

Copernicus CHIME's Imaging Spectrometer: From development to first flight model

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ABSTRACT

Spaceborne hyperspectral imaging is a rapidly growing field, driven by its strong potential for disruptive applications across a wide range of scientific, environmental, and operational domains, including land monitoring, agriculture, climate studies, and resource management. Since 2015, AMOS has been actively contributing to the development of next-generation hyperspectral instruments. CHIME (Copernicus Hyperspectral Imaging Mission for the Environment) hyperspectral imager is one such next-generation instrument, developed, manufactured, assembled, and tested at AMOS.

CHIME is a hyperspectral Earth observation imager which features more than 200 spectral bands spanning the 0.4–2.5 μm wavelength range. It covers a 130 km swath with a ground sampling distance of 30 m. One of the instrument's main challenges is achieving the very large swath width required to ensure a maximum revisit time of 11 days with a two-satellite constellation. The optical solution relies on a set of three separate (but identical) F#3.3 spectrometer units per instrument and the spatial splitting of the instrument swath across these units in the focal plane of a common Three Mirror Anastigmat (TMA) front telescope.

AMOS is responsible for the development of the CHIME Spectrometer Sub-system (SPS), the core element of the instrument, which ensures high spectral and spatial uniformity across a wide focal plane, while meeting stringent radiometric and geometric performance requirements. The SPS adopts a patented compact demagnifying freeform Offner design. High throughput is ensured by the broadband convex diffraction grating, while freeform mirrors guarantee image quality and distortion control. Manufacturing, integration, alignment and testing of the spectrometers are performed at AMOS, with its instrument performance validated before delivery to OHB as CHIME instrument prime contractor. After the successful test campaign of the Engineering Qualification SPS model (EQM), AMOS is currently working on the assembling and testing of the first CHIME SPS flight model, composed of three independent spectrometers. This paper presents the current status and measured performances of the first SPS flight model. A range of optical and spectral performances, including MTF, distortion, and spectral resolution, are reported.

Keywords: hyperspectral imaging spectrometer, CHIME, Copernicus, Offner spectrometer, optical alignment, modulation transfer function, spectral smile, keystone, flight model

1. INTRODUCTION

The Copernicus programme was established to meet the growing need among European policy-makers for accurate and timely information to manage the environment, mitigate the effects of climate change, and support civil security. CHIME (Copernicus Hyperspectral Imaging Mission for the Environment) mission [1], [2] will deliver routine hyperspectral observations in support of EU policies for the sustainable management of natural resources, with emphasis on soil properties, mineral resources and agricultural services, including food security and biodiversity monitoring.

To enable accurate, quantitative estimates of vegetation bio/geophysical and biochemical variables, as well as top-soil and mineral composition, CHIME carries an imaging spectrometer able to resolve land and coastal/inland water bodies over many contiguous spectral channels from the visible to the short-wave infrared. The CHIME satellites are developed by an industrial consortium led by Thales Alenia Space. OHB System is the prime contractor for the CHIME payload, and AMOS (Liège, Belgium) is responsible for the development, manufacturing, integration, alignment and test of the Spectrometer Sub-System (SPS), the core optical element of the instrument.

The CHIME instrument achieves its 130 km swath and 30 m ground sampling distance by splitting the field of view of a common front-end Three-Mirror Anastigmat (TMA) telescope across three separate, but optically identical, F/#3.3 spectrometer units. Each unit is a compact, demagnifying, freeform Offner-Chrisp spectrometer, relying on a patented design, developed in AMOS [4], in which two freeform mirrors (SM1, SM2) and a spherical, broadband convex diffraction

grating relay the image of an input slit onto the focal plane. A demagnification factor of $M = -0.6$ is used to relax the constraints on the front-end optics while preserving spatial resolution, and to create the mechanical clearance required to accommodate three units side by side. The main driving requirements for the spectrometer optical design are summarized in Table 1.

Table 1. Main SPS optical design requirements (system level).

