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HySim: A Tool for Space-To-Space Hyperspectral Resolved Imagery

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Abstract

This paper introduces HySim, a novel tool addressing the need for hyperspectral space-to-space imaging simulations, vital for in-orbit spacecraft inspection missions. This tool fills the gap by enabling the generation of hyperspectral space-to-space images across various scenarios, including fly-bys, inspections, rendezvous, and proximity operations. HySim combines open-source tools to handle complex scenarios, providing versatile configuration options for imaging scenarios, camera specifications, and material properties. It accurately simulates hyperspectral images of the target scene. This paper outlines HySim's features, validation against real space-borne images, and discusses its potential applications in space missions, emphasising its role in advancing space-to-space inspection and in-orbit servicing planning.

Keywords: image generation, hyperspectral imaging, multispectral imaging, space surveillance, space-to-space inspection

1. Introduction

Space-to-space inspection of orbiting spacecraft is seen a fundamental task in current and planned missions for in-orbit servicing and surveillance [1][2]. Compared to the standard monochromatic imagery, multispectral and hyperspectral resolved imagery bring enhanced information helpful in identifying and characterising surface materials, their status, degradation, or damage on the spacecraft to be inspected [3].

Despite the recent interest in these new applications, no available tool can simulate and assess the performance of eventual multispectral/hyperspectral imagers for space-to-space applications. Most of the available tools target Earth or planetary remote sensing applications with the eventual inclusion of atmospheric effects on the simulations [4][5]. However, these tools can be either directly generated or adapted to generate hyperspectral images for space-to-space-based observation scenarios.

We propose to overcome this gap by bringing to the community a new tool, HySim, which allows for simulating hyperspectral space-to-space images under a wide range of possible space-to-space scenarios, such as far fly-bys, close inspection, rendezvous, and proximity operation scenarios. HySim builds on existing open-source tools for defining objects (e.g. CAD or visualisation tools) and rendering images [6]. 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. The tool includes ad-hoc build functions for setting up accurate space-to-space imaging scenarios, including specific orbital and illumination conditions, setting up characteristics of the camera system (i.e. resolution, focal length, shutter time and eventual hyperspectral bands used to generate the images) and libraries for characterising reflectance and emission properties of the materials of the observed spacecraft. As a result, the tool is able to provide output hyperspectral images of the simulated scene. HySim was developed by Cranfield University with the participation of Astroscale and HEO. HySim is released under open-source license and is available in [7].

The paper outlines the key features and applications of HySim, showing the results of the validation performed through comparison with real hyperspectral and multispectral space-borne images in selected test case scenarios. An overview of the possible applications is also provided at the end of the paper, showing the key capabilities of this tool in numerous analyses and potential applications in future space missions.

The rest of this paper is organised as follows: Section 2 outlines possible mission scenarios and applications where hyperspectral imaging can be useful, highlighting the key requirements for image generation. Section 3 describes in detail HySim, focusing on the current implemented capabilities and software architecture. Finally, Section 4 shows the validation campaign results and the generated images' key features in realistic scenarios. Final remarks and an outline of the upcoming upgrades are presented in the paper's concluding section.

2. Hyperspectral space-to-space imaging applications

Hyperspectral and multispectral imaging techniques are technologies that extend monochrome-resolved imaging by capturing distinct monochrome images for different spectral bands. These spectral observations can range from just a few to thousands of bands, enabling the remote measurement of object composition based on their energy spectra. Many materials have identifiable spectra for detection or identification. Multispectral imaging (MSI) uses several spectral channels (around 3-10), providing basic colour information but not fine-scale spectral details. In contrast, hyperspectral imaging (HSI) employs numerous narrow bands (typically 50 to 1000) to achieve high spectral resolution. HSI captures the complete spectrum for each pixel, revealing precise spectral shape and features like absorption and emission, allowing for advanced material discrimination and identification.

In the following, we first list and describe the benefit of having MSI/HSI in possible space-to-space applications and then outline possible mission concept of operations, which set specific requirements for HySim simulations.

