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Status of the Design, Accommodation and Performance of the TRUTHS Hyperspectral Imager at the End of Phase B1

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ABSTRACT

The TRUTHS (Traceable Radiometry Underpinning Terrestrial and Helio Studies) mission is a concept initially proposed by NPL which will enhance our understanding of the Earth's changing radiation budget by an order of magnitude. This is a UK led mission within the ESA Earthwatch programme with prime, platform and instrument being led by Airbus UK.

At the heart of the payload is the ability to calibrate the high resolution hyperspectral imager with a SI calibration traceable to national standards using the payload's on-board calibration system (OBCS). This in turn provides accurate continuous measurements from the top of atmosphere of reflected, lunar and spectral solar radiance. This paper will concentrate on the hyperspectral instrument part of the payload.

The optical design boasts low polarisation sensitivity, good MTF and Smile, and has a compact accommodation to optimise the instruments size and weight footprint within the Payload. The electro-optical back end consists of one Teledyne CHROMA-D MCT detector, with low noise and high SNR achieved through cold operation through a passive cooling system. Pixel correction, customised spectral and spatial binning and compression provided by the electronics front end produces an output dataset with a Spatial Sampling Distance (SSD) of 50m over a spectral range from 320 to 2400nm with a Spectral resolution between 0.3 and 7 nm.

This paper will summarise the design status of the TRUTHS hyperspectral imager at the end of phase A/B1. The current spatial and spectral performance will be presented as well as the accommodation and thermal performance.

Keywords: hyperspectral, remote sensing, instrument design

INTRODUCTION

TRUTHS is an operational climate mission, aiming to enhance our ability to estimate the Earth's radiation budget by an order of magnitude. Through direct measurements, the mission's main objective is to establish a reference baseline of the state of the planet in the International System of units (SI units) against which future observations can be compared. This will enable climate model improvements and forecast testing, provide observational evidence of climate change, and help to assess the impact of mitigation strategies.

1.1 Instrument Architecture

A key instrument on-board the TRUTHS mission is the Hyperspectral Imaging Spectrometer (HIS): a dispersive imaging spectrometer that, in conjunction with an on-board calibration system (OBCS), is capable of providing an accurate, continuously calibrated datasets of spectrally resolved earth, solar and lunar radiance [1]. It measures light in the near-UV, visible, NIR, and SWIR wavebands, utilising a novel SI traceable on-board calibration system. As a system, TRUTHS has a challenging aim of providing a goal absolute radiometric accuracy better than 0.3% over the whole spectral range, with k=2 coverage factor. The payload can be used within its own right, or to cross-calibrate data from other space instruments.

The HIS, a push-broom imaging spectrometer, covers the spectral range from 320 nm to 2400 nm, with spectral resolution from 0.3 nm to 7 nm. In orbit, it will cover ~100 km in swath, with a spatial sampling distance (SSD) of 50 m. The instrument broadly consists of the telescope and spectrometer optics, a cooled detector and cryostat, front end electronics (FEE) and the mechanical structure and associated thermal control.

OPTICS

1.2 General Architecture

The HIS instrument is composed of 3 optical subunits that can be built in isolation: the telescope, which focuses the image at the slit; the spectrometer, which spectrally separates the incoming light; and the polarization scrambler, used to remove any polarisation bias. The optical design is illustrated in Figure 1: light enters at the top right, and the detector plane is in the top middle of the image.

