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A low-cost mid-wave IR microsatellite imager concept based on uncooled technology

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ABSTRACT

A new class of low-cost mid-wave infrared (MWIR) Earth observation (EO) data will become available with the flight of miniature MWIR EO instruments in micro-satellite constellations. Due to the frequent ground repeat times inherent in constellations, this data set would provide a unique alternative for those wishing to analyse trends or rapidly detect anomalous changes in the MWIR characteristics of the Earth's surface (e.g. fire detection) or atmosphere. To date, the MWIR imagers have been based on highly responsive cooled detector technology, which traditionally has been the only real option for collecting useful data in this waveband from space. However, state-of-the art microbolometers, adapted from their original design for operation in the LWIR, are thought to be a potential alternative for low-cost MWIR constellations. Following the laboratory evaluation of a modified microbolometer arrays in the MWIR, a low-mass instrument concept was designed and evaluated for a variety of candidate MWIR mission areas. If implemented, the imager concept would complement a larger imaging suite (visible, near IR, and long-wave IR) on a sub-100kg Surrey Space Technology Ltd. (SSTL) micro-satellite and open up several new potential mission areas for the SSTL-engineered Disaster Monitoring Constellation.

KEYWORDS: uncooled, microsatellites, mid-wave IR, hot spot detection

1. INTRODUCTION

This paper is a follow-on to [1] where we predicted some potential space applications in the mid-wave infrared (MWIR) for uncooled microbolometer arrays. In this study, we have explored the feasibility and utility of performing a low-cost MWIR imaging mission from a microsatellite (100kg) platform by the use of microbolometer arrays. In doing this, we will first summarize the advantages to this approach, namely enabling microsatellite Earth observation constellations. This is followed by a description of the key challenges and limits as well as the underlying assumptions that went into this study. Next, the proposed MWIR imaging payload, supporting laboratory evaluation, and imager concept's expected on-orbit performance is presented. Lastly an assessment of this approach is given as well as recommendations for further research.

This study has been conducted in close cooperation of Surrey Space Centre's and Surrey Satellites Technology Limited's (SSTL) strategy for developing future low-cost Earth observation capabilities as well as ULIS's efforts in exploring new applications for their uncooled microbolometer line. This study has been supported in part by the USAF Office of Scientific Research, the USAF European Office of Aerospace Research and Development, SSTL, and ULIS.

2. THE MICROSATELLITE CONSTELLATION NICHE

The atmospheric window from 3 to 5 microns classified as the mid-wave infrared (MWIR) has long been a waveband of interest in the remote sensing community. Due to the high contrast offered between hot bodies and both reflected solar and ambient emitted radiation, the MWIR is often used to help distinguish hot thermal events on the Earth's surface as well as to better characterize cooler thermal infrared data collect in the LWIR waveband (8 – 12 μm). Because of the reliance on cooled detector technology and scanning optical systems to capture large imaging swaths, heritage MWIR instruments are usually large and power hungry. Typically, MWIR imaging payloads require fairly large host satellite platforms and, therefore, have been the exclusive domain of major space organizations. Examples include the European

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Space Agency (ESA) Advanced Along-Track Scanning Radiometer (AATSR), the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer/2 (AVHRR/2), the National Space Development Agency of Japan (NASDA) Global Imager (GLI), and the National Air and Space Administration (NASA) Moderate-Resolution Imaging Spectrometer (MODIS) [2-5]. The legacy of high quality MWIR imaging data from these instruments can be characterized by a high radiometric performance, high temporal coverage (daily), but at a medium-low spatial resolution (1 km). Also characteristic of these instruments is a cost and design lifecycle necessitating the capture of a large set of user imaging requirements as well as the reliance on older but proven and more robust imaging technologies.

In order to increase the utility of the MWIR imaging products, there have been several efforts to decrease spatial resolution whilst preserving a high radiometric sensitivity and daily coverage. A prime example is the National Polar-orbiting Operational Environmental Satellite Systems (NPOESS) Visible and Infrared Imaging Radiometer Suite (VIIRS) instrument, which will provide 370 m ground sample distance (GSD) with the same NETD and daily temporal coverage as MODIS [6]. The German Aerospace Center (DLR) achieved another significant step towards MWIR instrument advancement when they demonstrated the first ever MWIR/LWIR instrument, small enough to fly on a sub-100 kg microsatellite [7]. This instrument, known as the Bi-Spectral Infrared Detector (BIRD), currently provides 290 m GSD, high dynamic range and radiometric resolution, but limited temporal coverage. Although BIRD has demonstrated the flight of a sophisticated LWIR/MWIR imaging payload on a microsatellite, the imager concept, based on cooled detector technology, still requires a dedication of the majority of the microsatellite payload mass/power budget. Therefore, increasing temporal coverage via a constellation would require a significant commitment to the MWIR/ LWIR mission area.

