TOWARDS IN-ORBIT HYPERSPECTRAL IMAGING OF SPACE DEBRIS

Steve Hobbs[(1)], Leonard Felicetti[(1)], Cameron Leslie[(1)], Samuel Rowling[(1)], George Brydon[(2)] , Mekhi Dhesi[(2)] , Toby Harris[(2)] ,Lounis Chermak[(3)] , Umair Soori[(3)]

[(1)] Cranfield University, SATM, Cranfield, Bedford, MK43 0AL (UK); s.e.hobbs@cranfield.ac.uk
[(2)] Astroscale, Zeus Building, Harwell Campus, Rutherford Ave., Didcot, OX11 0DF (UK); t.harris@astroscale.com
[(3)] Cranfield Univ., CDS, Defence Academy of the UK, Shrivenham, SN6 8LA (UK); l.chermak@cranfield.ac.uk

ABSTRACT

Satellites are vulnerable to space debris larger than ~1 cm, but much of this debris cannot be tracked from the ground. In-orbit detection and tracking of debris is one solution to this problem. We present some steps towards achieving this, and in particular to use hyperspectral imaging to maximise the information obtained.

We present current work related to hyperspectral in-orbit imaging of space debris in three areas: scenario evaluation, a reflectance database, and an image simulator. Example results are presented. Hyperspectral imaging has the potential to provide valuable additional information, such as assessments of spacecraft or debris condition and even spectral “finger-printing” of material types or use (e.g. propellant contamination).

These project components are being merged to assess mission opportunities and to develop enhanced data processing methods to improve knowledge and understanding of the orbital environment.

1 INTRODUCTION

Space debris as small as 5-10 cm are currently trackable using ground-based radars and telescopes. Objects smaller than this are harder to track but could still cause serious damage to a spacecraft if they were to collide. With satellite and debris populations continuing to grow rapidly, new methods of observing the debris population are needed, highlighting the demand for in-orbit observations to complement observations from the ground.

Missions to demonstrate in-orbit imaging have already flown and are generating valuable data using visible and near-IR imagers. Another promising technology for characterising materials is resolved Hyperspectral Imaging (HSI). Whilst most current spacecraft (and debris) imaging technology relies on monochromatic imagers, the use of spectral sensitivity could allow the identification of surface materials, degradation, spacecraft damage, faults, and access more of the electromagnetic spectrum. This information is crucial for planning debris removal missions or to understand the condition of debris for accurate prediction of debris collision products.

In the current phase of this research, we tackle three aspects of in-orbit hyperspectral imaging: (1) identify operational scenarios and the related concept of operations (CONOP) to define typical use cases and imaging requirements, (2) develop a database of hyperspectral reflectances for typical spacecraft materials, and (3) build an image simulation capability for in-space hyperspectral imaging of space objects.

HSI has the potential to observe a variety of space debris objects under a range of conditions (from distant fly-bys to close-range rendezvous). Typical hyperspectral sensor modes of operation (such as line scanning) place unique constraints on these observation conditions, for which we are developing bespoke hyperspectral imaging CONOPs.

To identify space debris, the reflectance characteristics and optical features of materials are measured using HSI in the laboratory. A database of this information is created and used to compare and differentiate spectra of unknown materials. This work uses the capabilities of material classification using the Adaptive Cosine Estimator (ACE) algorithm, which uses the target spectral signature to search for the presence of a spectrum in a scene.

Image simulation builds on existing open-source tools for defining objects (e.g. CAD or visualisation tools) and rendering images. Image rendering is a core capability, to cope with multiple reflections (spacecraft often use shiny materials) and is non-trivial for high-quality image simulation. A basic physics-based image simulator is independently developed to help with validation for simple shapes, and to support the quantitative interpretation of images.

In-orbit HSI has the potential to provide new capabilities in space debris detection and characterisation. Through spacecraft health monitoring and fault diagnosis, it additionally has utility for reducing debris sources. Collaboration between Astroscale, HEO robotics, and Cranfield University is bringing a unique mix of expertise in spacecraft proximity operations, spaceborne imaging of spacecraft, and spectral imaging technologies to enhance our understanding of this capability.