Parameter	Requirement
Spectral range	400 – 2500 nm
Spectrometer magnification	-0.6
Spectral resolution	< 10 nm
Spectral sampling interval	8.4 nm / binned pixel
MTF (spatial direction, ACT)	> 0.7 at Nyquist
Smile (EOL, binned pixels)	< 5.4 % (< 1.94 μm , revised)
Keystone (EOL, binned pixels)	< 2.2 μm
Detector format / pitch	1536 $\times$ 256 px ² , 36 μm (2 $\times$ 2 binned)

Because the limiting aperture stop of the front-telescope-plus-spectrometer system is placed inside the spectrometer, at the diffraction grating, each spectrometer unit can be radiometrically and optically calibrated independently of the front-end optics, and independently from the other units. This architecture also gives the CHIME concept a natural scalability: the number of spectrometer units can, in principle, be adapted to trade swath width against ground sample distance for future instruments built on the same optical philosophy.

Spectrometer optical design

The SPS relies on a customized Offner-Chrisp layout with a slit demagnification factor $M = -0.6$. The 90 mm-long, 60 μm -wide input slit is spectrally re-imaged by two concave freeform mirrors, SM1 and SM2, and a spherical convex diffraction grating operating in diffraction order $m = -1$. SM1 and SM2 are both compact freeform mirrors described by Chebyshev polynomial sag functions, as illustrated in the optical layout of Figure 1.

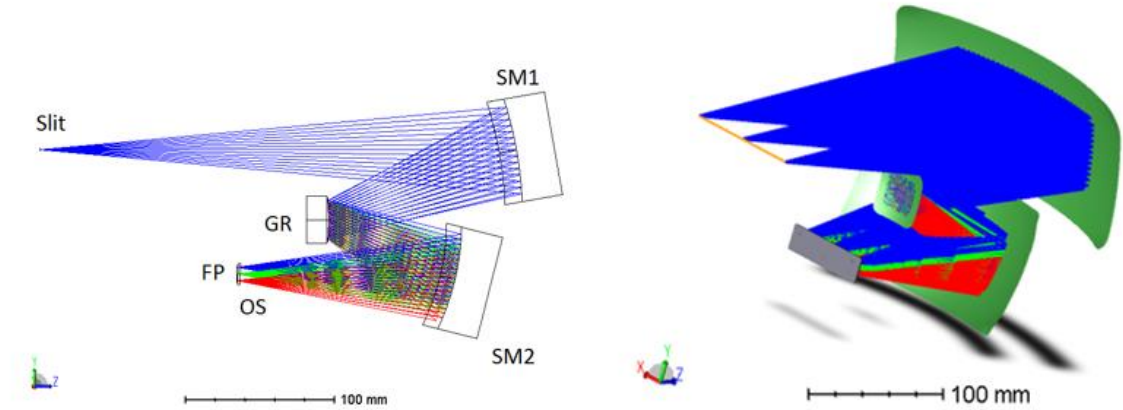


Figure 1. CHIME spectrometer optical design (left: Y-Z plane projection, right: 3D view). An order sorting filter (OSF) is added to the optical design in order to provide efficient rejection for the light from the spurious diffracted orders.



Figure 2 Photograph of one of the CHIME diffraction gratings (before coating)

The diffraction grating is a convex spherical substrate with a groove frequency of 47.68 grooves/mm (20.973 μm pitch) a photo of which is shown in Figure 2. To achieve sufficient diffraction efficiency over the full 400–2500 nm range in a single diffraction order, the grating uses a dual-blazed groove profile [3]. A thin fused-silica order-sorting filter is placed close to the detector to reject light diffracted into spurious orders.

The optical performance of each SPS unit is primarily assessed through three quantities: the modulation transfer function (MTF), a direct tracer of the spatial image quality; the spectral ‘smile’, which quantifies the spectral shift induced by the variation of spectral magnification along the slit; and the ‘keystone’, which quantifies the chromatic dependence of the spatial magnification. Nominal, as-designed sensitivity analyses predict that, without manufacturing and alignment tolerances, keystone and smile remain below 0.06 binned pixel peak-to-valley, and MTF across-track exceeds 0.77 at the detector Nyquist frequency — well within specification. Reaching this performance on hardware requires a dedicated integration, alignment and test sequence, in which the position of the mirrors, the slit and the detector are iteratively adjusted against the measured optical response of the assembled unit.