In this study, a departure from the approaches taken by VIIRS and BIRD is proposed. Through a more dramatic instrument miniaturization (size and power requirement reduction) whilst preserving the bulk of its ability to collect useful imaging data, it would become possible to integrate, at a relatively lower-risk, low-cost MWIR imagers as secondary payloads into existing Earth observation constellations replenishment programs. One example being the four- (soon to be five) Disaster Monitoring Constellation, flown by Surrey Satellite Technology Limited (SSTL) currently providing medium GSD (32 m) full daily coverage of the Earth in the visible and near infrared wavebands at a cost below that of a single traditional Earth observation (EO) satellite mission [8]. As the constellation ages or as new members join the international DMC consortium, additional EO microsatellites could be added each taking incremental advantage of advancements in low-cost imaging technologies. With time, as more and more MWIR instruments fill the constellation, they would together produce a data set comparable to that currently available with current systems. Because of the low level of risk involved, individual instruments could also be easily customized serving niche MWIR user communities currently ill-served. However, this approach presents some limitations with decreased radiometric resolution being the most significant, and realizing those limits in the instrument design and evaluation has been the focus of this paper.

3. CHALLENGES TO A LOW-COST APPROACH

Obviously, the dramatic miniaturization of an MWIR imager whilst preserving reasonable utility presents several challenges. In order to obtain quality radiometric resolution of a ground scene from space, instrument developers have traditionally relied on cooled detector technology. While these detectors continue to offer the best performance, the large bulk and power consumption of the associated coolers, as well as the risk of induced microvibrations, make them problematic for flight as secondary payloads on very small satellites. As an alternative, some space instrument developers have turned to uncooled detector technology, which has experienced large improvement in the LWIR waveband in the past decade. However, despite significant advances, uncooled detector technology will always hold fundamental limits in performance and this challenge becomes increasingly limiting when shifting their use to the MWIR. Lastly, the development of detectors responsive in the MWIR has normally been the domain of military organizations and hence the top performing detectors are usually restricted from the general market. Reliance on what is available commercially has been a further challenge to this design.

Another key challenge to instrument miniaturization is centered on the requirement for instrument calibration. In order to account for variations in detector pixel gain and offset, reference blackbodies are typically inserted within the MWIR imager's field of view in order to accurately reference the detector array prior to each image. On larger systems, this can be done with the aid of the same steering mirror used for image scanning in a whiskbroom configuration. In smaller systems, mechanical arms, mirrors, or paddles are often used. In most cases, cold space (3 K) is used for as a reference cold body with a reference hot body on-board the satellite. For MWIR instrument miniaturization, steering mirrors and large field black bodies present obvious problems regarding bulk and power consumption. Some alternatives for dealing with these issues are presented in section 4.5.

Lastly, when exploring a low-cost alternative to the production of MWIR data sets, it is important to evaluate any predicted benefits in light of the current availability, and often free, high quality MWIR imaging products offered by the current field of on-orbit instruments. The expense of development, fabrication, and use of scarce payload space must be justified by a reasonable utility of the payload data by the spacecraft owner. While performance concessions are made in the miniaturization effort, it will need to be clear what currently ill-served data user or particular niche mission areas will still be better served by the low-cost approach in a constellation. Potential niche applications for this imager concept are presented in section 6.

4. IMAGER DESIGN

In this section, the proposed solution (MWIR imager concept) to the miniaturization challenges summarized in the previous section will be detailed. With this concept, MWIR capabilities could easily be integrated into future microsatellite imaging suites eventually providing a high temporal coverage of the Earth at useful radiometric and spatial resolutions. What follows is an outline of the technologies utilized and how they were adapted to form a space instrument responsive in the MWIR.

4.1. Microbolometer Detector Array

The key enabling technology for this imaging instrument is the ULIS 320 x 240 amorphous silicon microbolometer detector array. Despite the availability of arrays with a 35 μm pixel pitch, the array chosen for this design has a pixel pitch of 45 μm. Even though the larger pixels require a larger optic for a given resolution and f-number, they have a relatively faster response time (4 ms verse 7 ms) which is important when considering pixel blur from low Earth obit. Also, the larger pixel allows for the collection of more scene radiation, which will offer an advantage over the smaller pixel in what is an already challenging application of uncooled technology. The detector will be used in the standard Peltier temperature stabilized vacuum package. However, the front Germanium cover glass has been replaced with a highly MWIR transmissive sapphire window coated for a 3 to 5 μm passband.