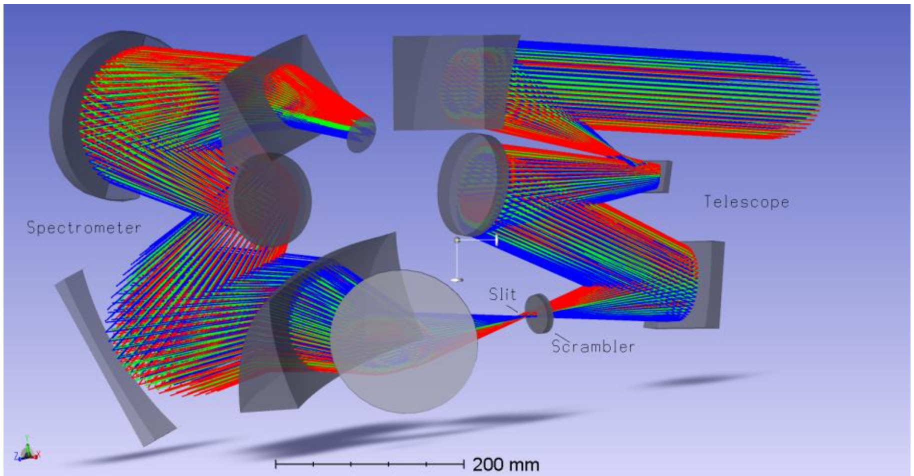

Figure 1: Full HIS optical design schematic

The HIS focal length is approximately 229 mm with a 70 mm entrance pupil.

The very wide spectral band has necessitated development of a wide band high reflectivity coating. Dielectric coatings work on interference and hence are difficult to design over a wide spectral range; they can also display large peak to peak variation. Metallic coatings tend to exhibit low UV reflectivity. TRUTHS have therefore opted for a hybrid design where highly thermally and mechanically stable Zerodur glass substrates are metal coated for high reflectivity in the infrared (IR) and an IR transparent multilayer dielectric coating is added to boost UV/visible reflectivity. A protective overcoat is also employed to enhance durability for cleaning and handling.

1.3 Spectrometer Optical Design

All the mirrors are freeform, and although relatively simple, free form manufacturing is always a challenge. The prisms are made from fused silica of very high optical quality. This is necessary to achieve the needed transmission over this large waveband and to avoid aberration due to striae. Although this configuration has been used in the past (e.g. for Chris), the high resolution required for TRUTHS dictates much larger prisms. In addition, the diffraction limited design drives the prisms to have power (curved faces) to compensate for other aberrations in the system. Effectively, these prisms could be considered as lenses with a very large wedge. Manufactures can create lenses with very little wedge or flat faced prisms with large wedge; combining the two is a challenge.

This optical configuration, however, provides a very good optical quality spectrometer. Figure 2 shows the modelled modulus of the optical transfer function (OTF) – i.e. the modulation transfer function (MTF) – of the spectrometer at 1500 nm. The result is limited by diffraction.

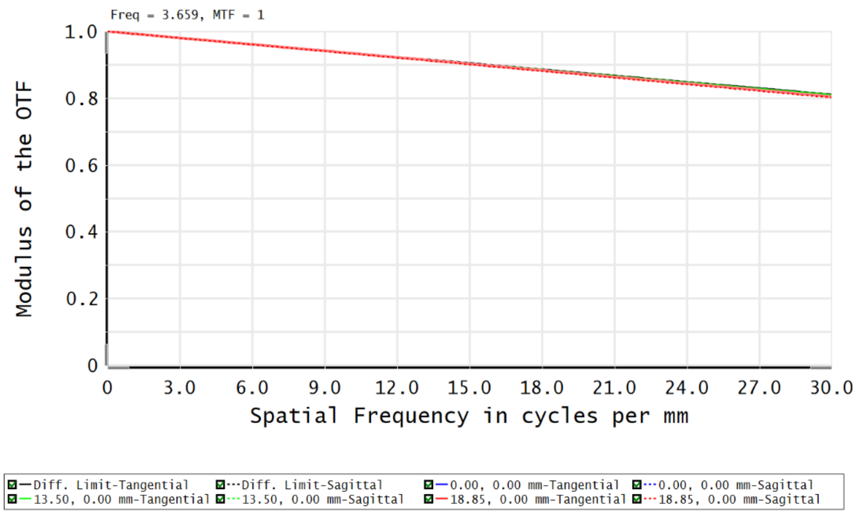

Figure 2: Optical MTF of a spectrometer only for some point on the slit at 1500nm. The sagittal curves are ACT and the tangential one ALT.

