Mid and thermal infrared remote sensing at the Jet Propulsion Laboratory

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ABSTRACT

The mid and thermal infrared (MTIR) for the Earth surface is defined between 3 and 14 µm. In the outer solar system, objects are colder and their Planck response shifts towards longer wavelengths. Hence for these objects (e.g., icy moons, polar caps, comets, Europa), the thermal IR definition usually stretches out to 50 µm and beyond. Spectroscopy has been a key part of this scientific exploration because of its ability to remotely determine elemental and mineralogical composition. Many key gas species such as methane, ammonia, sulfur, etc. also have vibrational bands which show up in the thermal infrared spectrum above the background response.

Over the past few decades, the Jet Propulsion Laboratory has been building up a portfolio of technology to capture the MTIR for various scientific applications. Three recent sensors are briefly reviewed: The airborne Hyperspectral thermal emission spectrometer (HyTES), the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and Mars Climate Sounder (MCS)/DIVINER. Each of these sensors utilize a different technology to provide a remote sensing product based on MTIR science. For example, HyTES is a push-brooming hyperspectral imager which utilizes a large format quantum well infrared photodetector (QWIP). The goal is to transition this to a new complementary barrier infrared photodetector (CBIRD) with a similar long wave cut-off and increased sensitivity. ECOSTRESS is a push-whisk Mercury Cadmium Telluride (MCT) based high speed, multi-band, imager which will eventually observe and characterize plant/vegetation functionality and stress index from the International Space Station (ISS) across the contiguous United States (CONUS). MCS/DIVINER utilizes thermopile technology to capture the thermal emission from the polar caps and shadow regions of the moon. Each sensor utilizes specific JPL technology to capture unique science.

Keywords: imaging, spectroscopy, QWIP, MCT, Thermopile, CBIRD, thermal, LWIR, Dyson

1. INTRODUCTION

The long wave infrared (LWIR) is typically expressed as the wavelength range between 7 and 14 µm while the mid wave infrared (MWIR) captures the 3 to 5 µm Earth atmospheric window. The longer wavelengths in this passband allows discrimination of earth surface features (such as carbonate and silicate signatures) while the shorter wavelength end allows retrieval of key greenhouse gases such as methane and other hydrocarbons. Spectral information from this wavelength range is extremely valuable for Earth Science research. Recent hyperspectral campaigns have supported the HyspIRI mission [1,2]. NASAs Hyperspectral Infrared Imager (HyspIRI) is a global mission focused on unique and urgent Earth science and applications objectives that are addressed by continuous spectral measurements in the visible to short-wavelength infrared (VSWIR: 380 to 2510 nm) portion of the spectrum and measurements from eight discrete multi-spectral bands in the thermal infrared (TIR: 3 to 13 microns) spectral range. A direct broadcast subset/processing capability is included in the HyspIRI mission to support near real-time applications and science. The HyspIRI mission will study the world’s ecosystems and provide critical information on natural disasters such as volcanoes, wildfires and drought. HyspIRI will be able to identify the type of vegetation that is present and whether the vegetation is healthy. The mission will provide a benchmark on the state of the worlds ecosystems against which future changes can be assessed. The mission will

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also assess the pre-eruptive behavior of volcanoes and the likelihood of future eruptions as well as the carbon and other gases released from wildfires. The TIR component of the HyspIRI mission will address science questions in five main science themes:

**Volcanoes**

Volcanic eruptions and earthquakes yearly affect millions of lives, causing thousands of deaths, and billions of dollars in property damage.

- What are the changes in the behavior of active volcanoes? Can we quantify the amount of material released into the atmosphere by volcanoes and estimate its impact on Earth’s climate? How can we help predict and mitigate volcanic hazards?

**Wildfires**

Both naturally occurring wildfire and biomass burning associated with human land use activities have come to be recognized as having an important role in regional and global climate change. There consequently exists a substantial need for timely, global fire information acquired with satellite–based sensors.

- What is the impact of global biomass burning on the terrestrial biosphere and atmosphere, and how is this impact changing over time?

