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Asteroids to Agriculture: Carving a Niche in Earth Observation Using Asteroid Prospecting Instruments on an Earth-Orbiting Cubesat Constellation

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ABSTRACT

Recent years have seen increased the development of concepts for constellations of SmallSats or Cubesats for Earth Observation remote sensing. These constellations focus on visible RGB imagery or multi-band imagery from a handful of wide-bands in the visible or near infrared wavelengths. Mid-wave infrared (MWIR) data provides a unique measurement, able to image both during the day and night. Recent developments in infrared detectors and the miniaturization of cryocooler technology enable this instrument to be packaged in a Cubesat form-factor.

Planetary Resources is developing a MWIR instrument (3-5 μm) for the purpose of prospecting near-Earth asteroids, particularly in the detection of the presence of water. In turning the gaze of the sensors to nadir from low-Earth orbit, a unique dataset is created that is currently lacking from existing commercial Earth observation platforms. Data products derived from the MWIR measurement are beneficial in agricultural decision-making process, especially in irrigation and water use.

Planetary Resources is launching two 6U spacecraft, the "Arkyd-6", which house a demonstration of our MWIR instrument. The 6U form-factor spacecraft accommodates an instrument sized just over 1.5U in volume. This demonstration is the first commercial use of MWIR imagery from low-Earth orbit. Ground resolutions of 15m per pixel are possible by increasing the size of the spacecraft to a 12U form-factor. At that resolution, actionable data is available at a scale that is relevant to agribusiness, as an indication to inform crop health and development.

This paper presents the MWIR instrument and its evolution. This includes spacecraft accommodation, measurements from low-Earth orbit and its potential for near-Earth asteroid exploration.

BACKGROUND AND INTRODUCTION

For the last few years, Planetary Resources has been developing the Arkyd line of spacecraft for the goal of prospecting and eventually mining resources from near-Earth asteroids. The Arkyd series spacecraft are an evolutionary platform, beginning with technology demonstration missions with the aim of producing a capable and robust deep-space robotic explorer.

The primary resource of interest to be obtained from near-Earth asteroids is water. Water in space is essential for exploration. It can be used in its components as rocket fuel, as radiation shielding, as well as primary to the needs of sustaining life.

Mid-wave Infrared (MWIR)

The wavelength from 3-5μm defines the mid-wave infrared portion of the electromagnetic spectrum. The MWIR measurement is comprised of reflected light as well as thermal emissive signal (see Figure 1). This allows for instrument imaging at night when a target's thermal signature can be detected. Imaging during the day will reveal additional information from reflected solar energy, based on the surface properties of the scene target. Historically, this measurement has been used for military applications with heat seeking needs.

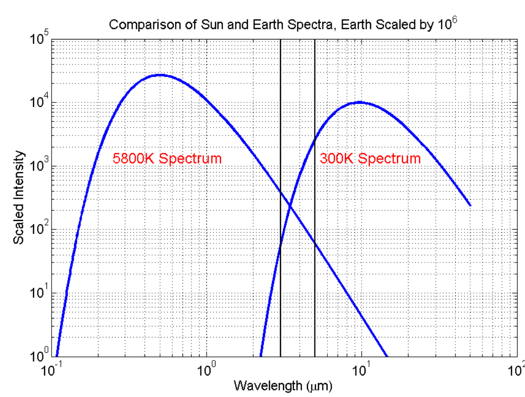

Figure 1: Sun and Earth Spectrum in the MWIR shown in relative flux from a terrestrial target

Thermal infrared measurements are commonly performed in the Long-wave Infrared (LWIR), but Planck's curves show that the MWIR the amount of emitted signal varies more as a function of temperature, allowing for more scene contrast at Earth surface temperatures (see Figure 2).

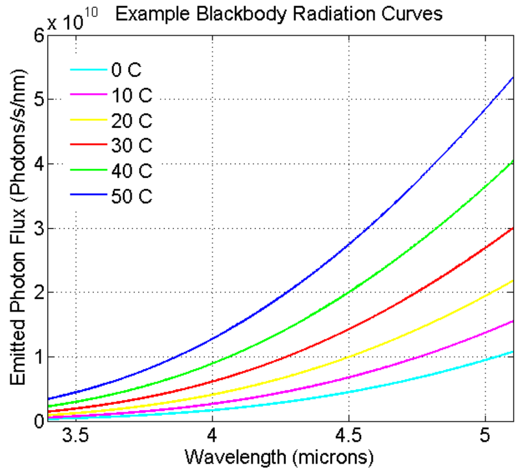

Figure 2: MWIR Blackbody Radiation Curves

Midwave infrared detectors are typically made from indium antimonide (InSb) or mercury cadmium telluraide (HgCdTe) and are required to be cooled to cryogenic temperatures for operation. The need for an active cryocooler in a small form-factor spacecraft provides added design and operational challenges in a CubeSat.

