REAL-TIME WILDFIRE DETECTION FROM SPACE - A TRADE-OFF BETWEEN SENSOR QUALITY, PHYSICAL LIMITATIONS AND PAYLOAD SIZE

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ABSTRACT:

Wildfires cause large scale devastation to human settlements and forests every year and their frequency and severity is on the rise. A major reason for this devastation is the significant delay in their detection due to their remote locations in forests. To mitigate this, a constellation of nanosatellites in Low Earth Orbit (LEO) equipped with multi-spectral visible to Infrared (IR) cameras is proposed leveraging the modular and affordable architecture of CubeSats. Coupled with the payload design, meticulously planned constellation and a ground support system, all surface points on the planet will be revisited at least once in an hour. Capturing a surface location with a high resolution in Mid Wavelength Infrared (MWIR) and Long Wavelength Infrared (LWIR) allows a precise estimation of thermal output of the surface. Simulations indicate that a fire of about four hundred square meters can be easily detected from this satellite payload. Through onboard data processing, wildfires can be already detected in space, minimizing bandwidth requirements for real-time alerts. This enables an early wildfire warning within 30 min by utilizing existing satellite internet networks. Additionally, compressed raw images will be transmitted on fixed ground station passes to provide a global thermal data updated every 90 min. The near real-time multi-spectral data provides opportunity for several other applications like weather forecasting besides wildfire detection.

1. INTRODUCTION

Human control of fire was the spark that drove the modern civilization hundreds of thousand years ago. It is tragic that mankind's inability to control the widespread wildfires are causing devastation of lives and property at an unprecedented rate. Wildfires are unpredictable, they occur due to human activity, lightning strikes or simply a dry sunny day (Liu et al., 2010). Our inability to control them stems from the long delay in detecting the wildfires early enough. With favouring winds and slopes, a wildfire front can move as fast as $15\,\mathrm{km\,h^{-1}}$, quickly covering large forest areas such as the south-eastern Australia in February 2009 (Cruz et al., 2012).The massive wildfires in California and Greece in 2018 have shown that despite the efforts and vigilance, they remain hard to monitor and control. Early detection of wildfires is paramount to their management and mitigation (Sifakis et al., 2011). Surveillance by means of drones, aircraft and watchtowers have still proven inadequate for their detection. The current generation of satellites, while highly capable of identifying wildfires, lack the spatial or temporal resolution to achieve timely detections.

Among the current missions, notable mention would be Compact Infrared Camera (CIRC) from Japan which was a LWIR imager (Katayama et al., 2009). The other mission would be the German FireBIRD Earth Observation (EO) mission with MWIR and LWIR images on their satellites in 570 km LEO (Lorenz et al., 2015). Another notable instrument is the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Adminstration (NOAA) whose data has been used for a wildfire detection system (Plank et al., 2017).

A project for real-time wildfire detection in Australia was tested using the Himawari-8 geostationary satellite (Xu, Zhong, 2017). Data from other geostationary satellites equipped with IR imagers like Meteosat Second Generation (MSG) and Geostationary Operational Environmental Satellites (GOES) have also been used for rapid detection of large, fast growing wildfires (Sifakis et al., 2011). Although designed for EO, some of the Sentinel missions of the European Copernicus program also provide the necessary data for detecting wildfires. Concepts also exist for detection using the Potassium signature for biomass burning (Wooster et al., 2013).

While these EO satellites are capable of detecting fires, they are individual systems not integrated with other sources such as drones, watchtowers, etc. The satellites provide a single view of earth's surface at one point in time with their own data downlink-processing-analysis-distribution systems. For users in need today, it is prohibitively slow and expensive to detect wildfires using EO satellite resources.

2. CHALLENGES

The problem of satellite based wildfire detection has both resolution challenges: spatial and temporal. The Rayleigh criterion determines the maximum achievable angular resolution θ (in rad) with the optical aperture D (in m) for wavelength λ (in m).For a 3U CubeSat, the largest physical aperture feasible is around 8 cm as remainder space is required for mechanical parts and other satellite systems.

$$\theta = 1.220\frac{\lambda}{D} \tag{1}$$

However, the spatial resolution, also known as Ground Sample Distance (GSD), is determined by the detector specifications, the focal length and the orbital altitude. The GSD cannot be

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better than the value calculated using Rayleigh limit and altitude, which is worse in higher wavelengths like the Thermal Infrared (TIR) spectrum.The revisit time is mainly determined by the field of view and orbital periods which can be permanent with a geostationary satellite to once in several days for a low earth orbit satellite. However, the geostationary orbit is 36 000 km from the surface, too far away to achieve useful wildfire detection. For example, to attain 200 m GSD at 12 µm wavelength, the aperture must be 2.64 m, quite large even for a conventional satellite. When the satellite is in LEO, say 500 km to 800 km altitude, the aperture requirements become much more reasonable, 36.5 mm to 58.5 mm. These dimensions are better suited for payloads aboard nano-satellites, with field of view and scanning patterns tuned for the required swath on ground.