The Offner configuration tends naturally to almost suppress any smile or keystone and to be telecentric in both slit and detector planes. The distortion of the slit image on the detector at any wavelength (the smile) and the distortion of the spectrum for any point of the slit (the keystone) can be limited to a few parts of a pixel. These considerations generate constraints for the telescope design: it must be telecentric in the image plane and provide no smile-limiting distortions from Earth to detector.

1.4 Telescope Optical Design

The starting point for the telescope was a classic off-axis 3-mirror configuration, avoiding any obscuration in the pupil. This 3-mirror configuration, though able to provide the needed telecentricity in the image plane, is difficult to design compactly with no distortion. The design has therefore evolved to use a 4-mirror configuration, which offers more degrees of freedom to fully avoid distortion.

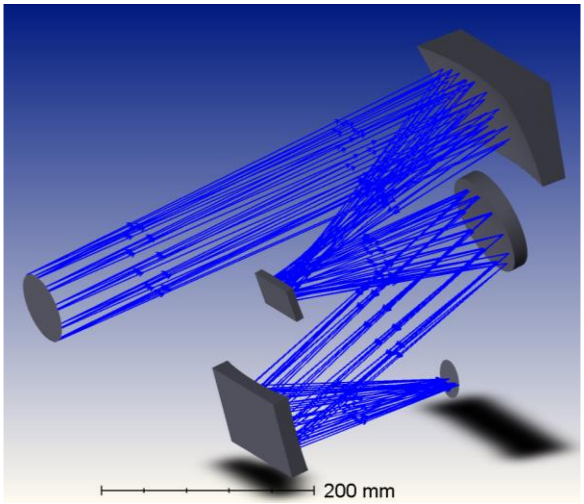

Figure 3: Optical layout of current telescope

The telescope is composed of freeform mirrors and offers the possibility of accommodating an intermediate field stop after the first mirror to reduce stray light and limit the light entering in the spectrometer. The telescope is optimised so that the optical quality is limited by diffraction over that whole field of view.

1.5 Polarisation Scrambler

The polarization scrambler considered in this phase for TRUTHS is a Dual Babinet Pseudo Depolarizer (DBPD). It is composed of 4 wedged prisms that are optically contacted to effectively create one flat plate. The DBPD generates a variable dephasing over the pupil and converts a given polarisation state to the sum of different states, so that the exit beam is considered unpolarised. The polarisation scrambler is more efficient at short wavelengths, the "depolarization power" varying with 1/λ.

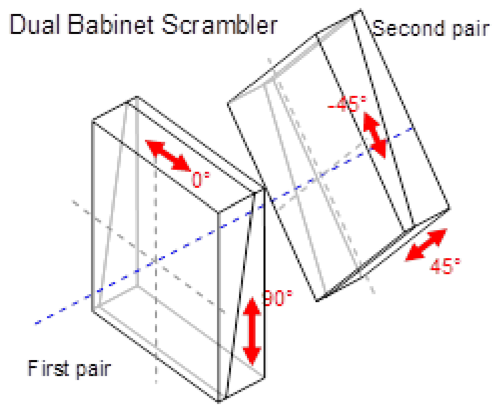

Figure 4: Schematic principle of a DBPD

The scrambler is realised in crystalline quartz. As illustrated in *Figure 4*, the machined flat input surface is aligned with the Z-axis (the optical axis). To create a single Babinet prism, two wedged prism are cut and contacted, and an effectively flat plate is created. Two Babinet prisms are bonded to create a dual Babinet configuration, with the second pair at 45 degrees with respect to the first, to further scramble the beam.