Proc. 2nd NEO and Debris Detection Conference, Darmstadt, Germany, 24-26 January 2023, published by the ESA Space Safety Programme Office
Ed. T. Flohrer, R. Moissl, F. Schmitz (http://conference.sdo.esoc.esa.int, February 2023)

2 SCENARIOS FOR IN-ORBIT IMAGING

In order to develop credible mission scenarios to exploit hyperspectral imaging, we have analysed (a) requirements and (b) constraints.

Requirements for hyperspectral imaging relate to the benefits which hyperspectral imaging offers. These include:

- Clear identification of specific materials / finishes on space objects,
- Assessment of surface condition for space objects (environment degradation or contamination),
- Improved ability to extract sub-pixel information.

One of the most significant constraints is the image acquisition time using current hyperspectral cameras. Another practical constraint is the information about a space object prior to imaging. If its orbit is unknown then imaging is largely opportunistic: targets have to be detected as they cross a field of view pointed in an arbitrary direction. Close targets give strong signals, but only for short times; more distant targets have lower velocity through the field of view but also have weaker signals.

For targets with reasonably well-known orbital parameters, a pointing mode can be planned to maximise the dwell time of the target in the field of view. It may also be possible to choose orbits for the imager which maximise likely dwell times for targets of interest, even if their exact orbit parameters are unknown.

Spectral inspection CONOPs can be broadly split into two categories: flyby missions and close-in missions. A flyby mission is when there is a relatively close approach between the observer and object of interest, however no adjustment is made to the observer's orbit during the approach and imaging phase. Whereas a close-in mission requires the observer to rendezvous with the object, navigating, approaching, and subsequently performing imaging at a much closer range. Within these two broad categories, various different modes of inspection exist. Additionally, a range of different spectral imaging technologies now exist, including filter wheels, colour filter arrays, acousto-optic tuneable filters, spatial scanners, and integral field spectrographs. As exemplified above, the choice of CONOPs and spectral imaging technology must be selected carefully depending on knowledge of the target and overall objective of the mission, in order to obtain maximal gain from the observation.

3 DATABASE OF REFLECTANCES

A fundamental resource needed to exploit hyperspectral images is a database of hyperspectral reflectances for typical space object materials. The imaging research group at Cranfield's Shrivenham campus have developed experimental techniques to measure hyperspectral reflectance across the wavelength range 0.4 – 2.5 μm. The method measures reflectance relative to a reference target, and is designed for targets with random (Lambertian) scattering.

Around twenty different materials relevant to space objects have been characterised. The spectra are useful for identifying spectral features of specific materials, even though they have not yet been fully calibrated. An advantage of HSI is that full calibration of the images is not required to be able to exploit the data.

3.1 Sub-Pixel Analysis

Data analysis techniques based on linear (spectral) mixture modelling have been developed and tested using the hyperspectral data. These allow the spectrum measured from a single image pixel to be analysed so that the contributions at sub-pixel level of different surfaces to the total signal for that pixel can be measured. This will be especially useful for images which are unresolved, or only coarsely resolved.

4 HYPERSPECTRAL IMAGING SIMULATOR

Image simulation is useful for mission planning and developing data processing algorithms. The simulator should be able to represent intact spacecraft and large debris objects. We chose to use or adapt an existing simulator to allow us to focus on applications and to have access to relatively advanced capabilities. Computer graphics have advanced significantly so that very high quality computer-generated imagery (CGI) is widely used in films. However, it is less widely developed for research-grade simulators, especially simulators which can be extended beyond the visible spectrum.

Reference [1] reports development of a hyperspectral simulator targetting terrestrial scene simulation (CHIMES) and its comparison with CameoSim. These COTS tools are tailored strongly for applications including an atmosphere, and so are less relevant for in-space image simulation. The core of an image simulator is the renderer, which typically simulates many light rays undergoing multiple reflections to form an image. Of the (open-source) renderers available for research use, we chose Mitsuba 3 [2]. It was one of the few renderers capable of being extended to handle hyperspectral reflection.

4.1 Imaging Simulator Concept

The concept of the image simulator (called HySim) has been to build a convenient processing pipeline around the Mitsuba 3 renderer. User inputs define:

- Target (geometry, position and pose),
- Camera (angular resolution, position and pose, image quality performance),
- Target surfaces' hyperspectral reflectances,
- Scene background,
- Scenario (imaging geometry, time – for time-dependent positions and poses).