4.2. Imaging Optics

In order to match the coming generation of MWIR imagers, a GSD of 300 m and a 95 km swath width (190 km for an imaging pair) at an altitude of 700 km was selected. The resulting optical requirement has a focal length of 105 mm, a relative aperture close to f / 1, and off-axis modular transfer function (MTF) at the Nyquist frequency of 6% (typical for SSTL imagers). The commercial market has not yet created a demand for fast (f/1 – f/1.5) optics operating in the MWIR primarily because cooled technology is still the major player in this waveband. Therefore, a fast LWIR germanium triplet was used with the LWIR filter coating removed and replaced with one in the MWIR. Germanium was chosen because of its transmission properties in the MWIR as well as it's high index of refraction given the low required f-number.

4.3. Electronics and Spacecraft Interfaces

One of the key advantages of using a COTS detector is the ease of electrical interfacing via the microbolometer array readout integrated circuit (ROIC). The analog output from the ROIC is similar to that found on some of our current imager systems, and so we had made use of our design heritage for image acquisition, storage and downloading. After leaving the detector ROIC, the analogue video signal enters the SSTL engineered electronics. The video signal is first digitized to an 12-bit digital stream and then read into a solid-state data-recorder (SSDR). The data is then held until ready for transmission to Earth under the control of a field programmable gate array (FPGA), which links the SSDR to a dedicated downlink. The FPGA also contains all the sequencing and timing logic for system, as well as all the control signals needed to operate the imager under the various data collection scenarios. The command and control of the FPGA is performed by a microcontroller. The microcontroller sends and receives telecommands and telemetry though Control Area Network (CAN) packets from other on-board controllers. It can also provide on-board image processing such as automatic feature detection and data-compression. The downlink speed will depend on the particular host satellite. Typical rates for microsatellites range from 9.6 kbps to a few Mbps.

4.4. Thermal control/mechanics

Although the microbolometer array does not requiring cooling, it does operate most effectively when it is thermally stable. Most of the thermal stabilization is controlled by the ULIS detector package via an insulated vacuum package and an integrated Peltier cooler. The detector package is furthered thermally isolated from the heat generated by the electronics by an aluminum barrier. The cavity created by the detector package, the rear optical element, and a cylindrical aluminum enclosure is also maintained at a stable temperature via additional Peltier coolers mounted on walls of the enclosure. The remainder of the thermal control is provided by insulating the optics and enclosing the entire camera, save the entrance aperture inside the spacecraft bus. The interior of the spacecraft, especially that abutting the nadir panel, is a fairly stable environment and thermal noise can be minimized with little additional measures. Mechanically, the imager is assumed to be mounted onto the standard SSTL DMC optics bench. The structure is comprised mainly of machined aluminum and the COTS lens housing.

4.5. Calibration

As previously mentioned in section 3, one of major challenges to MWIR instrument miniaturization has been to find a method for proper calibration without excessive bulk or power requirements or unnecessary risk of moving parts as potential sources of failure over the course of a multi-year EO mission. For precision MWIR imaging missions where frequent calibration is absolutely necessary, a movable paddle containing a hot blackbody has been designed to periodically cover the entrance pupil of the optic. For less precise mission areas where characterizing subtle flux variations across the scene is not required and non-uniformities in responsivity across the array are less vital (course fire detection, etc.), in-flight calibration will be forgone. In this case, the instrument will be calibrated on the ground prior to launch and any degradation or drifts in imager response during the life of the imager will be accepted.