MWIR REMOTE SENSING FOR ASTEROIDS

With Planetary Resources' goal to mine near-Earth asteroids for water, the ability to identify and quantify the amount of water on an asteroid is crucial for success. Study of meteorites believed to be asteroid material, teach us that visible spectrum observations are able to disprove presence of water bearing material on an asteroid; however proving the presence of water requires additional spectral information.

Because asteroids are in a vacuum and near the sun, water exists in the form of hydrated minerals, not ice. Phyllosilicates (clay is an example of a phyllosilicate) can retain up to 20% water by mass over the age of the solar system in a space environment. We know this from analysis of meteorites that have landed on the Earth [1].

Asteroids are commonly studied with infrared spectroscopy and while the specific water bands at 3.1μm are obscured by the water in our atmosphere, significant work has been done to fit the profiles of the water absorption bands (specifically, O-H bonds) for many asteroids. Importantly, with multiband imaging of an asteroid body from 2.9 to 3.4 microns, we can determine if the feature is due to hydroxyl molecules, a poor source of extractable water, or actual water and provide an estimate for the amount present in the material. As [2] clearly demonstrates with spectra taken from meteorite samples in the lab (see Figure 3).

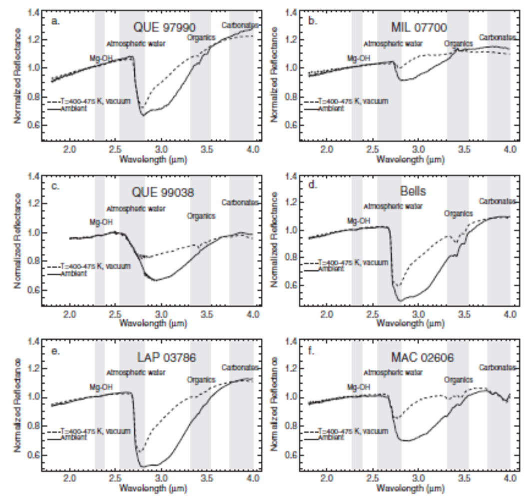

Figure 3: Variations of the hydration feature on meteorites [2]

The size and shape of the absorption feature are accurate, repeatable measures of the level of hydration present on the surface of the asteroid. A series of images with different transmission filters provides a sample of the water feature over the entire asteroid.

In addition to measuring the water content using reflected sunlight at the short edge of the MWIR bandpass, monitoring the thermal temperature on the asteroid provides information about material cohesion and structural concerns.

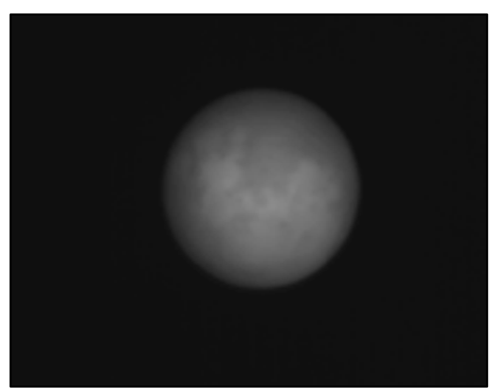

Figure 4: MWIR Picture of the Moon (Taken with Arkyd-6 Flight Instrument)

MWIR REMOTE SENSING FOR AGRICULTURE

Historically, remote sensing for agriculture purposes have used data from Landsat and similar spacecraft to create the Normalized Difference Vegetative Index (NDVI). This index is created from the relative difference of signal between the near-infrared and the red band of the electromagnetic spectrum as shown in Equation 1 below.

$$NDVI = \frac{NIR - R}{NIR + R} \quad (1)$$

NDVI works because at near-infrared wavelengths, photons are reflected by the organic molecules of healthy plants resulting in a larger signal with respect to the visible spectrum. Unfortunately, soil, canopy cover, and other spectral effects of the plant influence NDVI measurements and obscure the metric being evaluated.