AMOS has completed the manufacturing, alignment and test campaign of the Engineering Qualification Model (EQM) of the CHIME spectrometer, and is now performing the same sequence on the first flight-representative spectrometer unit, SPS FM1.1. This paper reports the current status of this activity. Section 2 summarizes the alignment results and the measured optical performances obtained for the EQM unit; Section 3 reports the corresponding results obtained on the first flight-model unit (FM1.1); Section 4 compares the two campaigns and discusses the lessons learned and remaining activities ahead of the delivery of the complete flight instrument to OHB.

2. EQM SPS ALIGNMENT AND PERFORMANCE RESULTS

Alignment approach

The alignment of an SPS unit starts once its mirrors have been mechanically aligned with respect to the grating. A pre-alignment phase is first carried out without the slit installed: the transmitted wavefront error (WFE) is measured and optimized by adjusting the lateral position of SM2.

The axial positioning of the SPS slit and of the detector, based respectively on MTF and SSRF measurements, is performed during the preliminary alignment phase. Once pre-aligned the unit is then finely aligned to optimize its three key optical performances — keystone, smile and MTF — using three compensators: the clocking of the slit assembly, the axial position and clocking of the SPS focal plane, and the lateral (y) decentring of mirror SM2. The relationship between each compensator and the resulting change in performance is captured in linear compensation matrices, and the required compensator motion is obtained by least-squares pseudo-inversion. Once the alignment converges, the mirrors and slit support are torqued to fix their position, and the optical performances are re-measured to confirm that torquing did not introduce any degradation.

EQM alignment results

Table 2 summarizes the optical performance of the EQM SPS unit measured at the end of the alignment sequence, after torquing of SM1, SM2 and the slit support. The smile and keystone are reported here as absolute peak-to-valley residuals over the full field of view and spectral range, together with the applicable request-for-deviation (RFD) threshold accepted for the EQM and the original specification.

Table 2. EQM final alignment performance summary.

Parameter	Measured	RFD (3σ)	Specification	Status
Keystone	< 3.7 μm	< 2.7 μm	< 2.2 μm	Partially compliant
Smile	< 3.3 μm	< 3.1 μm	< 1.94 μm	Partially compliant
MTF (445 nm)	> 0.7	> 0.68	> 0.7	Compliant
SSRF	Compliant across FoV	< 10.7 nm	< 10 nm	Compliant

The residual keystone and smile, while slightly above the original specification, were judged close enough to it and were accepted for EQM purposes. The EQM keystone and smile measurements are shown in Figure 3 and 4. Smile and keystone were shown to be symmetric across the field of view and spectral range, and mutually orthogonal at the central field point, as expected from the optical design.

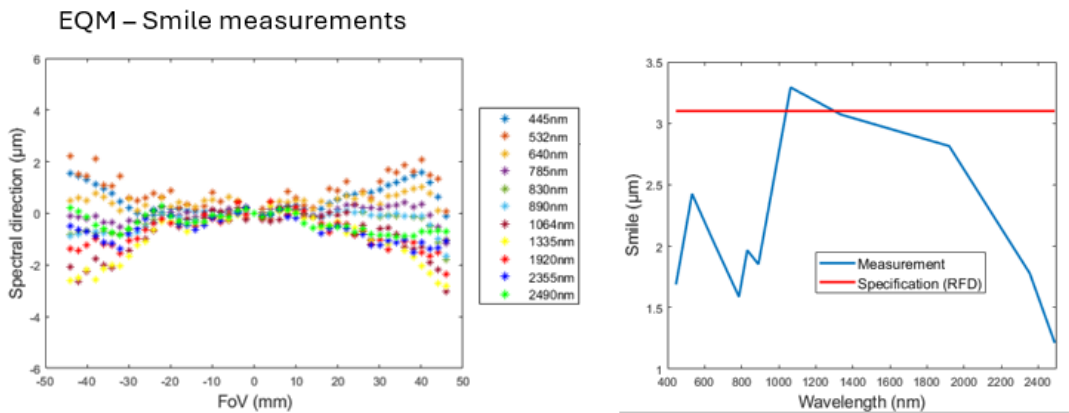


Figure 3Left panel: Centroid positions along the spectral direction as a function of the FoV for all wavelengths. right panel: Smile measurements as a function of the spectral range and comparison with the specification (RFD).