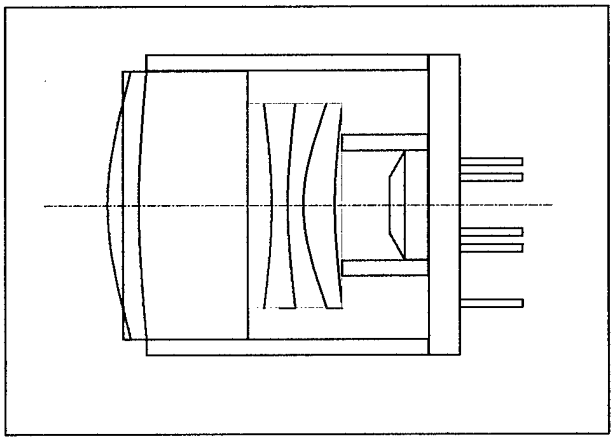
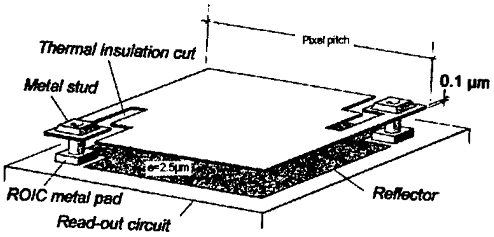


Fig. 1. Microsatellite MWIR Imager

5. LABORATORY EVALUATION

5.1. Theoretical MWIR response

Unlike photon detectors whose output signal is related directly to the energy or wavelength of incident photons, the microbolometer output signal, being a thermal detector, is related only to the incident optical flux absorbed. In theory, a microbolometers have a flat response across the entire spectra. However, in order to maximize the response in the LWIR, the microbolometer array manufacturer, ULIS, has designed a quarter wave optical cavity under the pixel structure (see figure 2). This cavity increases the absorption efficiency in the LWIR by re-capturing some of the missed LWIR flux via a reflector. The peak absorption wavelength dictated by the optical cavity is given by equation (1) where where *n* is the index of refraction of the transmission media in the cavity (air), *e* is the cavity depth, *k* is the resonant order, and λp is the peak resonant wavelength.



$$n \cdot e = \frac{(2k+1)\lambda_p}{4} \quad (1)$$

Fig. 2. Bolometer Pixel Microstructure

So, for $n = 1$ (air), $e \sim 2.5$ µm, and $k = 0$, $\lambda p = 10$ µm which corresponds to the standard ULIS microbolometer array product in the LWIR. For $k = 1$, $\lambda p = 3.33$ µm. Therefore, the standard ULIS microbolometer pixel structure should exhibit increased absorption factor in the MWIR, albeit not as high as that in the LWIR. However, given the increased signal levels in the MWIR over the LWIR for high temperatures as dictated by Planck's curve, we expect a reasonable response of the microbolometer pixel for MWIR mission areas.

5.1 Repsonsivity Measurements

In order to determine the increased absorption in the MWIR, the microbolometer's responsivity (volts per incident watt) was measured across the infrared optical spectrum (figure 3). As can be seen from the graph, there is a secondary peaked response in the MWIR although slightly shifted to the right from the predicted 3.33 µm. This can be attributed to variations in the CMOS surface topology on the reflector surface at the base of the optical cavity and the fact that the optical cavity is not exactly 2.5 µm.

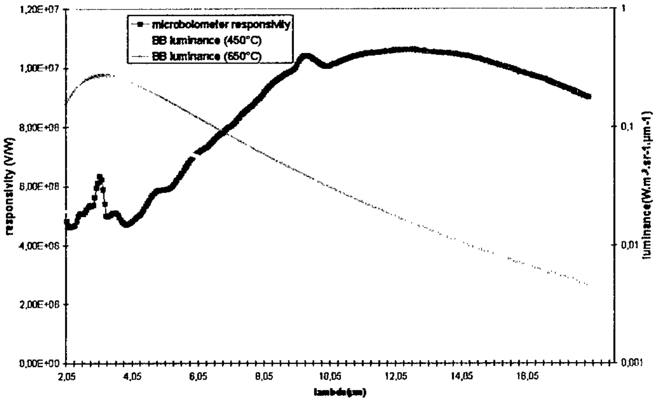


Fig. 3. Microbolometer Responsivity over the TIR Waveband

5.2. Noise Measurements

Because the microbolometer is a thermal detector, the photonic noise makes up only a minor part of the total noise. Therefore the greater the incident flux, the better the signal to noise ratio (SNR) will be, given the fact that the noise is independent of the signal. Referring back to figure 3, the SNR is, indeed, largely in favour of the MWIR for higher temperatures. The total noise rms has consistently been measured at 480 uV for the ULIS microbolometer array.

