nadir looking underside of the SAC-D satellite. The MWIR and LWIR cameras are located next to each other in this compartment with their optical axis contained in a plane normal to nadir and normal to the satellite velocity vector. The NIRST compartment is thermally separated from the main compartments of the satellite and its outer wall is shielded with MLI layers .

In view of improving the revisit time NIRST is designed with boresight pointing mechanism. To achieve across track pointing an optically flat, light weight Be mirror is used to steer the field of view of the cameras. The steering mirror can be rotated within a range from -15 to +15 deg around its 45 deg position (nadir pointing).

The MWIR camera operates in the spectral band of 3.4-4.2 μm (band 1) and the LWIR camera in the bands of 10.4-11.3 (band 2) and 11.4-12.3 μm (band 3). Each camera makes use of one array of 512x2 microbolometers. To achieve in-field spectral separation, bandpass filters are mounted in front of one line of the MWIR array and both lines of the LWIR array. The MWIR and LWIR cameras are optically aligned such that ground pixel radiance can be co-registered in bands 1 and 2 at the same time. Registration in band 3 is slightly delayed with respect to that in bands 1 and 2 due to the physical separation between the two detector lines of the LWIR camera.

Figure 1 schematically shows the field of view (FOV) of the NIRST cameras projected over the satellite track.