The other challenge is meeting the temporal resolution requirements for wildfire detection. With supporting winds and topography, wildfires spread at a blistering pace which requires almost real time monitoring. However, the initial build up of a wildfire can take quite long without winds and their probable occurrence can be predicted to some extent by the prevalent weather conditions (Liu et al., 2010). Finding the optimized revisit time is about balancing the relative threat by wildfire size and vulnerability in the Area of Interest (AOI). This can be achieved by improving payload's field of view, orbital manoeuvring and increasing number of satellites in the constellation.

3. CONCEPT

The technology for thermal imaging has existed and has been optimized over decades for primarily military and aerospace applications. In the last decade, the commercial availability of thermal imagers has driven the costs down by a large amount. These commercial devices do not offer the sensitivity of detectors used in conventional applications, but could be suitable for low cost imagers on nano-satellites. The use of commercial devices provides a low cost solution for thermal imaging at the cost of sensitivity which could be suitable for detecting high temperature events like wildfires, urban heat islands etc. The low cost also drives down the cost of a constellation compared to a single large satellite.

3.1 The constellation

A preliminary analysis using a Walker Star design similar to the Iridium constellation was done. The AOI for wildfires are mainly in the latitudes between 81° N to 60° S. Using an 80° inclination of orbits and estimated 205 km as the swath, 160 satellites are required to achieve revisit time of 60 min on the equator, with much shorter intervals at higher latitudes. Further constellation designs like Walker Delta, Streets of Coverage could be more appropriate depending on AOI. Also, a smaller number of satellites could be deployed to cover specific AOI with better temporal resolution. By using satellite pointing manoeuvres, this can be further improved. This publication focuses more on the individual CubeSat design focusing on the payload and feasibility of wildfire detection.

3.2 CubeSat architecture

The CubeSat architecture has revolutionized the miniature satellite industry with standardized volume and mass. A unit cube with a 10 cm side length is the modular base for satellites of size 1U, 1.5U, 2U, 3U, 6U, 12U and so on. For example, a 3U satellite is approximately 30 cm by 10 cm bx 10 cm volume. A large number of small and big companies now sell parts, subsystems, structures and even entire satellites specifically designed for CubeSat missions. Due to the relatively low costs, a new generation of space missions have been accomplished even as university projects (Heidt et al., 2000).

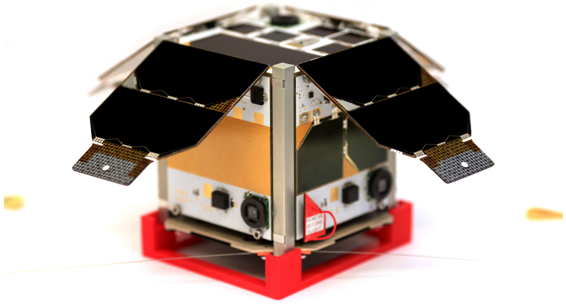

Figure 1. Munich Orbital Verification Experiment (MOVE) II engineering model (The MOVE-II Project, 2017)

One such student-led project was initiated in 2006 at Technical University of Munich (TUM), called MOVE (figure 1) (Langer et al., 2017). Three 1U CubeSats are already in orbit under the tutelage of MOVE and this project could be termed a spin-off application. For example, the power modules developed for MOVE were modified to be modular and extendable for 3U or 6U buses. For the 3U concept proposed here, the power budget estimation shows a nominal average requirement of 15 W which can be further reduced with AOI specific duty cycles. The available power depends on the orbit, attitude and panel architecture, with conservative estimates suggesting 12.5 W average power generation during normal pointing operation. Various components and parts such as communication, Global Positioning System (GPS), electronics, Attitude Determination and Control System (ADCS), etc. are at different stages of development or off-the-shelf equipment integrated into the bus. The novel CubeSat architecture provides up to 60 % space for the payload and increases reliability compared to commercially available CubeSat platforms (Grübler, 2017).