**Water Use and Availability**

Given current trends in population growth and climate change, accurate monitoring of the Earths freshwater resources at field to global scales will become increasingly critical.

- As global freshwater supplies become increasingly limited, how can we better characterize trends in local and regional water use and moisture availability to help conserve this critical resource?

**Urbanization**

Excess deaths occur during heat waves on days with higher–than–average temperatures and in places where summer temperatures vary more or where extreme heat is rare.

- How does urbanization affect the local, regional and global environment? Can we characterize this effect to help mitigate its impact on human health and welfare?

**Land surface composition and change**

The emitted energy from the exposed terrestrial surface of the Earth can be uniquely helpful in identifying rocks, minerals, and soils.

- What is the composition and temperature of the exposed surface of the Earth? How do these factors change over time and affect land use and habitability?
2. AIRBORNE EARTH SCIENCE: HYTES

The hyperspectral thermal emission spectrometer (HyTES) [3,4] has flown five low altitude campaigns over the past few years and is now preparing for an extensive tour across California. The instrument provides state-of-the-art hyperspectral imaging in the LWIR. HyTES operates from 7.5 µm to 12 µm. The core spectrometer has a compact design allowing minimal cooling. Recently, the sensor scan head size has undergone modifications to support operation in NASA’s ER-2 high altitude aircraft. These modifications have significantly reduced the overall size and weight of the instrument.

Although the HyTES imaging spectrometer kernel is compact, it was designed for ruggedized use in the field and specifically to fly on a twin otter platform. The basic characteristics are shown in table 1. There’s numerous peripheral hardware including aircraft racks, data computers and gimbal stabilization mounts which are part of the airborne implementation. The basic vacuum cylinder is approximately 0.6m x 0.4m, while the actual imaging spectrometer is handheld in size. The system is currently schedule to fly in the ER-2 at high altitude mid-2016. A photo of a technician working on the scan head is shown in figure 1. This part resides inside a vacuum assembly and is typically only accessed during modification.

QWIP technology [5,6] utilizes the photoexcitation of electrons between the ground state and the first excited state in the conduction band quantum well (QW). HyTES currently operates with a QWIP detector array stabilized at 40K to have a low dark current, hence SNR advantage. The QWIP is known for its high spatial uniformity (≤0.51%). This is a clear advantage for pushbroom, hyperspectral system over other detector technologies such as HgCdTe.

HyTES is looking at transitioning over to a new detector technology. Antimonide superlattice based long-wavelength infrared photodetectors using a complementary barrier infrared detector (CBIRD) [7,8] design offers the possibility of stabilized, uniform arrays with low dark current, higher operating temperature than QIWP and higher QE. The nearly lattice-matched InAs/GaSb/AlSb (antimonide) material system offers tremendous flexibility in realizing high-performance infrared detectors. Antimonide-based superlattice infrared absorbers can be customized to have cutoff wavelengths ranging from the short-wave infrared (SWIR) to the very long-wave infrared (VLWIR). They can be used in constructing sophisticated heterostructures to enable advanced infrared photodetector designs. In particular, they facilitate the construction of unipolar barriers, which can block one carrier type but allow the unimpeded flow of the other. Unipolar barriers are used to implement the barrier infrared detector (BIRD) design for increasing the collection efficiency of photo-generated carriers, and reducing dark current generation without impeding photocurrent flow.

Table 1. Basic Instrument design.

<table>
<thead>
<tr>
<th>Volume (scan head)</th>
<th>0.6m x 0.4m + peripheral struts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of spatial pixels x track</td>
<td>512</td>
</tr>
<tr>
<td>Number of spectral channels</td>
<td>256</td>
</tr>
<tr>
<td>Spectral range</td>
<td>7.5 - 12µm</td>
</tr>
<tr>
<td>Frame Speed</td>
<td>35 or 22 fps</td>
</tr>
<tr>
<td>Total field of view</td>
<td>50deg</td>
</tr>
<tr>
<td>Calibration</td>
<td>Full aperture blackbody</td>
</tr>
<tr>
<td>Detector temperature</td>
<td>40K</td>
</tr>
<tr>
<td>Optics temperature</td>
<td>100K</td>
</tr>
<tr>
<td>NE∆T</td>
<td>200mK</td>
</tr>
<tr>
<td>IFOV</td>
<td>1.7066 mrad</td>
</tr>
<tr>
<td>Low Altitude pixel size/swath</td>
<td>2m/1Km</td>
</tr>
<tr>
<td>High Altitude pixel size/swath</td>
<td>20m/10Km</td>
</tr>
</tbody>
</table>
3. SPACE BASED EARTH SCIENCE: ECOSTRESS

The ECOSystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) [9] will measure the temperature of plants and use that information to better understand how much water plants need and how they respond to stress. ECOSTRESS will address three overarching science questions:

- How is the terrestrial biosphere responding to changes in water availability?
- How do changes in diurnal vegetation water stress impact the global carbon cycle?
- Can agricultural vulnerability be reduced through advanced monitoring of agricultural water consumptive use and improved drought estimation?

The ECOSTRESS mission will answer these questions by accurately measuring the temperature of plants. Plants regulate their temperature by releasing water through tiny pores on their leaves called stomata. If they
have sufficient water they can maintain their temperature but if there is insufficient water their temperatures rise and this temperature rise can be measured with a sensor in space. ECOSTRESS will use a multispectral thermal infrared radiometer to measure the surface temperature that will be delivered to Houston for deployment on the International Space Station in 2018. The radiometer will acquire the most detailed temperature images of the surface ever acquired from space and will be able to measure the temperature of an individual farmers field.

One of the core products that will be produced by ECOSTRESS team is the Evaporative Stress Index (ESI). ESI is a leading drought indicator - it can indicate that plants are stressed and that a drought is likely to occur providing the option for decision makers to take action. The left side of figure 2 illustrates the ESI for the United States during the 2012 drought. The red areas indicate regions of high water stress.

ECOSTRESS will be implemented by placing the existing space-ready Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR) on the International Space Station (ISS) and using it to gather the measurements needed to address the science goals and objectives. PHyTIR was developed under the Earth Science Technology Office (ESTO) Instrument Incubator Program (IIP). From the ISS, PHyTIR will provide data with 38-m in-track by 69-m cross-track spatial resolution (science requirement is 100 m) and predicted temperature sensitivity of 0.15 K (science requirement is 0.3 K). A schematic of the current instrument design is shown on the right side of figure 2. The ISS orbit allows excellent coverage of the selected targets including diurnal coverage. The existing hardware was developed to reduce the cost and risk for the thermal infrared radiometer on the future HyspIRI mission. A double-sided scan mirror, rotating at a constant 25.4 rpm, allows the telescope to view a 53 degree-wide nadir cross-track swath as well as two internal blackbody calibration targets every 1.29 seconds (Note that the two-sided mirror rotating at 25.4 rpm provides 50.8 effective sweeps per minute). The optical signal is focused by a telescope onto the 65 K focal plane containing a custom 13.2-m-cutoff mercury-cadmium-telluride (MCT) infrared detector array. Spectral filters on the focal plane define 5 spectral bands in the 8-12.5 m range. The focal plane is cooled by two commercial cryocoolers. Electronics consist of six build-to-print and four commercial boards. Heat rejection for the ECOSTRESS cryocoolers and electronics is provided by the cooling fluid loop on the ISS Japanese Experiment Module External Facility (JEM-EF). ECOSTRESS can fit any of the nine JEM-EF payload locations but will be deployed at Site 10 (one of the two end locations).

4. BEYOND EARTH ORBIT: MCS/DIVINER

Mars Climate Sounder (MCS) flying on Mars Reconnaissance Orbiter (MCS-launch 2005) and Diviner flying on Lunar Reconnaissance Orbiter (LROlaunch 2009) are two examples of high fidelity thermopile based imaging sensors. MCS and Diviner are currently the gold standard for accurate thermal radiometry flying beyond Earth orbit and provide breakthrough science by measuring the infrared/far-infrared (1 to 100 µm) properties of the Martian atmospheric and the lunar surface, respectively [10, 11, 12].
Table 2. Expected Capability for ECOSTRESS.