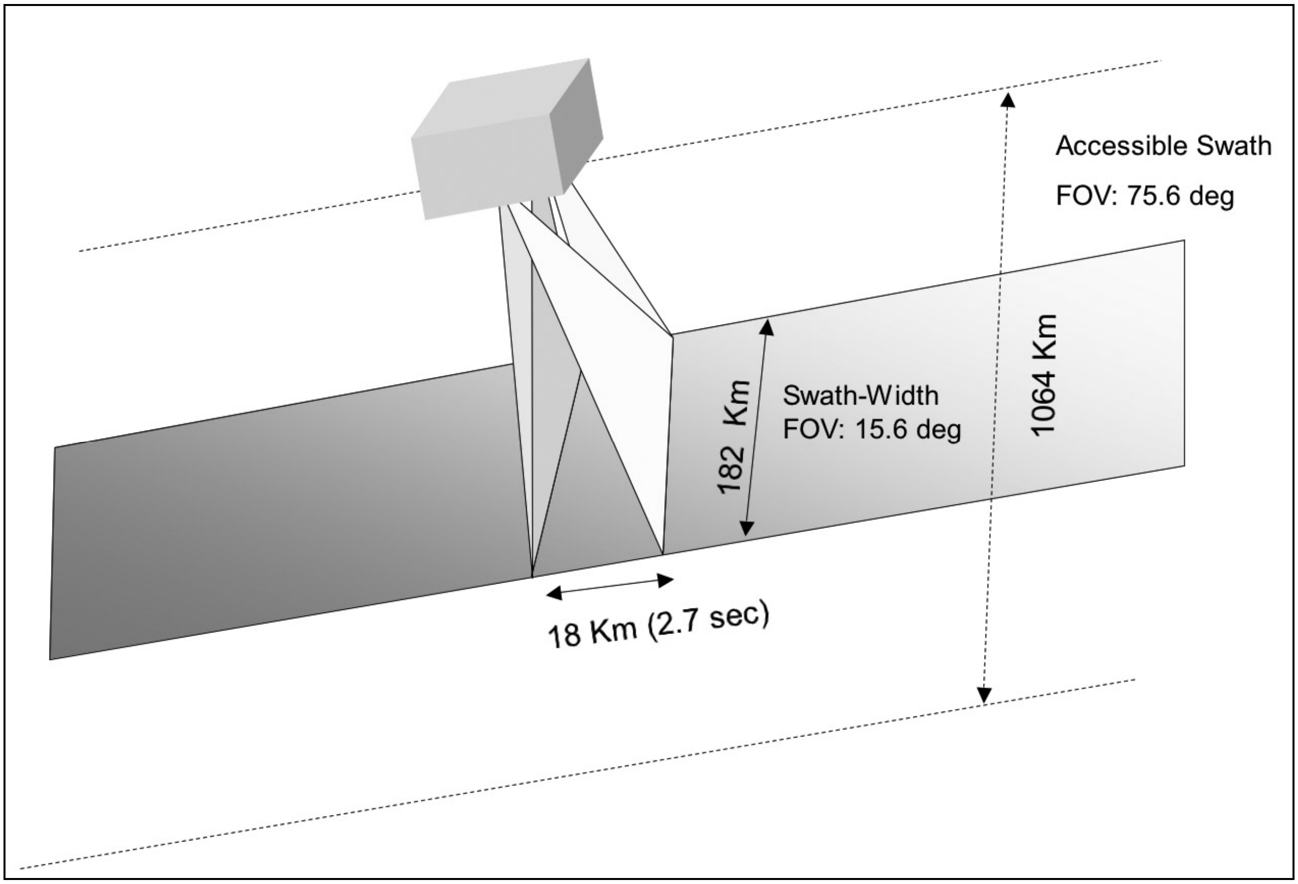

Figure1: The field of view of the NIRST cameras. The central shaded band shows the swath-width when the mirror points to nadir. The 2 beams of each camera represent the instantaneous views of each row of the microbolometer array. The outer lines (not to scale) represent the extremes of the area that is accessible by means of the pointing mirror movement.

It is seen that the combination of the camera FOV and boresight pointing across the satellite track allow measurements to be performed within 500 km of each side of the track.

Regarding the camera optics an effective focal length of 73 mm was selected for both cameras. This focal length was derived for imaging a ground pixel of 351 m onto a detector pixel of 39 μm at an orbital height of 657 km. Tables 1 and

2 summarizes respectively the scanning geometry parameters and the temperature ranges and resolutions required for the NIRST.
To achieve the desired thermal resolutions, for both cameras the microbolometer detectors will be used in conjunction with f/1 optics.

TABLE 1	
Parameter	Value
Ground pixel size (boresight pointing to nadir @ 657 km altitude)	351 m
Swath width	182 km
In field separation (ground level)	18 km
Boresight pointing	±30º from Nadir
Across track maximum observable	1060 km
Pixel IFOV	0º.03

<table>
<tr><th colspan="5">TABLE 2</th></tr>
<tr><th colspan="2">Band</th><th>MWIR</th><th>LWIR 1</th><th>LWIR 2</th></tr>
<tr><td colspan="2">Central wavelength</td><td>3.8 µm</td><td>10.85 µm</td><td>11.85 µm</td></tr>
<tr><td colspan="2">Band Limits</td><td>3.4 – 4.2 µm</td><td>10.4 – 11.3 µm</td><td>11.4 – 12.3 µm</td></tr>
<tr><td rowspan="2">Temperature</td><td>Min.</td><td>300K</td><td colspan="2">250K</td></tr>
<tr><td>Max.</td><td>700K</td><td colspan="2">500K</td></tr>
<tr><td colspan="2">NETD</td><td><0.5K @ 400K scene</td><td><0.3K @ 300K scene</td><td><0.4K @ 300K scene</td></tr>
<tr><td colspan="2">Temp. accuracy</td><td>2.5K @ 400K scene</td><td>1.5K @ 300K scene</td><td><2K @ 300K scene</td></tr>
</table>

3. MICROBOLOMETER DESCRIPTION

The NIRST instrument makes use of two linear arrays of microbolometers, one optimized for operation in the MWIR band and the other for the two LWIR bands. Each array comprises three components: (i) Si micromachined bolometer pixels; (ii) readout integrated circuits (ROIC) monolithically built in the Si wafer; and (iii) radiometric package. These components are respectively described in the following.