3.3 Payload

The primary payload is the largest component consisting of the IR camera and the Payload Processing Unit (PPU). They form the heart of the wildfire detection capability that this concept is based on. A secondary payload is a visible to Near Infrared (NIR) camera which augments the primary payload data with about half the GSD. The PPU receives information from both the cameras in addition to the precise time, orientation and location information from the satellite bus. The PPU creates geo-referenced data from all sources and stores the data for relevant AOI which is transmitted on next ground station pass.

Relevant AOI could be programmed into these satellites, even on demand. It could be any area that is relevant such as known high wildfire threat areas. During a dry and hot weather prediction for a region, those AOI can be broadcast to the satellites for extra vigilant monitoring. The forests known to have surroundings inhabited by people and property are of particular interest. A network of ground stations is required to receive the large amount of data generated by the constellation.

3.4 On-orbit processing

To prevent the cycle of downlinking all satellite data and to improve the response time for warning notifications of wildfire detections, the PPU also analyses the geo-referenced thermal data onboard for each GSD observed. When a relatively hot pixel is detected in the AOI, the system does not wait for the data to be transmitted and analysed on ground. Instead, the satellite sends a short message with the possible wildfire location information over an orbital connection such as the GlobalStar network. Such networks have a wide coverage in orbit allowing all detections to be quickly downlinked and relayed to the end-user in a matter of minutes. The bulk pre-processed data captured by all satellites in the constellation is downlinked over subsequent ground station overpass in roughly 60 min to 90 min.

A downside to on-orbit processing is the much higher power consumption. A load estimate shows it is feasible to manage this increased power requirement within this design. A possible wildfire detection also automatically changes the operating mode of satellites covering the AOI to active tracking. In this mode, more data is captured per GSD to improve the accuracy and reduce noise.

4. RADIOMETRIC SIMULATION

For the basic radiometric analysis, an emitting source on the earth's surface is simulated. As imager focuses on TIR spectrum only, this source can be approximated by a black body. The emission of a black body is described by the Planck's law:

$$B_\lambda(\lambda, T) = \frac{2 \cdot h \cdot c^2}{\lambda^5 \cdot (\exp(\frac{h \cdot c}{\lambda \cdot K_b \cdot T}) - 1)} \tag{2}$$

Where λ is the wavelength of the radiation, T the temperature of the surface, c the speed of light, h the Planck's constant and K_b the Boltzmann constant. By integrating the Planck's law over the wavelengths in spectrum of interest and the solid angle, the emission of radiation in the direction of the IR camera can be calculated. This is only valid for an ideal black body, thus for earth's soil its specific emissivity should be factored in.

For a realistic simulation, environmental influences need to be taken into account. The given sensitivity of the sensor and the given losses while going through the lens system are included in the calculation. Furthermore, the radiation has to pass the atmosphere and a MODerate resolution atmospheric TRANsmission (MODTRAN) dataset is used to calculate the atmospheric transmission (Berk et al., 2014). The relative transmission of IR radiation in the 1 µm to 14 µm spectrum through Earth's atmosphere is shown in Figure 2. As this data is not continuous, the atmospheric transmission coefficients were included in small steps while integrating the Planck's law.

The two highlighted atmospheric transmission bands with maximum intensities are used for further calculations: MWIR 3 µm to 5 µm and LWIR 8 µm to 12 µm. Figure 3 shows the incident power in these bands on each pixel of the thermal imager dependent of the earth's soil temperature. In this simulation the observed area is 40 000 m^2 per pixel from an altitude of 600 km and the aperture size is 8 cm. Additionally, a first estimation of the sensitivity limit of the thermal imager is introduced.

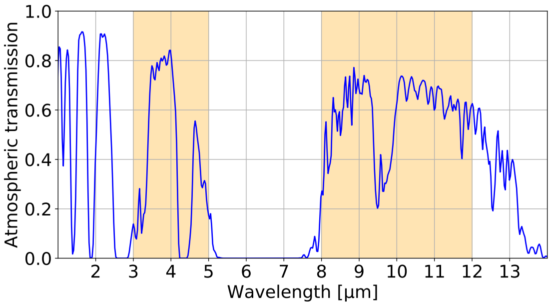

Figure 2. The relative atmospheric transmission in the IR spectrum, the two bands with least absorption are highlighted.