<table>
<thead>
<tr>
<th>Ground Sample Distance</th>
<th>69m x 38m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath Width</td>
<td>400km</td>
</tr>
<tr>
<td>Wavelength Range</td>
<td>8.0 - 12.5µm</td>
</tr>
<tr>
<td>Number of bands</td>
<td>≥ 5</td>
</tr>
<tr>
<td>Radiometric Accuracy</td>
<td>≤ 0.5</td>
</tr>
<tr>
<td>Radiometric Precision</td>
<td>≤ 0.15</td>
</tr>
<tr>
<td>Calibration</td>
<td>Full aperture blackbody</td>
</tr>
<tr>
<td>Detector temperature</td>
<td>65K</td>
</tr>
<tr>
<td>Optics temperature</td>
<td>Ambient</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>200 - 500K</td>
</tr>
<tr>
<td>Data Collection</td>
<td>≥ 1.5hr/day</td>
</tr>
</tbody>
</table>

MCS and Diviner use JPL thermopile arrays and a three-mirror anastigmat (TMA) optical design where the metering structure is milled from a single block of aluminum. By thermally insulating the metering structure from the rest of the instrument and wrapping the instrument in thermal blankets, it is possible to due away with strict temperature control of the telescope and still achieve radiometric accuracy below 1 K over between 240 to 360 K scene temperatures. The thermopile array is only sensitive to relative changes in temperature between the absorber and substrate so one can achieve excellent radiometric accuracy without a complicated thermal design. Figure 3 shows how Diviner is able to measure 30 K region on the lunar poles with an accuracy greater than 1 K even though the instrument operates around 32 C. MCS and Diviner have 9 spectral channels defined by strip filters place over each row.

While photon detectors are typically very sensitive compared to thermal detectors, photon detectors require extreme cooling to operate at long wavelengths because they lose sensitivity as the thermal energy of the carriers approach the bandgap energy. Thermal detectors, on the other hand, (bolometers, pyroelectric detectors, and thermopiles) can operate uncooled at long wavelengths, making them well suited for spaceborne missions where mass and power resources are scarce. However, there are deficiencies with some thermal detector types. Pyroelectric detectors require a chopper and are not available in array formats. Microbolometer arrays developed for night vision are commercially available and have been used on two space instruments (THEMIS on Mars Odyssey and the ISAR shuttle instrument) and selected to fly on the New Frontier mission OSIRIS-REx and Europa Clipper. Thermopiles have several properties that are particularly advantageous over microbolometer arrays:

- they are broadband ($\lambda = 0.1$ to 100 µm) (microbolometers are designed for 300 K and are tuned to measure $\lambda = 10\mu m$ [13,14]);
- they have negligible excess 1/f noise so the SNR can be improved by frame averaging and time-delay and integration (TDI). Thermopiles are completely passive devices and require no bias voltage. Conversely, microbolometers are biased and, consequently, suffer from 1/f noise so one does not realize a $\sqrt{N}$ increase in SNR where N is the number of frame averages. Therefore, TDI is ineffective with microbolometers [15];
- they are insensitive to instrument temperature drifts which is important when radiometric accuracy is critical to success (microbolometers must be controlled to millikelvin while thermopiles can be controlled to kelvin) [16];
- they are highly linear to incident radiation (50x more linear than microbolometers) [17].
Diviner uses a previous generation thermopile array and a simple thermal design to make highly accurate thermal lunar maps. Because thermopiles require no strict temperature control, the focal plane and telescope temperature can drift in temperature by 1 K while still imaging permanently shadowed 30 K regions of the lunar poles with an accuracy of 1 K [see (c)].

5. CONCLUSION

Over the past few decades, the Jet Propulsion Laboratory has been building up a portfolio of technology to capture the MTIR for various scientific applications. This paper is by no means an exhaustive examination of the sensors but does hit on three very distinctive existing detection technologies: QWIP and CBIRD technology for large format push-broom sensing, MCT for high speed push-whisk platforms, and thermopile arrays for outer planetary, extended wavelength examination of cold objects.

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