The simulation is quasi-static, although, using time-dependent positions and poses, and then merging the sequence of images it is possible to simulate the blur due to motion of the target through the camera's field of view.

Mitsuba 3 is a powerful renderer with a large library of models for surface reflectance. The diffuse (Lambertian) scattering model has been used so far, but we can also use models to represent surfaces with specular reflection components [3]. The output file format is a standard one used in the computer graphics industry: OpenEXR.

HySim has been hosted on GitHub and will be published for further open-source development.

4.2 Validation

As for any simulation, validation has been a crucial task. Two main approaches have been used:

1. Comparison with a simple physics-based image simulator,
2. Analysis of output images to assess their agreement with defined imaging geometries and other features.

The simple physics-based simulator calculates the signal and noise expected for a single pixel of an image. Table 1 and Figure 1 define the imager and show example results for pixel signal for four different ranges (of target from the camera).

Table 1. Standard values for image simulation (assuming illumination and viewing perpendicular to the surface)

Parameter	Value	Parameter	Value
Aperture diam.	10 cm	Resolution	1 m
Shutter time	1 s	Reflectivity	100%
Quantum eff.	100%	Bandwith	10 nm
Sun temperature	5800 K	Solar disk	68 μsr

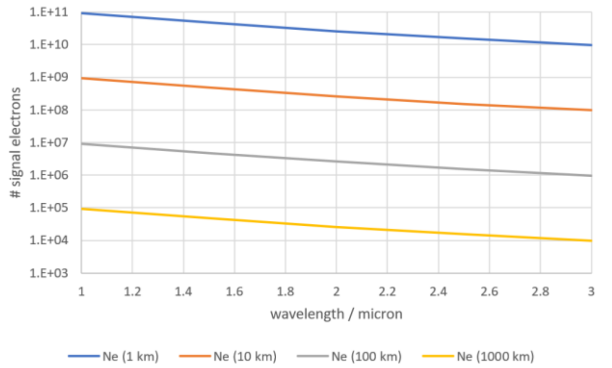
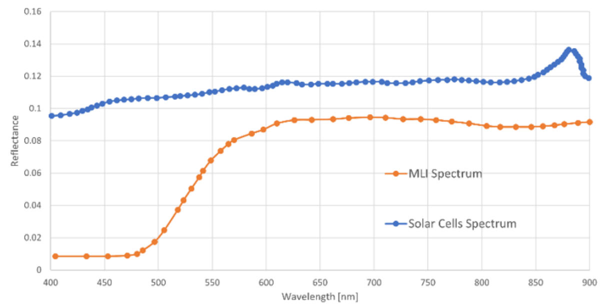


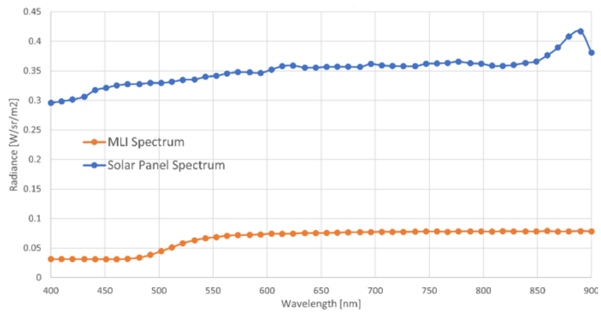
Figure 1. Expected signal (number of electrons per shutter time) for the imaging parameters of Table 1.

In the visible / near-infrared part of the spectrum, shot noise is often the dominant source of noise and so the signal-to-noise ratio (SNR) is practically the square root of the number of signal electrons. Although the signal levels seem strong, if the shutter time is reduced to, say, 1 ms to control image blur, and the reflectivity, quantum efficiency, and viewing geometry are less ideal, then the signal reduces significantly and signal quality (SNR) may become a problem.

Figure 2 shows an example of the qualitative checks which have been made of HySim. The shapes of the input spectra are correctly represented in the output image. Other similar checks have been made of HySim's performance to give us strong confidence in its results.



(a) Input hyperspectral reflectances



(b) Spectra obtained in output images

Figure 2. Comparisons between input and output spectra for HySim

4.3 Example Results

Figure 3 presents an example output image from HySim using a geometrical model based on the TerraSAR-X spacecraft. This is an early test case representing close-range imaging, able to resolve the satellite in detail.