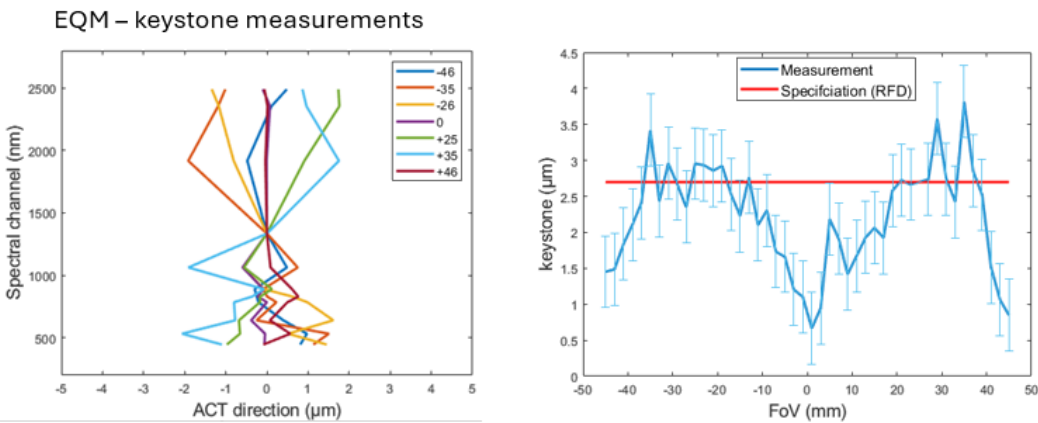


Figure 4 Left panel: spectral channel as a function of the ACT direction for different FoVs. Right panel: keystone measurements as a function of the FoV

MTF at 445 nm, corrected for the geometrical MTF contribution of the OGSE ground support equipment, was found compliant across the whole field of view (left panel, Figure 5). At longer visible wavelengths the MTF measurement was affected by speckle noise on the OGSE illumination sources resulting to noisy and inaccurate MTF results. The spectral resolution (SSRF) was also measured during the alignment phase and was found compliant with the specification across the visible range at all measured wavelengths (right panel, Figure 5).

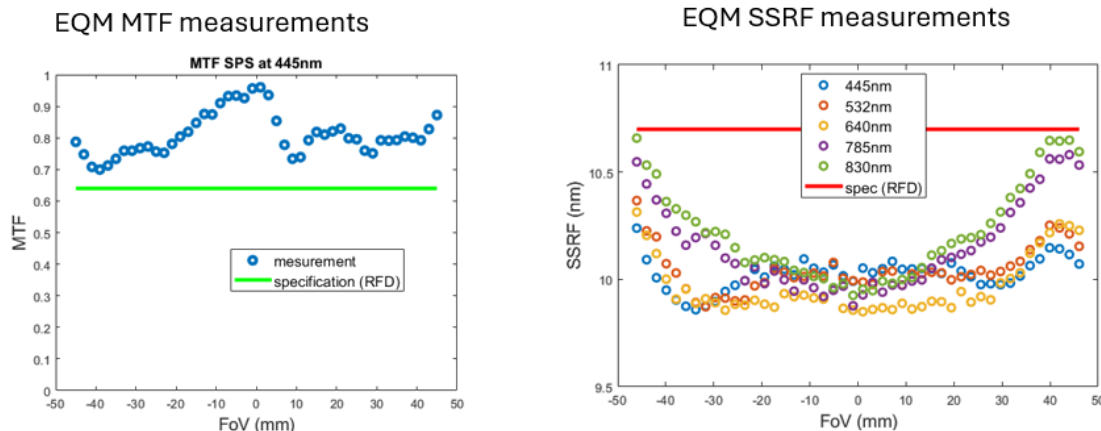


Figure 5 Left panel: MTF for the 445nm as a function of the FoV, Right panel: SSRF as a function of the FoV (for 445, 532, 640, 785 and 830nm).