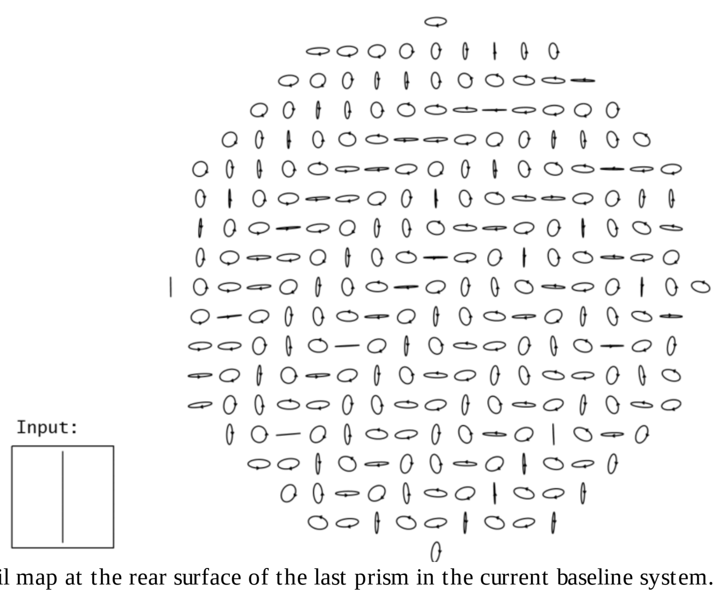

Figure 5: Polarisation pupil map at the rear surface of the last prism in the current baseline system.

Placement of the scrambler within the telescope can be in a collimated or converging beam. That is to say, either at the telescope entrance or before the slit. In both cases it generates a degradation of the MTF due to the so-called "diamond effect"; in the case of the converging beam option it also adds chromatic aberrations. Obtaining large diameter crystals at a suitably high optical standard is seen as a risk, so the current baseline is the smaller scrambler nearer the slit.

In regards to the "diamond effect": the birefringence of the crystal prisms generates a dephasing as well as a variation of deviation as a function of the direction of the incident polarization. This results in an image-walk-off per prism and thus, for the four prism scrambler, 4 images. This walk-off is controlled by the wedge angle of the prisms, and the location of the images by the rotation of the prism assemblies.

Figure 6 gives an example of the diamond effect in a simplified system where the scrambler is in the entrance pupil. With modifications to the design, these spots could be arranged to have the images in a straight line in X or Y.

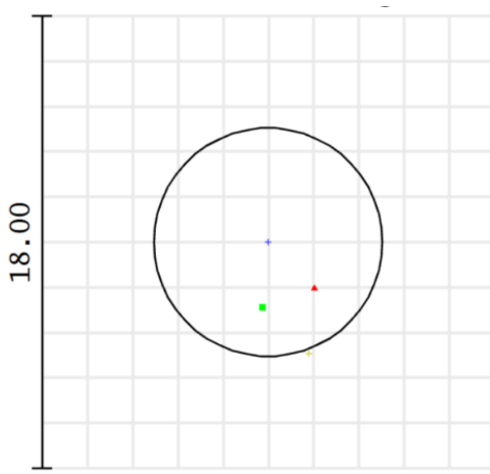

Figure 6: Illustration from a simplified paraxial 191 mm focal length system at 1500 nm wavelength where the prism are at 45 deg to each other. Airy's disc is given for reference

The polarisation sensitivity (PS) of the full HIS instrument is plotted in Figure 7 as a function of wavelength for different field angles. The required PS is indicated in blue. In the current HIS design, the orientation and direction of variation are manageable with the design of the scrambler.

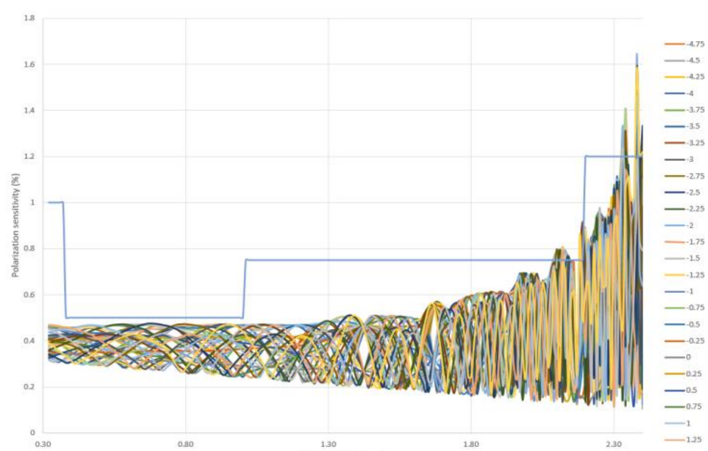

Figure 7: Polarization sensitivity (%) of the full instrument as a function of wavelength for different field angles