3.1. Microbolometer pixel

The linear array consists of two parallel lines of 512 resistive microbolometer pixels fabricated on Si wafer. The separation between the lines is 2 mm. This configuration allows for in-field spectral separation with different bandpass filters placed in front of each line. The pixels are constructed on top of dedicated CMOS ROIC. The pixel pitch selected, 39 um, was such that a line of 512 pixels would not exceed 20 mm. This limitation in die width is inherent to the standard distance for the photorepeater used in CMOS foundries.
To meet the requirements of NIRST, a number of pixel designs were generated to further increase the sensitivity through increasing the thermal isolation and radiation collection efficiency of the pixel. In addition, the time constant of the pixel has to be short. Considering a satellite ground speed of ~ 6.8 km/s, the integration time required to achieve 350 m ground pixel is ~ 51 ms. The new pixel designs aim at achieving a time constant at least five times shorter than this integration time so as to avoid degradation of image quality. The time constant t is dictated by C/G with C being the heat capacity of the pixel and G the thermal conductance between the pixel and the wafer (heat sink). Because G is reduced in order to achieve increased thermal isolation, a short time constant requires that C be conversely reduced.
The pixel platform consists of a Si_3N_4 bridge suspended over the wafer on two vertical posts. Thermally, the bridge acts as a heat absorbing element of which thermal isolation is assured by the vacuum gap separating it from the wafer. Structurally, the bridge serves as an encapsulator and mechanical support for the bolometer element. The latter is a thin

VO_x film with a temperature coefficient of resistance of about 2.2 % at room temperatures. Figure 1 shows the temporal characteristic of the response of one possible baseline pixel to a square wave pulse of radiation. The time constant, defined as the fall time from the maximum to 1/e of signal amplitude, is measured to be 4 ms. In Fig. 2 the low frequency responsivity of the pixel is shown as a function of supplied current, *I*. It is seen that responsivity increases with increasing current and reaches saturation at current values exceeding 5 uA. At I = 5 uA, the responsivity and detectivity of the pixel were measured to be respectively 40000 V/W and $8x10^8$ cm.$Hz^{1/2}$/W. Using these data, the corresponding pixel NETD has been computed for 350 m ground pixel, f/1 optics, and 0.6 transmission. The NETD for the MWIR band, 3.4-4.2 um, is 150 mK for 400 K ground pixel. The NETD's for the two LWIR bands, 10.4-11.3 um and 11.4-12.3 um, are respectively 250 and 290 mK for 300 K ground pixel.