2.1 Space-to-space MSI/HSI applications

To understand key space-to-space applications of MSI/HSI technologies, we have analysed requirements and limitations in several mission scenarios. The key advantages that MSI/HIS bring to eventual inspection operations, include:

- Precise identification of specific materials and finishes of objects in space.
- Assessment of the surface condition of space objects, including environmental degradation and contamination.
- Enhanced capacity to extract sub-pixel information.

These features allow for defining specific MSI/HIS applications in space-to-space operations, such as:

- Material discrimination and determination, based on the analysis of the spectral properties of the surfaces of the observed target
- Enhanced object detection, especially when illumination conditions are not optimal, e.g., objects are in eclipse, presence of significant background noise, etc.
- Object categorisation and identification, determining to what broad group of RSOs the observed object belongs (e.g., box wing spacecraft, a rocket body, a defunct spacecraft, etc.) and determining information about its unique identity, function, or history.
- Surface ageing or damage assessment, by analysing the variation of spectral intensities of the different surface materials.
- Thruster plume identification for detecting eventual manoeuvres of the spacecraft, by analysing surrounding areas around the observed spacecraft.
- Pose estimation, based on the recognition of the observed materials of the target rather than directly from the shape evolution of the object in the image.
- Object status evaluation, understanding whether the object is active or inactive by analysing near IR spectral emissions.

HySim allows for the generation of realistic multispectral and hyperspectral images as taken from an ideal sensor located in space even before the mission takes place. In a sense, HySim will enable and ease the development of dedicated image processing algorithms for such applications by providing in-silico-generated images.

2.2 Mission scenarios and operations

To create reliable mission scenarios for harnessing hyperspectral imaging capabilities, we have conducted an analysis encompassing both requirements and limitations applied to a set of possible mission operations. Space-to-space observations implementing MSI and HSI would face constraints due to the time required for image acquisition using currently available hyperspectral cameras. Another practical limitation is the lack of information about a space object before imaging. When an object's orbit is unknown, imaging becomes largely opportunistic, with targets detected as they traverse a field of view oriented in an arbitrary direction. Close targets provide strong signals but for brief periods, whereas more distant targets move at lower speeds through the field of view, resulting in weaker signals.

For targets with reasonably well-known orbital parameters, a pointing mode can be planned to maximise the time the target remains within the field of view. It may also be possible to select orbits for the imager that maximise the expected dwell times for targets of interest, even if their exact orbital parameters are uncertain.

Spectral inspection concepts of operations (CONOPs) can generally be categorised into two groups: flyby missions and close-in missions.

Figures Fig. 1 and Fig. 2 show two possible pointing approaches during the flyby missions. In the passive pointing (Fig. 1), the observer approaches the object of interest without making adjustments to its attitude during the approach and imaging phase. On the other hand, the active pointing (Fig. 2) the sensor tracks the target through the duration of the flyby. As a result, the capture images and will have different features that need to be accurately simulated by HySim based on the selected mission scenarios.

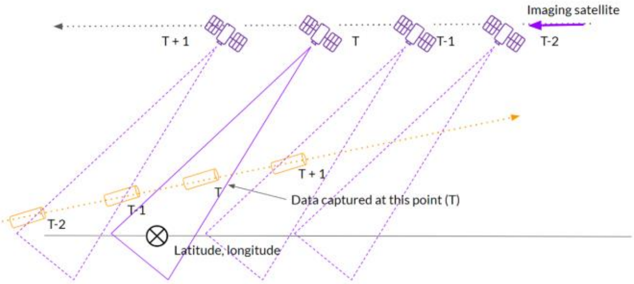

Fig. 1 Passive pointing flyby mission CONOPS.

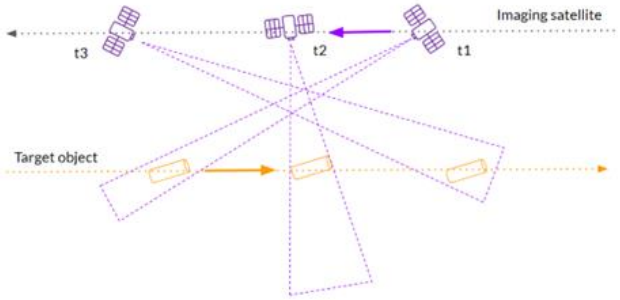

Fig. 2 Active pointing flyby mission CONOPS.