1.6 Smile and Keystone

Keystone is the maximum variation of centroid position ACT with respect to the wavelength for each field direction. Smile is the maximum variation of centroid position in the spectral dimension with respect to the field orientation for each wavelength. In this design the smile is negligible whatever the wavelength and keystone varies as per Figure 8.

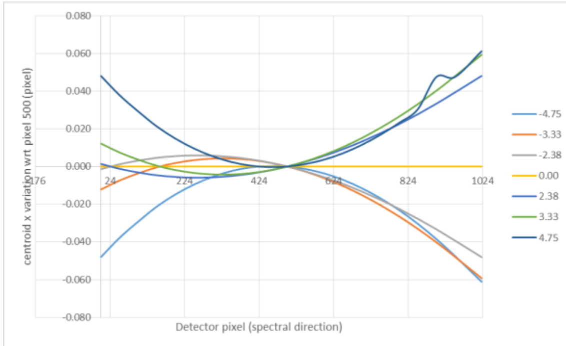

Figure 8: Keystone representation for 7 field orientations

DETECTOR

The HIS instrument uses a Teledyne Chroma D MCT (Mercury Cadmium Telluride) detector. Chroma D is a family of detectors that are constructed from fundamental building blocks, which can be configured for mission-specific needs. In this case, a 2k x 1k array will be designed for use on TRUTHS and incorporated into a new detector package.

The HIS functions as a pushbroom, so the detector measures the ground across-track along the 2k pixel axis, while the spectral measurements are made in the 1k pixel axis. The ALT measurements are achieved as the ground location being imaged changes with spacecraft movement (and time). These dimensions are illustrated in Figure 9.

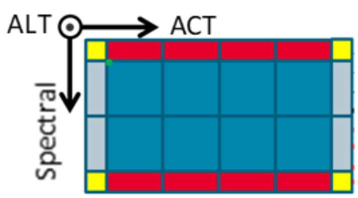

Figure 9: Detector axes: ACT, ALT and spectral

Table 1: Detector parameters

Parameter	**Value**
Across Track (ACT) pixels	2048
Spectral pixels	1024
Pixel pitch	0.018 mm
Cut on wavelength	300 nm
Cut off wavelength	2500 nm
ADC bits	14

Detector specifications, including cut on/off wavelengths are listed in Table 1. In the UV, reflections in the detector coating were expected to result in low quantum efficiency (QE). To improve this performance, an anti-reflection coating has been developed and tested, which reduces UV reflections and improves the QE at these shorter wavelengths. Figure 10 shows the tested QE for two sensor chip assemblies (SCA).

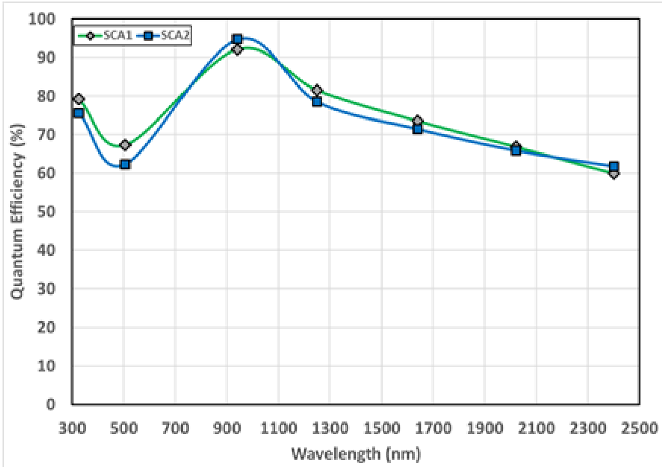

Figure 10: Tested quantum efficiency of new detector coating.