The figure shows that there is lower incident power in the 3 µm to 5 µm band which is only detectable by the sensor after 270 K but increasing rapidly towards higher soil temperatures. In the 8 µm to 12 µm band, the radiation can already be detected at 150 K. After 650 K the incident power in the MWIR band exceeds the incident power in LWIR band. This enables the thermal imager to get more information about higher temperatures on earth.

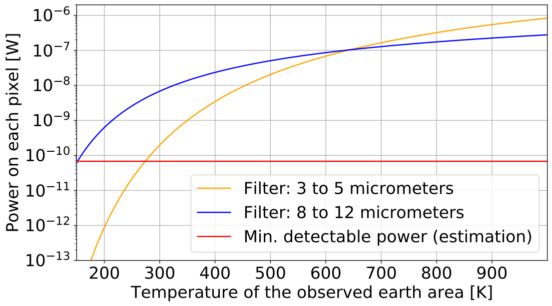

Figure 3. Simulation of incident power on each pixel of the thermal imager as a function of earth's soil temperature.

The main goal of the thermal imager is detection of wildfires on earth. To simulate sub-pixel fires, a fraction of the observed area has an increased temperature. In Figure 4 a simulated spectrum is depicted which shows emission of normal soil and soil with a fractional fire included, both observed after the atmosphere. The soil temperature is set to 300 K and the fire is estimated to have a 1000 K temperature covering 1 % of the area. In 8 µm to 12 µm, there is a marginal difference in intensities with and without the sub-pixel fire. However, in 3 µm to 5 µm the power density is a magnitude higher and therefore a promising spectral band to detect wildfires.

To sum up the radiometric analysis, the IR imager can detect very low temperatures in the 8 µm to 12 µm band and allows soil temperature measurements. The detection of fires is achievable in the 3 µm to 5 µm band as it shows much higher intensities at fires which are detectable by the thermal imager. Thus, these two bands increase the dynamic range of the whole imager and gives significant improvements in the use case of fire detection. A more complex model could be simulated by incorporating topography, relative emissivities, water bodies, floral composition etc. However, even with conservative estimates of radiant intensities and their measurements, fire detection using a cost effective dual band TIR imager is feasible.

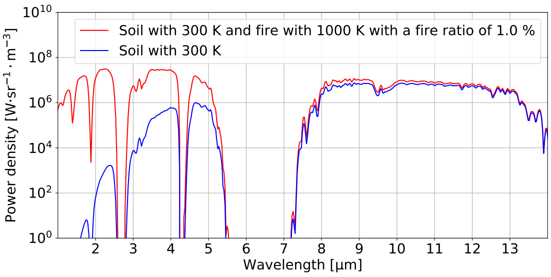

Figure 4. Simulation of the power density after the atmosphere at varying wavelength emitted by soil with and without fire.

5. INFRARED DETECTOR

The IR camera is a multi-spectral imager measuring incident power in at least two TIR bands, mid-wave and long-wave. A 50 mm optic results in a resolution of 204 m from 600 km orbit and 17 µm pixel pitch. The sensor itself is a micro-bolometer Extended Graphics Array (XGA) sized array with a 17 µm pitch, wideband 3 µm to 12 µm response and 50 mK Noise Equivalent Temperature Difference (NETD). The sensor area is divided into two zones with different spectral filters MWIR and LWIR. A mechanical shutter with a temperature sensor and high emissivity black body coating operates as a sun shield and calibration surface.

There are several kinds of IR detectors in the market depending on the spectrum and sensitivity required. The common principle behind all detectors is absorption of the radiation in a spectrum of interest. The absorption leads to a change in some physical property which can be measured, such as increased temperature leading to a change in the electrical resistance. Cooling is often required as the temperature of the detector itself causes it to emit some IR radiation which results in measurement noise. Thus, the IR detectors are broadly divided in two types: cooled and uncooled detectors.

The cooled detectors usually operate in temperature ranges of 4 K to 250 K leading to exorbitant power requirements. The most common cooled detector for thermal imaging is Mercury-Cadmium-Telluride (MCT) based detectors which is a narrow gap semiconductor. MCT is special because it detects radiation in both thermal atmospheric windows, 3 µm to 5 µm and 8 µm to 12 µm. Quantum well IR photodetectors also exist for extremely high sensitivity and they also operate in cryogenic regimes. For 3U CubeSat operation, cooling to cryogenic temperatures is not a good option due to the extreme power requirements.