On the other hand, a close-in mission requires the observer to rendezvous with the object, navigate towards it, approach closely, and then conduct imaging at a much closer range. Within these broad categories, various modes of inspection are available.

Fig. **3** shows an example of the approach and stand-off inspection of the target. While approaching the RSO, stand-off inspection can commence when the observer is approximately within a range of about 10 km (subject to sensor resolution). This early phase of inspection enables the observation of the RSO before the close-in inspection, aiding in planning the close-in examination. Stand-off inspection initially yields low-resolution imagery, which gradually improves as the observer gets closer to the RSO. This approach capitalises on the considerable distance between the observer and the RSO, resulting in a stable observation geometry with minimal observable motion of the RSO. Once the observer approaches within 100 meters, it stops manoeuvring and observes the target from a fixed position along the v-bar axis.

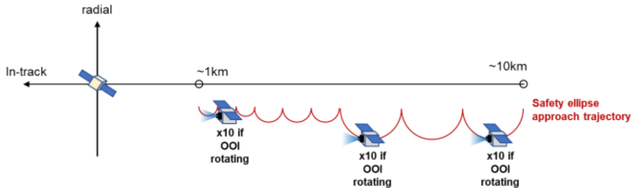

Fig. 3 Approach and stand-off inspection imaging CONOPS

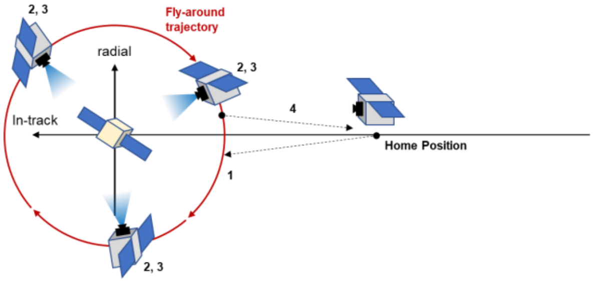

Fig. 4 Fly-around observation close-in CONOPS

Another example of close inspection is shown in Fig. 4. In this case, the observer employs a controlled-motion manoeuvre to orbit the RSO. Spectral images are captured repeatedly during this orbit to achieve comprehensive surface coverage, after which the observer returns to the home position.

The requirements imposed by such kind of mission CONOPS have informed the development of HySim, which now embeds capabilities to set up any of these scenarios, at least for a first-order analysis.

3. HySim software development and architecture

The development of HySim responds to the need to simulate and generate multispectral and hyperspectral images for space-to-space applications. In the following subsection, we provide an overview of the software development and architecture used for developing HySim.

3.1 HySim top-level requirements definition

Main top-level requirements imposed during the development phase of HySim were[*]:

1) HySim shall generate simulated images of space objects relevant to hyperspectral (0.4 – 2.5 μm) space-to-space imaging, as per the mission applications described in Section 2.
2) HySim shall allow the user for setting up a space-to-space scenario by specifying:
   - Space object (geometry, spectral and reflective properties, and its orbital position and orientation – in a convenient coordinate system)
   - Imager (camera, its orbital position and orientation)
   - Environment (Sun location/direction)
3) The output image shall be in a multi-band standard image file format with convenient meta-data.

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[*] Please note that this is highlights the main, but not all, requirements followed during the design process.

4) The generated images shall be validated against physic-based examples as well as real hyperspectral or multispectral images provided by HEO.

It is worth mentioning that the key features implemented in the current version of HySim [7] fully meet all these top-level requirements.

