EVALUATING THE UTILITY OF LOW-COST SENSORS FOR DEEP SPACE APPLICATIONS.

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Introduction: Red-edge remote sensing has applications in vegetation analysis as well as extra-terrestrial applications. This is particularly relevant to Moon, Mars and asteroid exploration, where minerals exhibiting red-edge spectral phenomenology have been identified. Recent processor and sensor availability have created the possibility of development of low-cost sensors able to return useful scientific results. This work focusses on the utility of low-cost sensors for deep space red-edge detection applications and reports on initial tests in near-space environments.

In order to identify the most useful low-cost, red-edge imager design from the diverse range of potential solutions, a tailored trade space was developed from which suitable sensors could be chosen [1]. The trade space was developed in the context of using the chosen sensor in a low-cost hyperspectral instrument suitable for deep space applications and STEM research. COVID-19 restrictions severely impacted budget and access to manufacturing, so a weighted approach was used in the trade study [2,3]. This comprised creating a normalised sum of all attributes considered to detrimental to utility according to the following formula:

$$C_r = \sum (2C_c)M_cV_cP_c \quad (1)$$

where C_r is the camera constraint, C_c is the cost (doubled to reflect severe budget constraints), M_c is the camera mass, V_c is the camera volume, and P_c is the camera power draw.

Sensor utility, U_c, representing an overall desirable attribute of the camera, was also generated from a normalised sum of relevant attributes using the following formula:

$$U_c = \sum R_cF_cS_{nr} \quad (2)$$

where U_c is the utility of the camera, R_c is the camera resolution and F_c is the camera frame rate [5].

The sensor utility was directly influenced by the deep space environment, particularly availability of radiation to which the sensor can detect, in the environment it was expected to operate [6]. Table 1 highlights the solar flux (Sf) available to a sensor sampling red-edge wavelengths (defined as between 600-800nm) at differing parts of the solar system.

Property	**Value (W)**	
S_f at Earth surface	295.0	
S_f at Mars surface	174.1	
S_f at Ceres orbit	45.4	
Sensor QE	**Monochrome**	**Colour**
QE at 600 nm (%)	55	40
QE at 700 nm (%)	45	30
QE at 800 nm (%)	30	25

Table 1: Deep Space remote sensor and solar flux properties.

The quantum efficiency (QE) and noise characteristics of a sensor is also of critical importance to sensor design as it needs to distinguish incident energy above noise. QE of monochrome and bayer-filtered colour cameras at three red-edge wavelengths are also shown in Table 1.

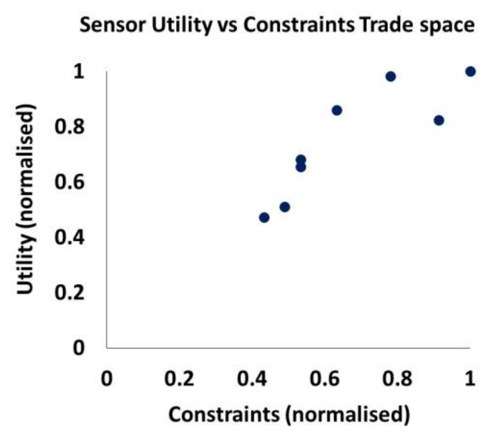

Figure 1: Sensor utility vs constraints results.

Figure 1 shows the trade results from a selection of eight COTS camera sensors with sensitivities relevant to deep space and could be afforded on a constrained budget. Large increases in constraints with modest increases in utility occurred towards the top right of the graph. The lower left regions indicate where larger increases in utility for lower increases in gain occurred.

Raspberry Pi Camera: The Raspberry Pi (RPi) Mk 1 and 2 cameras, which have been popular with STEM applications, possess high utility vs constraints in the trade space analysis described above. The Mk 1 NOIR camera was chosen to develop a 0.5U cubesat-sized payload for near-space testing. Ground-based calibration is an important process for enabling a camera to return useful scientific results [6]. This entailed imaging targets including colour swatches and vegetation in direct sunlight with 850nm wide-bandpass and IR cut filters. The targets were also sampled with a laboratory-grade SR-3500 spectro-radiometer. Least-squares regression was used to derive calibration formulae that converted the camera's digital numbers to reflectance values. Regression coefficient R^2 values ranged from 0.81 to 0.94 from this process. On obtaining reflectance values from ground testing, further calibration practices were tested for near-space applications. Dark subtraction has been a popular method for space-based remote sensing [7] and its utility was trialled for near-space applications. Imagery returned from the balloon flight was processed with, then without, dark subtraction and the results compared with VIS/NIR LANDSAT 7 imagery [8] collected within two weeks of the flight.