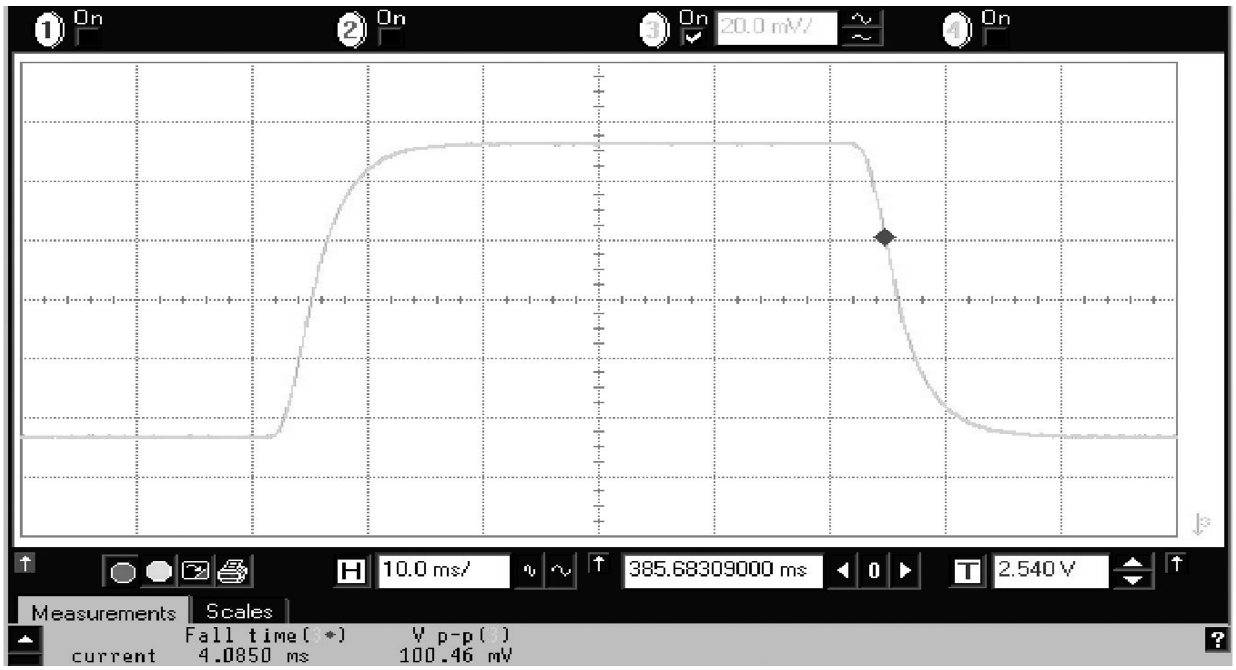

Figure 2: Temporal characteristics of pixel response to a square wave pulse of radiation. The time constant, defined as the fall time from the maximum to 1/e of amplitude, is measured to be 4 ms.

3.2. ROIC

The ROIC consists of a revision of an integrated circuit previously developed for the 512x3 detector arrays [1]. The revised version addresses the 512x2 array format required by the mission as well as the need to increase the robustness of the ROIC. The ROIC is to be embedded in Si wafer using CMOS technologies prior to fabrication of microbolometer pixels. The readout electronics is designed to exhibit a radiation hardness level of 10 krad.

One purpose of the ROIC is to minimize the pixel offset voltages and die temperature drifts. To this end each active microbolometer pixel is associated with three reference pixels in a Wheatstone bridge configuration, *i.e* as a quad cell unit. The reference pixels are structurally similar to the active pixel but, unlike the latter, remain insensitive to changes in background temperature. This arrangement allows for differential measurement of output voltage between the two unbiased nodes of the Wheatstone bridge, therefore minimizing the offset. To cancel out the effect of die temperature drift, one reference pixel was constructed such that its resistance varies with die temperature in the same way as the resistance of the active pixel.

The circuits are laid out in a fashion that all pixels are integrated in parallel with their own signal chain. The target chain noise is 150 nV/$Hz^{1/2}$. The output of the quad cell pixel unit is buffered by a low noise buffer and integrated by a switched capacitor integrator. The integration time is in the range from 7 to 140 ms, corresponding to a ground pixel from 50 to 1000 m with typical low earth orbit parameters. The analog output is digitized by means of a comparator producing counts when the integrated signal reaches an upper or lower reference value. The digitized output are written to a digital register while the preceding data are read out from a second register at a speed from 0.8 to 1.5 MHz. In terms of data output rate, the pixel output can contain up to 15 bits so that its quantization would be in the format of two 10-bit words. Without a data compression scheme, the total image data bit rate will be 600 kbps for the three spectral bands and for an integration time of 51 ms.

3.3. Packaging

Two radiometric vacuum packages respectively intended for the MWIR and LWIR microbolometer array are being developed. In each package, the array will thermally be anchored to a single stage thermoelectric cooler plus a temperature sensor for the purpose of temperature control. Also integrated in each package are a cold shield assembly and dedicated MWIR or LWIR bandpass filters for the three spectral bands of NIRST. The target size and weight of each package are respectively 50 mm x 65 mm x 50 mm and 150 g. The target package pressure is less than 10 mTorr by the end of the 7 year package lifetime.