Torquing of the mirrors and slit support was confirmed not to affect the smile, keystone or MTF: measurements repeated before and after torquing.

EQM optical performance test campaign

Following alignment, the EQM SPS unit underwent a full optical performance test campaign, covering focal-plane characterization, MTF, spectral resolution (SSRF), smile, keystone, magnification, spectral sampling interval (SSI), throughput, polarization sensitivity and stray-light, complemented by a reduced set of tests repeated after the environmental (thermal and vibration) test campaign.

The spectral sampling interval was measured, using the well-known emission lines of an HgXe spectral lamp spanning first and higher diffraction orders, to be 8.4002 nm/bin pixel. The magnification was found stable and well within specification across the field of view and spectral range, consistent with the very low distortion predicted by the optical design.

The measured throughput of the EQM unit fell below the specification, a shortfall attributed to the diffraction grating being uncoated (bare Ni-P) at the time of the EQM test campaign. The polarization sensitivity of the EQM unit, expressed as its degree of polarization (DoP), was found to exceed the 3.3% specification threshold across the measured visible range. Two contributing causes were identified: the grating being uncoated at EQM stage, and the unavailability of a contemporaneous OGSE polarization calibration, which required reuse of a calibration file acquired several months earlier.

Stray light was measured for both the homogeneous- and non-homogeneous-scene configurations. The homogeneous-scene stray light was found compliant with the specification, whereas the non-homogeneous-scene stray light was found only partially compliant, exceeding the specification within about 15 mm of the slit transition zone. Two possible root causes were identified for this non-compliance: (1) stray light generated by the OGSE ground support equipment itself, and (2) a ghost signal from back-reflection off non-black elements of the detector mounting.

A reduced set of MTF, keystone and smile measurements, repeated after the environmental test campaign, confirmed the stability of the EQM optical performance.

3. FM1.1 SPS UNIT ALIGNMENT AND PERFORMANCE RESULTS

FM1.1 alignment results

The first CHIME flight-model spectrometer unit, SPS FM1.1, was integrated and aligned following the same procedure and using the same three compensators as for the EQM: slit clocking, SPS focal-plane axial position and clocking, and SM2 lateral decentring. After the alignment converged, SM2 and the slit support were torqued, and the keystone, smile and MTF were re-measured and shown to be unaffected by torquing, in line with the EQM experience.

Table 3 summarizes the final FM1.1 alignment performance against the specification thresholds carried over from the EQM campaign. In contrast with the EQM, all three key performances — keystone, smile and MTF — were found fully compliant, as illustrated in Figures 6, 7 and 8. To the three key performances the SSRF was also measured during the alignment phase and was found compliant with the specification across the visible range (right panel figure 8).

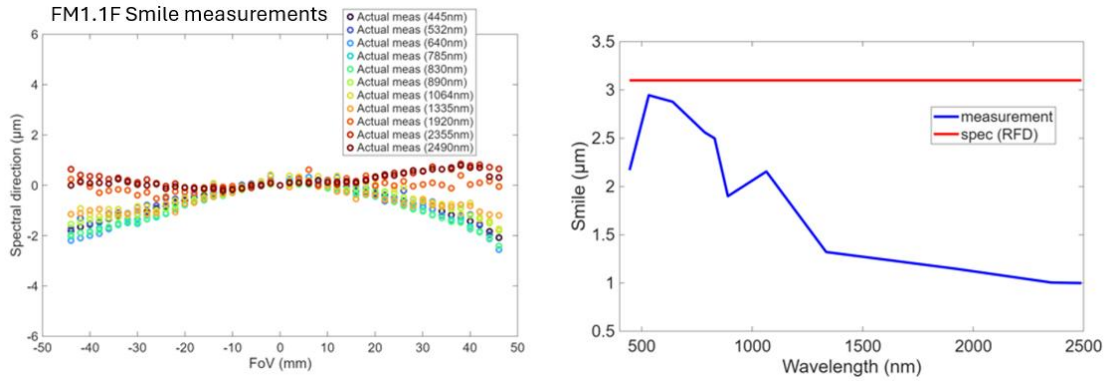


Figure 6 Left panel: Centroid positions along the spectral direction as a function of the FoV for all wavelengths. right panel: Smile measurements as a function of the spectral range and comparison with the specification (RFD),