Uncooled detectors are usually maintained at an ambient operating temperature and a change in their electrical properties due to heating on absorption of thermal radiation is detected. Most commercial thermal imagers today are based on the uncooled micro-bolometer technology with the 12 µm pixel size being commercially popular. The military applications for a miniature thermal imager has led to work on 5 µm pixel pitch but they remain a challenge. Micro-bolometers have proven they can detect wildfires from the data in LWIR as in the CIRC mission. They are also planned for use in another LWIR only imager in Technical University of Berlin Infrared Nanosatellite (TUBIN) mission scheduled for launch in 2020 (Barschke et al., 2017).

While micro-bolometer offers significant advantages in weight and power consumption, they have a thermal time constant, the time to absorb radiation and heat up. Most commercial micro-bolometers have about 10 ms to 20 ms of time constants, and about 3 time constants are required to stabilize to 96.5 % of the final value. For satellites, this raises the concern of motion blur, as the ground speed of camera is 7 km s^{-1}. So in 30 ms, the satellite would have moved 210 m already, about the same as one GSD. Also, micro-bolometers have much lower sensitivity in MWIR bands as they are designed to have highest performance in LWIR bands (A. Crastes et al., 2013). However, they still have some sensitivity in the MWIR bands and that can be used for this particular application as the MWIR intensity of a fire is also higher.

6. OPTICAL DESIGN

For this application, a 17 µm pixel pitch on the micro-bolometer is better as the optical requirements become more manageable. With aprroxima 70 mm aperture, to achieve 200 m resolution at the 600 km orbit, for 12 µm pixel pitch the optics must be 36 mm f/0.52 system, a difficult lens design, specially for broadband spectrum from 3 µm to 12 µm. With 17 µm pixel pitch, it is 50 mm f/0.72 system, still challenging but more reasonable in terms of cost and feasibility for this mission.

To compare, the CIRC mission used a 78 mm f/1.2 lens with a detector pixel pitch of 25 µm (Katayama et al., 2010). The conventional approach is using a more sensitive cooled detector with scanning such as the whisk broom technique used by several large satellites. The advantage is large swath and good resolution but at a significantly higher cost due to the expensive detector, high power requirements, and consequently larger launch mass. However, sub-pixel sized wildfires can be detected since they have larger intensity in the MWIR band.

Designing a thermal imaging lens which works from 3 µm to 12 µm band is a challenge, but has been accomplished for a military application: IR missile seekers. The broadband lens design is quite challenging as the most IR materials such as Germanium, Zinc Selenide have large variation in their refractive indices over this spectrum. Missile seekers are usually cooled detectors with the modern state-of-the-art systems having dual-band sensitivity which require similar broadband optical design. Athermalization is quite challenging as the dispersion due to change of temperature is quite large over the standard operating temperatures of satellites. This is a highly sought after technology since aerospace applications benefit from such having thermal stability, specially in military applications. (Uçar, Kabak, 2010)

There are several options to achieve detection in two bands: have array of two detectors with unique filters for one each; use a multi-zone filter on one detector; use a beam-splitter with two detectors. Each approach has its advantages and disadvantages, for example, a high f-number system causes the interface of two filters to have a cross-talk region in a multi-zone filter design. This leads to a large part of the detector to be unusable. A high f-number system is also problematic for the beam-splitter design as the detector side working distance is not that large. Arraying of detectors is a common approach, but that increases the image size requirements and consequently, the optics must be quite large as well. For the CubeSat form factor, two detectors are feasible to be placed with one filter for each of them.

7. CONCLUSION

A CubeSat constellation with thermal imaging camera and an extensive ground support system is proposed to streamline rapid wildfire detection to end-user notification. Wildfires need quick detection to prevent their propagation into a large-scale catastrophe. A low-cost solution for thermal imaging is to use uncooled micro-bolometer technology. Wildfires have peak intensity in MWIR band whereas ambient temperatures on earth have peak intensities in LWIR band. By using dual band IR detectors, sub-pixel wildfires can be detected using by correlating MWIR and LWIR measurements. Designing a satellite with IR imager working in 3 µm to 12 µm spectrum is difficult but feasible. Radiometric analysis and study of existing satellites suggests it is feasible to build the proposed satellite to detect wildfires as claimed. The thermal stability of the IR imager and CubeSat would be a challenge to function over its targeted lifetime in space. Athermalization simplifies the imaging design to some extent and the thermal stability of the imager including detector and its optics is critical to peak performance. The first satellite is planned for launch in late 2020 with the data available for research purposes.

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