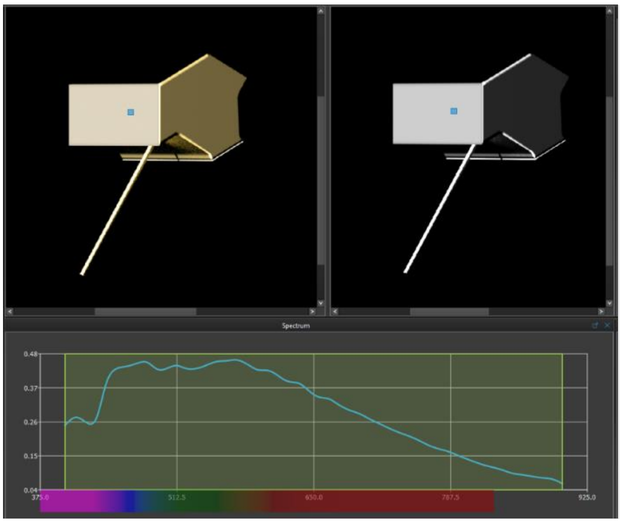


Figure 3. Example HySim output images for TerraSAR-X using Spectral Viewer 3.0 (top left: full-spectrum representation, top right: image based on selected portion of spectrum; bottom: spectrum for selected window (small pale blue square in image))

5 DISCUSSION

Efforts so far have focussed on developing individual technology areas such as the scenarios, the reflectances database, and the image simulator. The full value of the work comes from integrating these elements to develop mission scenarios which could contribute to the goal of improved knowledge of the orbital environment. This work is planned in several phases (some of which go beyond currently planned activities).

The next step is to integrate the separate project areas to develop and evaluate credible mission scenarios to exploit the capabilities of hyperspectral in-orbit imaging.

Beyond this we plan to extend the database of space material reflectances, and to improve its integration with the image simulator. For the simulator itself, we plan to extend its spectral range into the thermal infrared (to include both reflected and black-body thermal radiation from space objects). Work is also needed to develop the data analysis techniques to exploit the observations available. Orbit determination is feasible, but developing a convenient processing pipeline for this requires further work. There is also great potential for image analysis to improve characterisation of the space objects.

6 CONCLUSIONS

In-orbit imaging of space objects seems increasingly necessary to understand the space environment: it complements what is possible from the ground. Hyperspectral imaging has particular potential because of the information content which it captures. However, there are operational and technological constraints which need to be understood (or overcome through technology developments) to make best use of the technology. In particular, hyperspectral cameras currently need longer acquisition times than conventional imagers. Our project is helping us to understanding how best to exploit HSI and we look forward to space missions demonstrating this capability.

7 CONTRIBUTIONS

The project's conception is primarily provided by TH. GB and MD led the scenario evaluation tasks. The hyperspectral reflectance dataset is the work of LC and US. SH and LF planned the simulator development; its implementation is primarily the work of CL and SR. SH led the validation tasks. All contributed to the mission discussions.

8 ACKNOWLEDGEMENTS

Material samples to build the database were provided by Dr Jenny Kingston. It is important also to recognise the impressive work by the Mitsuba team at EPFL's Realistic Graphics Lab. We acknowledge the support of the UK's dstl who funded this study.

9 REFERENCES

1. Zahidi, U.A., Yuen, P.W.T., Piper, J., and Godfree, P.S. (2020). An end-to-end hyperspectral scene simulator with alternate adjacency effect models and its comparison with CameoSim. *Remote Sensing*, **12**, 74.
2. Jakob, W., Speierer, S., Roussel, N., Nimier-David, M., Vicini, D, Zeltner, T., Nicolet, B., Crespo, M., Nicolet, B., and Zhang, Z. (2022). Mitsub 3 renderer, version 3.0.1, https://mitsuba-renderer.org
3. Nayar, S.K., Ikeuchi, K., and Kanade, T. (1991). Surface reflection: physical and geometrical perspectives. *IEEE Trans. Pattern Analysis and Machine Intelligence*, **13**(7), 611-634.
4. Janacek, M., and Moses, W. (2008). Optical reflectance measurements for commonly used reflectors. *IEEE Trans. Nuclear Science*, **55**(4), 2432-2437.