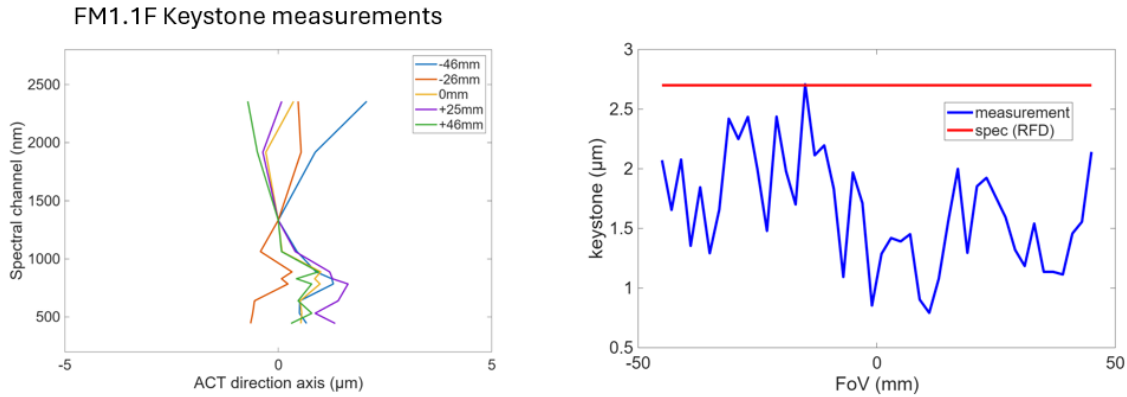


Figure 7 Left panel: spectral channel as a function of the ACT direction for different FoVs. Right panel: keystone measurements as a function of the FoV

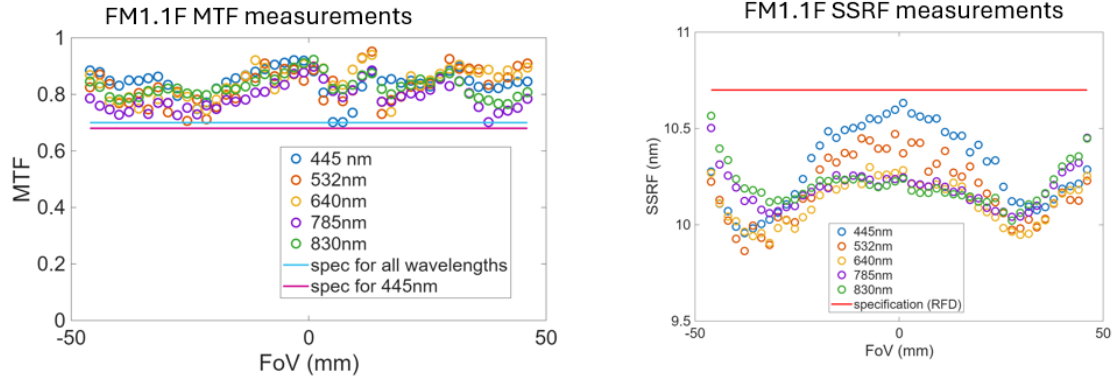


Figure 8 Left panel: MTF as a function of the FoV (for 445, 532, 640, 785 and 830nm), right panel: SSRF as a function of the FoV (for 445, 532, 640, 785 and 830nm),

Table 3. FM1.1 final alignment performance summary.