Balloon Flight Results: Two RPi cameras were flown in a visible and 850 nm NIR configuration to return four-band multispectral images near West Wyalong, NSW, Australia. The payload reached 30 km altitude and experienced temperatures and pressures (-45°C, 0.01 bar), similar to the Martian surface [6]. Figure 1A shows normalized difference vegetation index (NDVI) processed from RPi multispectral imagery collected at maximum altitude, demonstrating at a qualitative level that the sensor payload was able to operate under Mars-like conditions. The black arrow denotes where pixels were sampled for comparison with the LANDSAT 7 image.

Sensor quantitative analysis from the balloon flight is ongoing however Fig. 2B show comparison between the normalised intensity values of blue, green, red and 850nm NIR bands of the RPi cameras (blue, red) and LANDSAT 7 image (orange). The dark-subtracted curve ("Altitude_D", blue line, Fig. 2) agreed closely with the LANDSAT 7 curve (orange line) while the non-dark-subtracted curve ("Altitude_ND", red line) showed far less agreement. It is possible that atmospheric effects lead to the difference in the "Altitude_ND" result. This phenomenon will be investigated in future near-space missions. Analysis of non-vegetated areas such as bare Earth and built environments from near-space is ongoing, subject to the availability of future balloon flights.

Outcomes and Next Steps: The custom systems engineering trade space identified low-cost sensors theoretically able to support deep space remote sensing of materials exhibiting red-edge phenomenology. From these recommended sensors, the RPi Mk 1 camera was chosen for testing in a near-space environment. Initial balloon flights demonstrated that the camera was able to return meaningful remote sensing in an environment analogous to the Martian surface. The successful testing of this camera will allow future balloon flights to trial the RPi sensor in a pushbroom sensor configuration. Hyperspectral data obtained from such an instrument will then be used to test its utility for red-edge remote sensing in deep space.

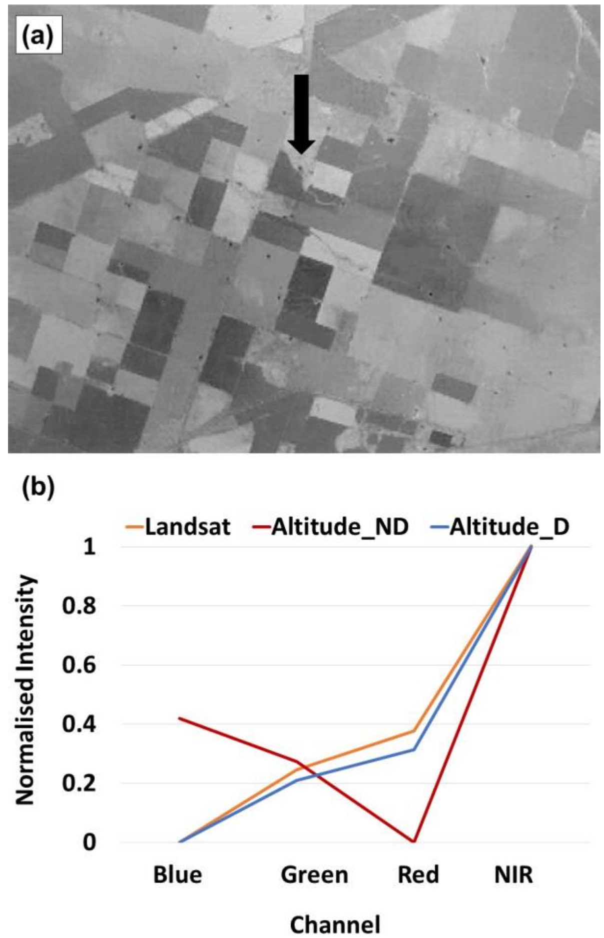

Fig. 2. (A) Processed NDVI image from maximum altitude. (B) Processed reflectance curves for RPi camera and LANDSAT image.

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