Another drawback of NDVI is that it typically provides a late indication of plant stress. This lagging indicator provides information after damage to the plant is irreversible, limiting the actions a grower can take to mitigate loss. Conversely, plants typically show early indications of stress through thermal differences due to reduced evaporation [3]. The first response to stress is to close the stoma of the leaves which increase the temperature of the leaf. The sensitivity of temperature in the MWIR makes it a good measurement for plant stressors at a stage when a grower still time to take appropriate action.

In addition to measurements of plant health, MWIR measurements can assist in bare-soil fields to locate relative water moisture inconsistences. Thermal indicators of bare soil can be the effect of soil type inconsistencies across a field (sandy, loamy, clay), or effects of irrigation, drainage, and tiling.

Earth-Observation Imaging

As mentioned previously, the Earth's atmosphere absorbs the 3.1μm water band of specific interest for detection of hydrated minerals at asteroids. Further reducing the measured signal is a CO2 notch in atmospheric transmittance around 4.3μm, making Earth-based MWIR remote sensing complex then that at an asteroid.

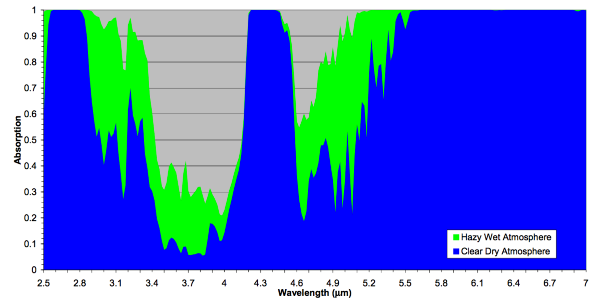

Figure 5: Earth Atmospheric Absorption [4]

Although the signal MWIR received at the detector is attenuated, it is possible to extract radiometric information by compensating for Earth's atmospheric effects.

One advantage of the MWIR measurement over many other common Earth observation sensors is that it is capable of 24/7 operations for day and night imaging.

FIELD RESEARCH AND DEVELOPEMNT

For more then a year, Planetary Resources has been conducting a research and development field campaign built around understanding the MWIR instrument and its measurement. A test system has been built for accommodation on a manned aerial platform, compatible with common Cessna airplanes. An on-board operator is responsible for controlling the instrument and sensor package while the pilot flies prescribed GPS flight lines over ground targets of interest. This aerial test campaign allows for the collection of data to understand the MWIR measurement over relevant targets and develop products that can be derived from an Earth-observing spacecraft platform.

Aerial Test System Hardware Complement

The aerial test system consists of the MWIR instrument. A commercial optic is used to attempt to mimic the ground resolution of an orbital instrument. As an airplane flight altitude is significantly lower then a low-Earth orbit spacecraft, the aerial platform ends up with higher ground resolution, which is post-processed to emulate spacecraft measurements.

In addition the MWIR instrument, the aerial sensor suite consists of a color (RGB) camera for contextual information, a NDVI-filtered camera, as well as a GPS/INS system to aid in the geometric registration of the images collected.

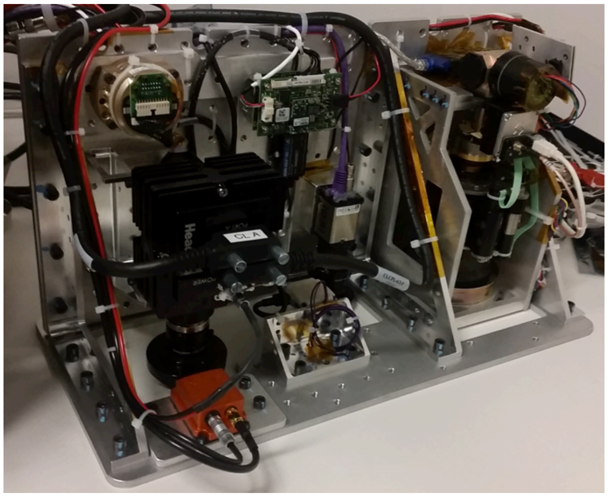

Figure 6: Aircraft Sensor Pod Hardware Suite

A CessnaCam Pod made by Airborne Scientific is used to mount the sensor package to the belly of compatible Cessna airplane models, common to many aircraft rental services.