5.3. Noise Equivalent Power

In the MWIR waveband, as applied to on-orbit Earth observation, it is much more useful to examine the noise equivalent power (NEP) as opposed to the figure most often used in the LWIR, noise equivalent temperature difference (NETD). In the MWIR, mission areas are typically centred on distinguishing hot events from the dramatically cooler background so a focus has been given to NEP. Since it has been shown that the responsivity is approximately half that in the MWIR as the LWIR, we can assume it will take roughly twice the flux in this waveband to create an equivalent output signal. For a conservative estimate, if we take the normal operating flux for the microbolometer in the LWIR. For a 20 °C scene under f/1 conditions, we would expect the flux in the LWIR (8 to 14 µm) to be around 7×10^{-8} W. Doubling this requirement gives a conservative estimate for the MWIR NEP of 1.4×10^{-7} W. Without any atmospheric or optical losses, this would correspond to approximately a 210 °C blackbody viewed in the MWIR. This approximation has been confirmed experimentally where signals below 200 °C have been detected with reasonable contrast. Therefore 200 °C (or 1×10^{-7} W) has been determined to be a good value for NEP to use for the expected on-orbit performance in the next section.

6. EXPECTED ON-ORBIT PERFORMANCE

In this section, the data presented in section 5 has been used to calculate the expected on-orbit performance of the MWIR imager concept presented in section 4. To do this, atmospheric effects and optical transmission have been added to the laboratory data. The upwelling spectral irradiance (power per incident area per unit wavelength) from various brightness temperatures has the following form after they are propagated through a MODTRAN 3.7 mid-latitude summer atmosphere [9].

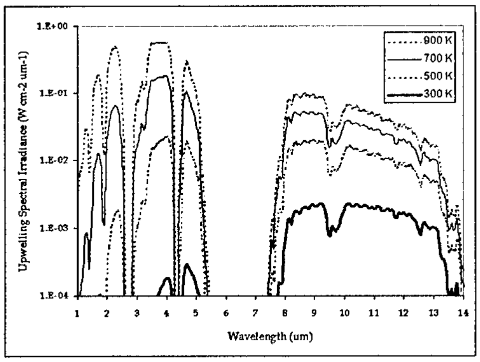


Fig. 4. Ground Pixel Brightness Temperature Profiles Across the Thermal Infrared

As can be seen, the signal strength becomes quite significant across the MWIR for temperatures above 500 K. In a direct application of the laboratory data presented in section 5, the following charts have been generated using the same atmosphere modelled above as well as a notional optical transmission of 80% across the waveband. For completeness, on-orbit curves are also shown for the same microbolometer array across the two candidate LWIR bands 8-10 um and 10- 12 um.

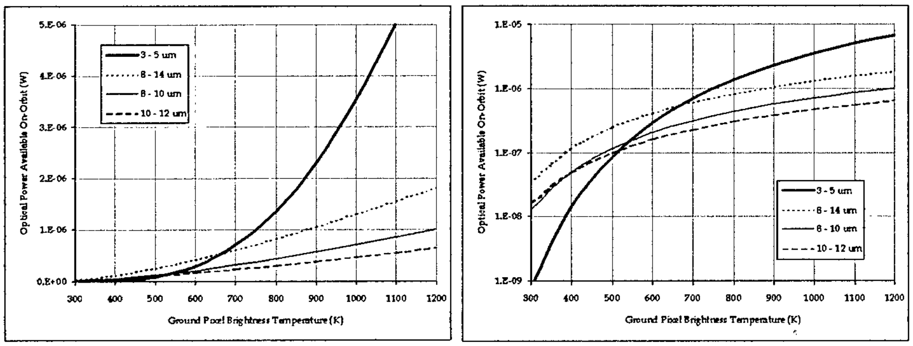


Fig. 5. Optical Power Available After Atmospheric Losses for Various TIR Wavebands and Brightness Temperatures

As the ground pixel's brightness temperature surpasses 660 K, the signal strength in the MWIR begins to surpass that in the LWIR (8 – 14 µm). This temperature drops to 535 K when compared to the smaller LWIR wavebands, 8 - 10 and 10 – 12 µm, which would typically be used over the - 14 µm band to allow for the application of split window algorithms. It is also notable that in the MWIR, the background signal, approximated here by a 300 K pixel, is much lower than in the LWIR. So, although there is a lower level of signal strength in the MWIR for cooler ground pixels, the signal gain can be amplified to a greater extent than in the LWIR, which also includes a strong element from the background. From the curves, it can also be seen that, on-orbit, the microbolometer pixel, using f/1 optics, would be able to begin to detect a ground pixel with a brightness temperature of around 550 K. Assuming that a ground pixel is at

300 K and partially consumed by a hot event, that pixel would de detectable when its effective brightness temperature crosses the 550 K threshold. What percentage of the ground pixel that would be required to be consumed by the hot event at a given temperature is illustrated in figure 6.