3.2 HySim software architecture

Given the necessity of generating realistic images and, at the same time, embedding complex definitions of objects and mission scenarios, we opted for the utilisation of existing and available rendering software. A survey of the available rendering software was carried on, exploring options such as CameoSim [8], PBRT v4 [9], POVRay [10], Mitsuba 3 [6], LuxCoreRender [11], Cycles Renderer [12], OctaneRender [12], Unity [13], Unreal Engine [14]. The trade-off, made against the requirements in Section 3.1, resulted in the selection of Mitsuba 3. This graphic library is an open-source physically based renderer developed by the Graphic Lab of EPFL for research purposes. Mitsuba 3 is the only spectral renderer capable of outputting spectral images along with PBRTv4, which is much less convenient to use (no Python support, longer rendering times). Many renderers are used for artistic purposes and do not implement physics-based methods, which directed our choice to Mitsuba 3.

Fig. 5 shows the software architecture diagram adopted for HySim. The diagram shows the data flow adopted for acquiring the simulation inputs, managing the databases of materials and sensors, and interfacing with the Mitsuba engine to generate the desired images. The key functions of the software are therefore organised as follows:

- User Interface. To produce a hyperspectral image, a user configures a "Scene". Inside a Scene is all information describing the target spacecraft, chaser/imager spacecraft (Sensors, materials, etc.) and their environment (Lighting conditions). This information is passed to the program using human-readable configuration files. The user edits these files as required, and the software reads them automatically when run. Any outputs will be exported to the directory in which the program is run.
- Main code. HySim primarily manages inputs and outputs to Mitsuba 3 to allow a user to conveniently produce hyperspectral images of a target satellite in orbit. The code is written entirely in Python 3.9 and controls Mitsuba using its Python-based application programming interface (API).
- Internal Database. HySim contains a database of pre-defined materials and sensors that the user can choose from. This feature is optional, and HySim also supports the ability to define one from scratch.

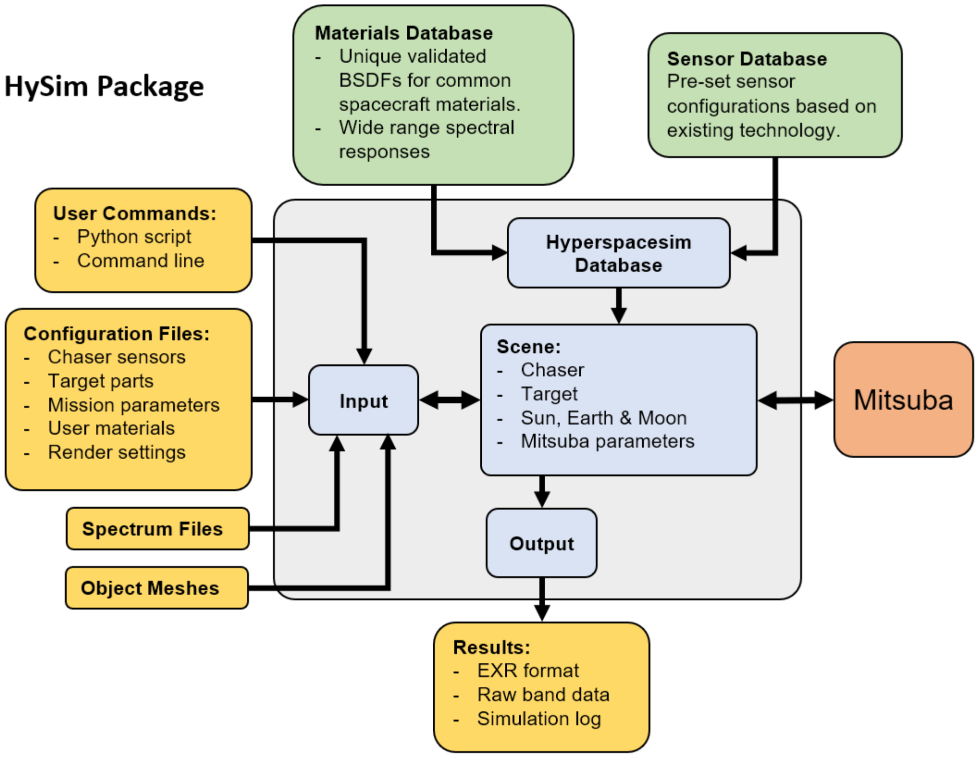

Fig. 5 Diagram of HySim's software architecture

3.3 User interface and software inputs

The current version of HySim uses a command line interface which enables the run of test case scenarios set through the definition of data files in a "case directory. These include component meshes, sensor spectral data and materials data. Further information can be found in the user guide associated to HySim, which can be found in [15].