Figure 7: Cessna 172 with Belly-mounted Pod

Aerial campaigns consist of flights in the day and at night to compare the thermal emissive signal to that which includes a solar reflective contribution. In addition, the diurnal pair allows for measurements of thermal inertia.

2016 Growing Season Aerial Campaign

The 2016 agricultural growing season is a focus of the research and development effort to specifically address two questions in the assessment of the MWIR instrument's viability as an agricultural crop-monitoring tool:

- How well does the MWIR instrument identify meaningful differences of soil moisture within a field?
- How well does the MWIR instrument identify thermal anomalies in a field that are indicative of plant stress?

To answer these questions, ground truth measurements of soil moisture, temperature, and canopy temperature are collected along with the aerial sensor measurements.

Planetary Resources has partnered with local growers to allow field access for proper ground truth measurements to be made, as well as provide expert knowledge in the growth and development of seasonal crops. MWIR aerial images throughout testing are shared with the growers to help determine what the causes are for thermal differences as seen in the images.

Figure 8 shows a daytime image taken from the MWIR instrument of an early-season center-pivot irrigated field. The lighter areas of the image indicate portions of the field that have sandier soils. At these locations, the early stage growth of the corn showed it lagging behind the rest of the field, a potential predictor of decreased yield.

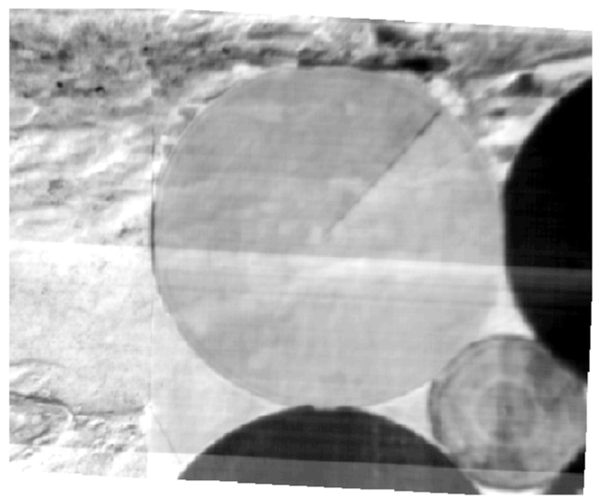

Figure 8: MWIR Image of Center-Pivot Irrigated Corn Field (Early Season)

In-field ground truth measurements were collected simultaneously with the aerial flights within a flight campaign. These ground truth measurements were geospatially referenced along with the MWIR flight data for comparison and correlation.

In addition to the real-time measurements, soil samples were taken of specific fields and sent to a laboratory for measurement of emissivity across the MWIR spectrum. Average emissivity across the soil types was between 0.79-0.90 from 3.4-5.1μm.

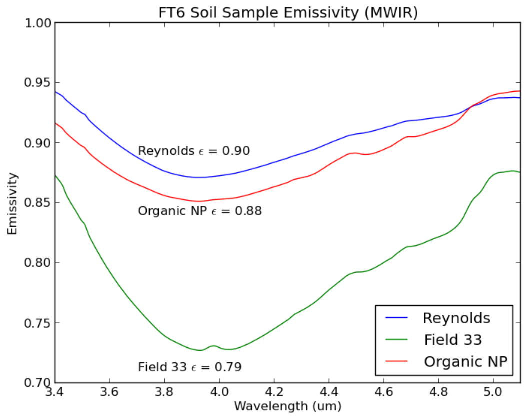

Figure 9: Soil Emissivity in the MWIR Over a Sampling of Fields

FLIGHT INSTRUMENT DEVELOPMENT

The Arkyd spacecraft MWIR instrument as described is built around an indium antimonide (InSb) detector, cooled via sterling cryocooler to cryogenic temperatures of 77K. The Integrated Dewar and Cryocooler Assembly (IDCA) is the core of the instrument and remains constant, while the front-end optical assembly is modified based on the platform (aerial test vs. 6U CubeSat vs. 12U CubeSat spacecraft).

Table 1: MWIR Instrument Characteristics

Parameter	Aerial	A6	A100
Spectral Range	3.4-5.1 um		
Array Size	640x512		
Focal Length (effl)	17mm	200mm	720mm
Ground Footprint	1.9km x 1.5km	19km x 15km	7.3km x 5.8km
GSD	3m	>30m	15 m

The common IDCA camera core allows for experience with the detector technology and its readout and software common to all flight and test platforms.