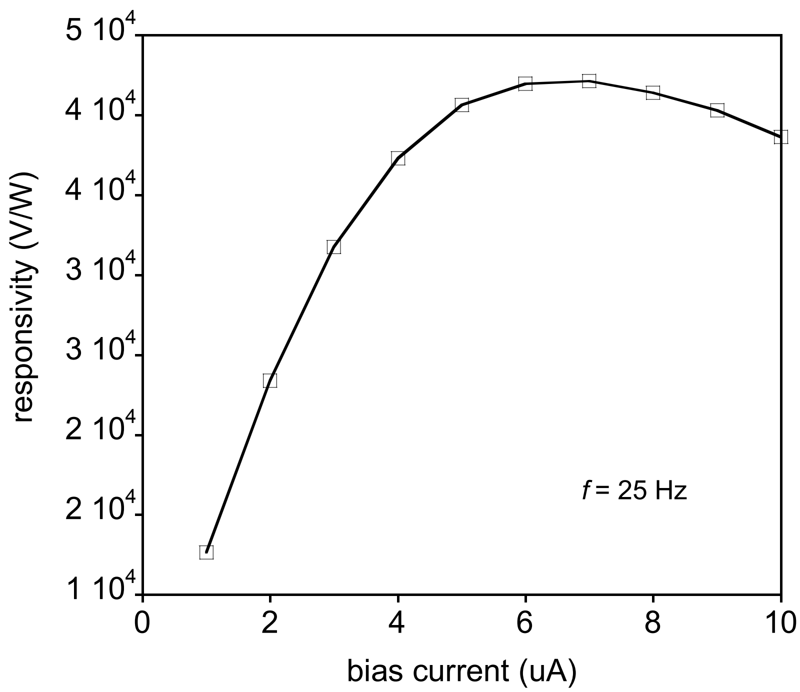

Figure 3: Responsivity of a pixel as a function of bias current at 25 Hz modulation frequency. The solid line is provided as visual aid.

4. OPERATIONAL CONSIDERATIONS FOR NIRST

The primary purpose of NIRST is to monitor the extent and retrieve the temperatures of forest fires and other high temperature events (HTE). This will be accomplished by applying the double band algorithm to the data obtained in bands 1 and 2. Figure 4 shows the spectral characteristics of solar reflection, biomass fire, and ground thermal emission across the infrared spectrum. Considering that the satellite will mostly be in the sunset zone, the contribution of solar reflection is negligible. In effect, solar contribution should only be considered in the occasional event that the satellite happens to be at its utmost northern path during the northern hemisphere summer solstice . In this case the Sun will be at an elevation of 30deg over the ground at nadir. It is seen in Fig. 4 that the solar reflection characteristic differs significantly from that of HTE's even when the ground is covered by high reflectance clouds (or ice). In all cases the contribution of solar reflection in the LWIR bands is negligible.

Another purpose of NIRST is to provide additional data for the Aquarius experiments in retrieving sea surface temperatures. This will be done using the split band algorithm with the data obtained in the two LWIR bands. For this purpose the satellite altitude will be corrected as it flies over different latitude zones of the Earth to account for mismatches induced by the Earth rotation. The mismatch can attain almost 4 deg at the equator and result in a mismatch of 3.6 pixels between the contiguous rows of microbolometer array.

TABLE 3	
FOV	15.6 deg
Focal length	73 mm
Optics F number	F/1

The ability of pointing the NIRST FOV across the track to monitor the areas not directly along the satellite track means that any HTE can be followed up within an acceptable revisit time. Table 4 shows the mean revisit time and the maximum number of days a HTE could be missed for each repeat cycle, for some areas of possible interest. The repeat cycle of the SAC-D orbit is 7 days. The Tierra del Fuego and Jujuy are Argentina provinces that are located to the furthermost northern and southern limits of the country.