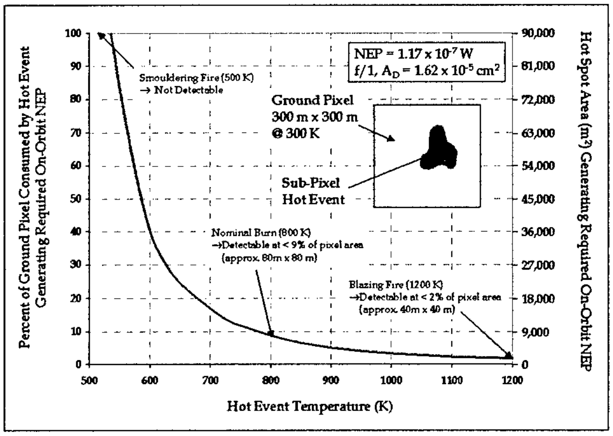


Fig. 6. Minimum Size Sub-Pixel Events Required for Imager Detection

As has been pointed out on the figure, a ground pixel needs to have a brightness temperature greater than 550 K even to be detected. That is, the entire ground pixel would have to be in the initial stages of smoldering combustion. However, as the temperature sub-pixel event increases, the pixel's overall signal strength increases considerably. By 600 K, only 40 % of the ground pixel would need to be consumed by the hot event and at 800 K, the temperature of a typical forest fire burn, this value falls to less than 9%. For an extremely hot event (e.g. volcanic eruption or flaming combustion) at 1200K, less than 2% of the pixel would need to be consumed for the imager to detect it. For the designed 300 m ground sample distance, this corresponds to a blazing fire 40 m by 40m.

7. ASSESSMENT: UNCOOLED TECHNOLOGY AND ON-ORBIT MWIR IMAGING

The authors realize that uncooled technology will, for the time being, continue to play only a minor role in the design next generation of MWIR space-based Earth observation instruments. The fact that a ground pixel needs a brightness temperature of at least 550 K to even be visible is considerably limiting in its ability to capture a large set of imaging requirements. For example, mission applications based on emissivity differences across the ground scene are simply not possible. The noise equivalent power is simply too high to compete with the firmly established cooled detector approach. However, there are niche applications for uncooled technology that are worth mentioning. The most obvious being the ability fly MWIR imagers on satellite platforms where they are currently prohibited. Rather than designing the MWIR channel as a major consumer of payload resources (space, mass, and power), uncooled technology would permit MWIR imagers to fly as a secondary or tertiary payloads. This means that fewer resources or risk will be associated with the MWIR payload. Hence, the MWIR imager could be more easily be customized or dedicated to serve niche, high scene temperature user communities.

Additionally, the ability to fly as a secondary payload increases the chances for integration into a Earth observing constellation—a concept yet to be realized using cooled technology. Perhaps until the benefit of MWIR constellations is appreciated by those controlling the funding resources, uncooled technology can help pave the way and demonstrate the concept at a significantly lower risk and cost. Lastly, a significant niche advantage is uncooled technology's significantly lower power requirements as compared with cooled technology. Because this MWIR imager is only pulling 1-2 Watts from the spacecraft bus, it can be operated continuously, an impossibility with an imager based on cooled technology. Operating continuously, MWIR imagers in constellation can autonomously canvas the globe for predefined criteria (hot spot thresholds, etc.). When this criteria is satisfied, additional sensors, including higher demand MWIR imagers based on cooled technology, can then be tasked to better characterize the area of interest.

8. CONCLUSION

In conclusion, uncooled detector technology (i.e. microbolometers) hold promise for certain niche applications for on-orbit Earth MWIR observation. It is recommended that uncooled technology be used for the MWIR, in conjunction with the LWIR, on small satellite missions where payload constraints would otherwise prohibit. As low-profile secondary payloads, the LWIR and MWIR data has potential to add low-cost and low-risk EO enhancements to existing remote sensing suites. Uncooled technology should also be considered for mission scenarios benefiting from constant operation (monitoring) as possibly a complement to higher performance sensors based on cooled detectors.

Lastly, as the commercial microbolometer industry continues to make advances on detector performance, the on-orbit MWIR EO mission area should be periodically revisited. Although thermal detectors are fundamentally limited, their advantages regarding power consumption and simplicity should keep them on the list of candidate MWIR detectors for future low-cost EO missions.

9. DISCLAIMER

The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

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