3.4 HySim software outputs

The images generated by HySim can be outputted in two different formats. These are:

- PNG. A PNG file is created for each spectral band (Band_0.png, Band_1.png, Band_2.png …)
- EXR. A single multichannel OpenEXR file is created and named by the user.

The purpose of EXR format is to accurately and efficiently represent high-dynamic-range scene-linear image data and associated metadata, with strong support for multi-part, multi-channel use cases. OpenEXR is widely used in host application software where accuracy is critical, such as photorealistic rendering, texture access, image compositing, deep compositing, and DI. A detailed definition of the OpenEXR file can be found in [16]. Such file can also be opened by open-source viewers such as Spectral Viewer [17], as shown in Fig. 6 for the case of TerraSAR-X imaging. The top left figure shows full-spectrum representation, the top right an image based on a selected portion of the spectrum and the bottom figure the spectrum for selected the window (small pale blue square in image).

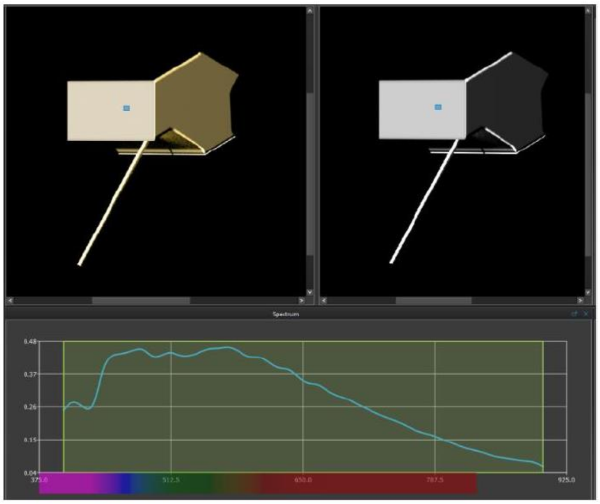

Fig. 6 Example HySim output images for TerraSAR-X using Spectral Viewer 3.0

4. Validation and simulation campaign results

This paper focused on the validation of HySim through comparisons with real laboratory hyperspectral and multispectral space-borne images in selected test case scenarios. The reader can also find the validation made against simpler physic-based analytical simulations in [18], whose results are not repeated here for sake of conciseness.

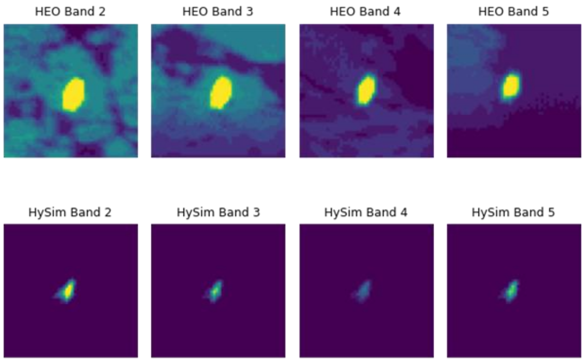

Fig. 7 Comparison between the real world S2S HEO imagery data (top row) and the HySim renders (bottom row).

A key test case is the simulation of TerraSAR-X to compare to the real-world multispectral space-to-space images provided by HEO Robotics. A render of an image is produced by HySim representing the radiance incident on the sensor at that time. In the image generation via HySim, the sensor was located and oriented in the same orbital as the images provided by HEO robotics, and a CAD model of the TerraSAR-X spacecraft was used alongside the definition of the spectral properties of all the surfaces of the spacecraft. The same illumination conditions were also reproduced. Fig. 7 demonstrates that the render and the real data match sufficiently well, with the simulation accurately depicting the attitude of the target and the agreement in the multi-band band containing the object at its largest apparent size. The differences observed between the rendered image and actual data can be attributed to several factors. These include the post-processing applied to the real data, the estimations made regarding TerraSAR-X materials and camera resolution, inaccuracies in modelling motion blur, and the absence of atmospheric effects or a realistic Earth background in HySim. All of these factors have been identified as aspects requiring improvement in future simulation enhancements.