THERMAL CONTROL

Maintaining the HIS within strict thermal limits is complicated by the mission environment: the spacecraft orbit drifts through the year, and regular manoeuvres are required for calibration, solar and lunar measurements, simultaneous overpasses to other sensors, and the characterisation of Pseudo-Invariant-Calibration-Sites. The result is a wide range of possible illumination conditions for which the thermal design must meet performance requirements.

The HIS optical bench stability is ensured using a thermal enclosure covered with laminar heaters. The enclosure surrounding the optical bench is cooled radiatively using two radiators linked by embedded heat pipes to withstand direct solar flux. The mean temperature of the structure is controlled at 20°C with a maximal gradient of 2°C, minimising the structural and optical surface deformations due to thermoelastics. The FEE is regulated at around 20°C by use of a 'warm radiator' and a dedicated heating line to maintain stability.

Furthermore, variation in the thermal background incident on the detector must be kept to a minimum in order to meet the absolute radiometric accuracy requirement, which is critical to the ambitious mission objectives. One option is to cool the optical chain; however, if the thermal stability of the optical bench can be assured to within very strict limits, ambient operation of the optics becomes possible. Operating at ambient temperatures would greatly simplify the instrument design as well as the assembly, integration & verification (AIV) process. The immediate surroundings of the detector, within its cryostat, make a large contribution to the thermal environment. So, a cold shield is used, cooled to cryogenic temperatures using the same system as the detector.

MECHANICAL DESIGN

The baseline concept of the HIS structure is based on aluminium machined parts. The optical configuration allows for a natural split in the structure between the telescope and spectrometer optics. These subassemblies will be integrated independently, after which the telescope shall be mounted to the spectrometer, aligning at their mutual slit. To increase the stability of each optical subassembly, struts (isostatic mounts – ISM) are designed between the telescope and spectrometer.

The focal plane assembly (FPA) is integrated into its cryostat and onto the spectrometer bench. To maintain the alignment to the ambient optics when at the operating temperature of 150 K, the FPA is designed to be athermal. The HIS structure design also includes locations from which a thermal cover will be supported. The optics will be integrated on baseplates with isostatic mounts. The design of these bipods is chosen to reduce stresses in the bonded joints for a cold, non-operational case.

Figure 11 presents the HIS accommodation based on the optical configuration at the end of phase B1. The spectrometer and telescope are circled in a yellow, dashed line and purple, solid line respectively. The assembly envelope is 580 x 750 x 750 mm.

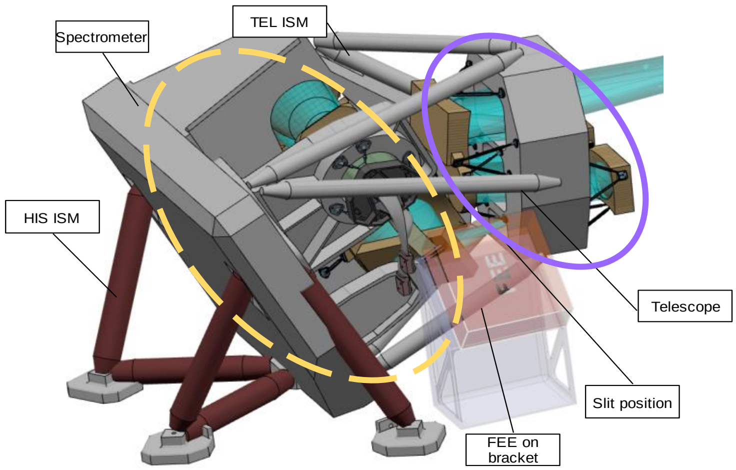

Figure 11: HIS mechanical architecture

REFERENCES

[1] Lake, K. et al, TRUTHS: Towards the in flight calibration of a hyperspectral imager to SI traceable standards, 2022