Parameter	RFD (3 σ)	Status
Keystone	< 2.7 μm	Compliant
Smile	< 3.1 μm	Compliant
MTF	> 0.70 (all λ); > 0.68 (445 and 2490 nm)	Compliant
SSRF	< 10.7 nm	Compliant

As for the EQM, the smile and keystone were found symmetric over the field of view and spectral range, and mutually orthogonal at the central field point. MTF was measured at different visible wavelengths and found compliant along the whole field for all wavelengths, without the speckle-related degradation reported at higher visible wavelengths on the EQM. The SSRF, measured at different wavelengths, was well within specification, corroborating the correct axial position of the focal plane established during the preliminary alignment phase.

FM1.1 optical performance test campaign

The FM1.1 unit was subsequently taken through the same optical performance test sequence applied to the EQM.

The spectral sampling interval, derived from the same HgXe spectral-lamp method used for the EQM, was measured to be 8.398 nm/bin pixel, complaint with the specification. Magnification was verified from centroid measurements along the spatial direction and were found stable and well within the specification.

The verification of throughput, polarization sensitivity and stray-light are yet to be done.

4. DISCUSSION AND CONCLUSION

The comparison of the EQM and FM1.1 alignment campaigns illustrates a clear and consistent maturation of the SPS integration and alignment process. On the EQM, the keystone and smile residuals remained slightly above specification (< 3.7 μm and < 3.3 μm respectively, against specifications of < 2.2 μm and < 1.94 μm) and were accepted for EQM purposes, while the MTF at 445 nm met specification but could not be reliably characterized at longer visible wavelengths owing to speckle noise on the OGSE illumination. By refining the OGSE test-bench illumination and detection chain, advancing the alignment procedure to perform slit and detector axial positioning during the preliminary phase, and incorporating higher-performance optical elements, FM1.1 SPS unit achieved full compliance on keystone, smile and MTF, without requiring any deviation.

At performance-test level, the EQM campaign identified two non-conformities that were understood and closed by analysis rather than by hardware rework: a throughput shortfall attributed to the diffraction grating being uncoated at EQM stage,

and a stray-light non-compliance for non-homogeneous scene. Both findings directly informed the flight-model build standard and test planning, and are being tracked through to FM1.1 verification and the subsequent flight units.

Overall, the results reported here demonstrate that the freeform, demagnifying Offner-Chrisp spectrometer design developed by AMOS for the CHIME SPS meets its driving optical requirements — modulation transfer function, spectral smile, keystone, spectral resolution and spectral sampling — on flight-representative hardware, and that the alignment and test methodology matured between the EQM and the first flight model translates into measurably improved compliance. AMOS is now pursuing the assembly, alignment and test of the remaining spectrometer units of the first CHIME flight instrument, ahead of the environmental test campaign.

Future work will report the alignment of the second and third SPS flight units of the FM1 instrument as well as the performance results of all three units and the results of the FM1 environmental test campaign.

Table 4. Side-by-side comparison of EQM and FM1.1 alignment and test outcomes.

Item	EQM	FM1.1
Keystone (alignment)	< 3.7 μm – partially compliant	Compliant (< 2.7 μm RFD)
Smile (alignment)	< 3.3 μm – partially compliant	Compliant (< 3.1 μm RFD)
MTF @ 445 nm	Compliant (> 0.7)	Compliant (> 0.68)
MTF, other visible λ	Degraded by SACCO speckle	Compliant across visible range
SSRF	Compliant across FoV (< 10.7 nm RFD)	Compliant (< 10.7 nm RFD)
Spectral sampling interval	Compliant	Compliant
Magnification	Compliant	Compliant
Throughput	NC – uncoated grating	TBD
Polarisation sensitivity	Out of spec (DoP > 3.3%) – uncoated grating and unavailability of calibration data	TBD
Stray light (non-homog. scene)	Partially-compliant – OGSE bench stray light and detector back-reflection ghost	TBD
Stray light (homog. scene)	Complaint	TBD

The comparison in Table 4 highlights that the two non-conformities raised at EQM level — grating throughput and stray-light for non-homogeneous scene — are understood, and tracked through to the flight build, while the alignment-sensitive performances (keystone, smile, MTF) show a clear improvement on the first flight unit, achieved without any hardware redesign.

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