Fig. **8** presents a HySim feature showcase model of the ISS. Here, the light source is defined to be sunlight and inputted using the Wehrli85 sunlight irradiance spectrum at 1AU. HySim models the light in a scene with a path tracer that uses a random walk starting from the sensor for a given number of samples per pixel. The physical quantity received by the sensor is radiance, which is the radiant flux received per unit solid angle, per unit projected area (W·sr−1·m−2). When observing a target, the radiance depends on the target's properties, but it is also entirely scene-dependent, i.e., depending on sources of radiation, the angle of the incident radiation upon the target face, any atmospheric effects, or any other bodies present.

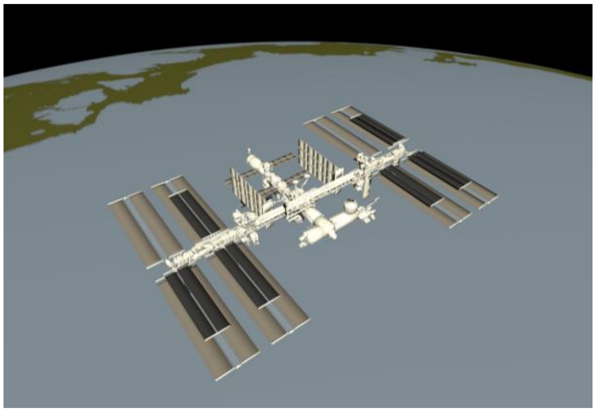

Fig. 8 RGB rendered image of the ISS generated via HySim

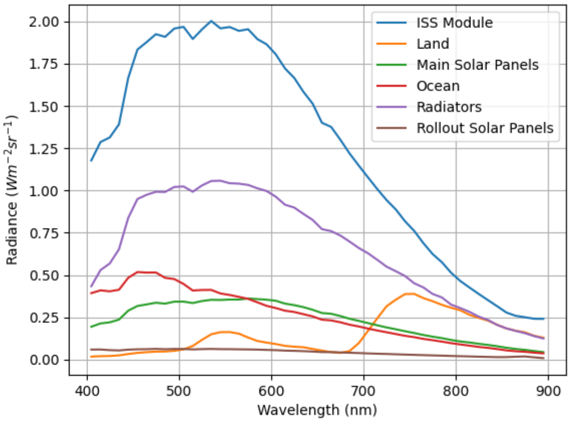

Fig. 9 Rendered radiance of each component present in the hyperspectral image of the ISS

Fig. 8 shows the render represented in RGB. All components are visible in the scene in addition to the two textures used on a bitmap texture of land and sea on the Earth. A 6x6 pixel kernel of each component was picked by hand, and the spectrum at each point was exported for comparison. Fig. 9 plots the rendered radiance against wavelength for various components in the scene.

5. Conclusions and future work

HySim enhances the current state-of-the-art simulation capabilities of space-to-space imaging, providing a useful tool for generating hyperspectral and multispectral space-borne images. The preliminary validation results presented in this paper show that the tool is able to reproduce outputs from real space-to-space imagers. Hysim has been tested in several ways (as reported here, and more generally during development) and has performed as expected. This gives us confidence that the simulator can be trusted, with caveats that the reflectance models available so far are only for diffuse scattering, that target motion during imaging is represented by combining a sequence of snapshot images, and that simulator enhancements will be required to represent background scenes.

Planned upgrades will include additional features such as a wider and more detailed material database, motion blur effects due to a finite-time shutter time, implementation of advanced reflection models into the scene, the inclusion of atmospheric effects and a realistic Earth background for the nadir pointing images. The tool is potentially useful to pre-assess the performance of specific algorithms and pipelines for processing MSI/HSI since the early stages of the mission design of eventual space hyperspectral/multispectral enabled inspection missions, on-orbit servicing and even, more in general, space-based surveillance missions. Expected applications of HySim include material determination and assessment of object geometry, RSO fingerprinting, attitude analysis, pattern of life, capability assessment and intent.

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