Arkyd-6 Technology Demonstration

The first demonstration of Planetary Resources' MWIR instrument in space will be as part of the Arkyd-6 spacecraft. Planetary Resources has built two identical 6U form-factor CubeSats, both manifest to fly on separate launches within the next year. The NOAA imaging license granted to the Arkyd-6 spacecraft is the first known license granted for commercial MWIR imaging from low-Earth orbit.

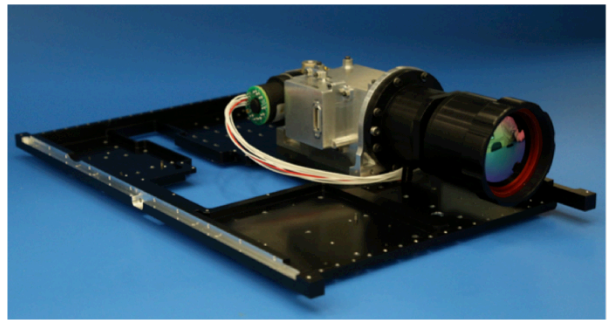

Figure 10: Arkyd-6 Instrument Assembly

The Arkyd-6 spacecraft serves as an overall technology demonstration platform for Planetary Resources. In addition to hosting the MWIR instrument, the spacecraft is made of custom-designed power and avionics as well as in-house built ADCS sensors and actuators.

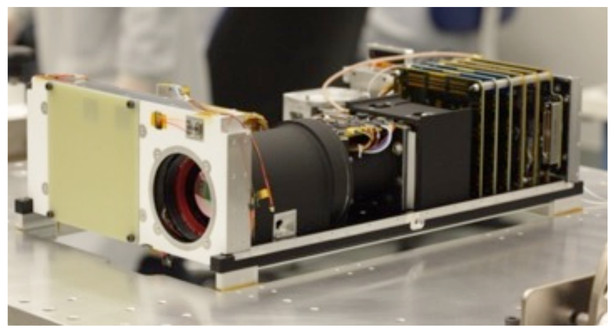

Figure 11: MWIR Instrument Mounted in Arkyd-6 Spacecraft Assembly

The ground resolution of the Arkyd-6 MWIR instrument will vary between 30-70m based on orbital altitude. Due to the modest ground resolution, the Arkyd-6 mission objectives serve as technology pathfinders, verifying the operation of the MWIR instrument core in a spaceflight environment, and validating the instrument data processing chain from collection on the spacecraft through processing on the ground.

Arkyd-100 Demonstration

In order to achieve the ground resolution necessary for agricultural purposes, a larger optic diameter is required then can be fit in the physical constraints of a 6U CubeSat form-factor. For this reason, the Arkyd-100 spacecraft will expand to a 12U CubeSat form-factor. This allows for a MWIR instrument with an 8" diameter optic, capable of achieving 15m GSD from 550 km sun-synchronous orbit.

Figure 12: Rendering of Arkyd-100 Spacecraft in Low-Earth Orbit

The form-factor of the Arkyd-100 spacecraft enables larger surface area for solar arrays, allowing more power, which in turn provides more computational abilities. Higher power and higher bandwidth communication architectures are also enabled by the 12U platform.

A pathfinder of the Arkyd-100 spacecraft will demonstrate the on-orbit MWIR product necessary to achieve commercial viability for an Earth observation agricultural market.

CERES CONSTELLATION

The Ceres constellation will be the first constellation of commercial MWIR-capable spacecraft for the purpose of Earth observation from Low-Earth Orbit. The Ceres constellation consists of ten Arkyd-100 spacecraft placed in a Sun Synchronous Orbit. Mission design demonstrates that a daily revisit of ground target locations is achievable for a diurnal (day/night) MWIR image pair. Accounting for weather obscurations, this cadence allows for a weekly distribution of a thermographic image product to agricultural customers around the world.

SUMMARY

Through laboratory testing, aerial testing, and spacecraft instrument flight development and qualification, Planetary Resources has shown that the MWIR measurement has commercial viability in the Earth Observation market. Originally selected for its utility for asteroid prospecting, the MWIR instrument provides benefit to the global agricultural industry. The development and iteration of the MWIR instrument and the Arkyd series spacecraft provide key opportunities in Earth orbit, prior to the exploration and prospecting of near-Earth asteroids.

Acknowledgments

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