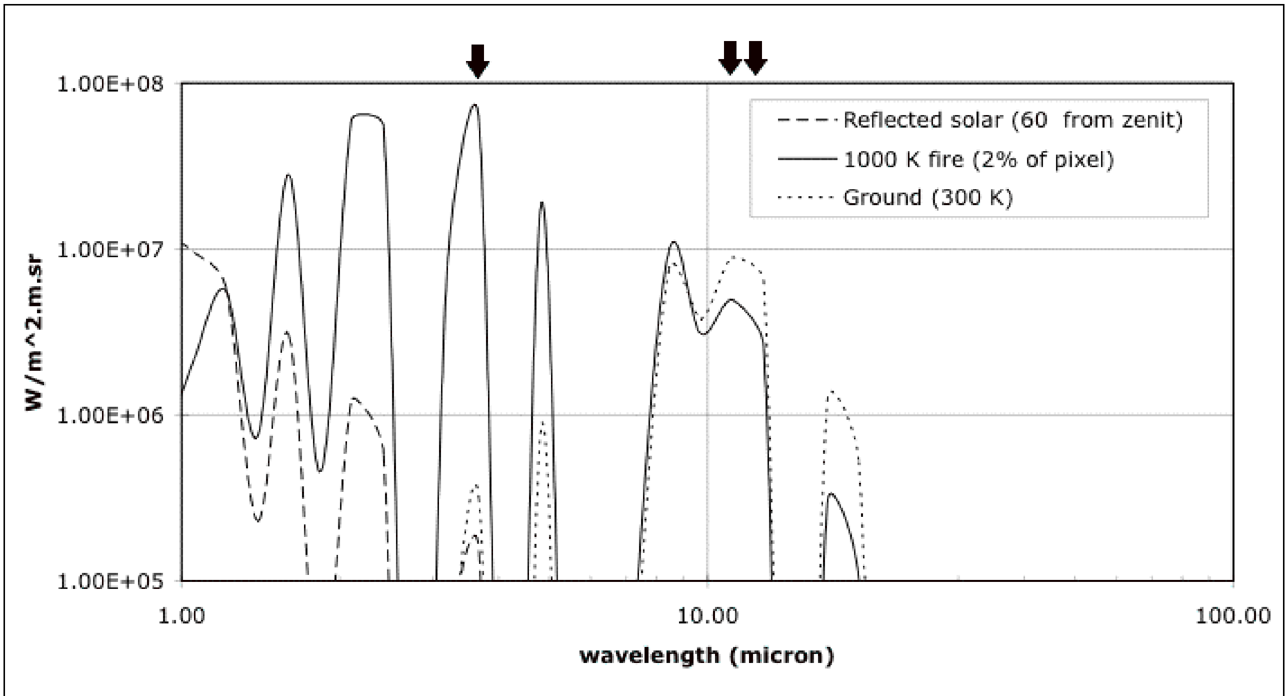

Figure 4: The apparent radiances outside the atmosphere (corrected by atmospheric absorption). The solar reflection is represented by a terrain covered by clay. Reflection in clouds can increase this radiance by an approximate factor of 8 (depending on wavelength). The 2% of the pixel can be though as a 7 m depth front of fire that extends across the whole pixel in width. The arrows on the top of the figure point to the locations of the NIRST spectral bands.

TABLE 4			
Latitude	Example location	Mean revisit interval (days)	Maximum missing days
±67º	Northern Canada	0.5	0
±55º	Tierra del Fuego, mid Canada	0.7	1
±23º	Jujuy	1.2	2

REFERENCES

1. T.D. Pope, C. Alain, L. Le Noc, H. Jerominek, L. Ngo Phong, and W. Zheng, 2005. Performance of a 512x3 pixel microbolometer detector for space imaging applications, in *The 2005 International Conference on MEMS, Nano, and Smart Systems*, W. Badawy and W. Moussa Eds., Odyssey Press, pp. 275-276