

CALHYS: A 5-Metre Resolution VIS/SWIR Hyperspectral Payload for the ESA SCOUT HiBiDiS Mission

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ABSTRACT

The HiBiDiS mission (Hyperspectral Biodiversity Scout), led by SITAEL and selected for the second ESA SCOUT cycle, aims to advance the understanding of biodiversity and ecosystem function through detailed, multitemporal and multi-angular hyperspectral imaging of forest areas from a small satellite platform. This paper presents the design and analysis, at the end of the early-2026 consolidation phase, of CALHYS (Compact Agile Land-imaging Hyperspectral Spectrometer), the VIS/SWIR imaging payload developed by AMOS. CALHYS reaches a ground sampling distance of 5 m from a 400 km sun-synchronous orbit, a factor of six finer than PRISMA and EnMAP, within a mass below 50 kg and a power envelope below 50 W. It covers a continuous 0.45 to 1.7 μm range with 10 nm sampling and 125 bands on a single broadband InGaAs detector. The optical architecture combines a common 1280 mm front telescope with two co-aligned, all-reflective Offner-Chrisp-derived spectrometers in a staggered-slit configuration. Patented innovations, namely freeform design and a 0.6x slit demagnification, shrink the spectrometer volume and yield an athermal, monolithic aluminium bench. A complete performance analysis confirms compliance with the radiometric, spectral and spatial requirements and demonstrates a credible, low-risk path toward high-resolution hyperspectral Earth observation from small platforms.

Keywords: *hyperspectral imaging, imaging spectrometer, freeform optics, diffraction grating, Earth observation, biodiversity, ESA SCOUT, small satellite.*

1. INTRODUCTION

Biodiversity loss is now recognized as one of the most critical environmental risks of the coming decades, with consequences for ecosystem health that are both long-term and, in many regions, already acute. Observing biodiversity from space is intrinsically difficult: much of the relevant information lies in genetic and species-level diversity that is not directly visible from orbit. The scientific community has therefore defined a set of Essential Biodiversity Variables (EBV), conceptually analogous to the Essential Climate Variables tracked by the Copernicus missions, that capture the measurable proxies of ecosystem state. A subset of these variables, in particular canopy biochemistry, functional traits and vegetation structure, can be retrieved from spaceborne optical measurements.

Operational hyperspectral missions such as PRISMA and EnMAP provide rich spectral information but at a ground sampling distance of about 30 m, which is too coarse to resolve the spatial heterogeneity of forest stands or to separate the contributions of canopy and understorey. The HiBiDiS mission (Hyperspectral Biodiversity Scout) addresses this gap. It is the first satellite concept designed to look through the forest canopy and characterise the hidden understorey by combining three viewing angles, a 5 m GSD and a full VNIR-to-SWIR spectrum. Acquiring the same scene from several perspectives reveals the multi-layered structure that nadir-only missions cannot reach.

HiBiDiS is being developed within the second cycle of the ESA SCOUT programme, an industry-driven scheme in which companies and scientists jointly propose a mission rather than implementing a top-down ESA definition. The candidates missions have completed a nine-month consolidation of the science case and the technical concept, at the end of which two were selected for implementation. The payload presented here, CALHYS, is designed jointly by AMOS and Aerospacelab and benefits directly from the heritage of both partners: the AMOS imaging-spectrometer heritage for the spectrometer unit, and the Aerospacelab heritage for the front telescope and the payload electronics. This paper reports on the consolidated CALHYS design and the supporting optical, radiometric and budget analyses.

2. MISSION AND PAYLOAD REQUIREMENTS

The high-level mission requirements were established by the consortium during the early phase of the project. The combination of the required GSD and the revisit performance drive a trade-off between operating altitude and orbital repeat cycle. A sun-synchronous orbit with a 10:30 LTAN/LTDN is baselined, providing an acceptable solar zenith angle and low cloud cover, while a repeating ground track guarantees comparable viewing geometries for the multitemporal analysis. The pairing of a 16 μm effective detector pitch (10 μm native, 1.6x magnification) with a 1280 mm focal length yields the 5 m GSD at an operating altitude near 400 km. At this altitude, drag

compensation becomes a major operational driver, addressed at platform level by a SITAEL HT100 Hall-effect thruster [1]. The recurrence analysis shows that a 7-day revisit can be met by a single spacecraft provided the field of regard exceeds about plus or minus 25 degrees.

The top-level payload performance specifications, derived from the science case, are summarized in Table 1.

Table 1. Top-level CALHYS payload specifications (reference orbit 400 km).

Parameter	Value
Ground sampling distance	5 m
Swath width	10 km
Spectral range	0.45 to 1.65 μm (goal 0.4 to 1.7 μm)
Spectral sampling interval	10 nm (120 bands)
Acquisition line rate	120 Hz
MTF at Nyquist (excl. platform)	> 0.15 ACT / > 0.20 ALT (goal 0.20 / 0.25)
Spectral co-registration (smile)	< ± 1 nm (2 nm p-v)
Spatial co-registration (keystone)	< 1/5 pixel (2 μm p-v)
Signal-to-noise ratio @ 120 Hz	> 120 (goal 150) at reference radiance
Radiometric accuracy	< 5% absolute / < 3% relative (inter-pixel)
Out-of-band rejection	< 2% outside 3-FWHM
Polarization sensitivity	< 3%
Mass	< 50 kg
Power (operational, steady state)	< 50 W
Volume	< 600 x 600 x 450 mm
Operational lifetime	3 years

3. INSTRUMENT CONCEPT AND ARCHITECTURE

CALHYS is built around two co-aligned grating spectrometers whose slits are slightly offset in both the along-track and across-track directions, a configuration known as staggered slits. A single reflective front telescope images the ground onto each slit with a 5.5 km swath. Because the two slit swaths overlap by about 1 km, the overlap region guarantees perfect inter-slit co-registration while the combined swath of the payload reaches 10 km. Each spectrograph disperses the light from 0.4 to 1.7 μm onto its detector. The broad sensitivity of the InGaAs sensor allows the complete spectral range to be covered with a single detector, which removes the spectral co-registration errors inherent to multi-detector designs.

The InGaAs detectors do not require cryogenic cooling. Their temperature is controlled by a thermo-electric (Peltier) cooler mounted directly behind each sensor, linked to a cold radiator facing deep space through a high-conductivity strap. Each detector and its front-end electronics connect to the Instrument Control Unit and Data Processing Unit, which form the electrical interface to the satellite bus.

Following the approach validated on CHIME [2], [5], the payload combines a low-CTE front telescope (Zerodur mirrors, CFRP truss, Invar interfaces) with a nickel-plated aluminum-silicon alloy for the spectrometer unit. This alloy matches the coefficient of thermal expansion between the amorphous optical plating and the substrate, preserving mirror surface accuracy over a wide temperature range. Each subsystem is athermal by design, so the instrument does not require complex active thermal control beyond keeping the slits in the telescope focal plane. An aluminum-silicon optical bench supports the telescope on one side and the spectrometer unit and sensors on the other. It is isostatically mounted on the platform panel through bipod feet, and also carries the star trackers to ensure accurate instrument pointing. MLI provides the baseline thermal enclosure.

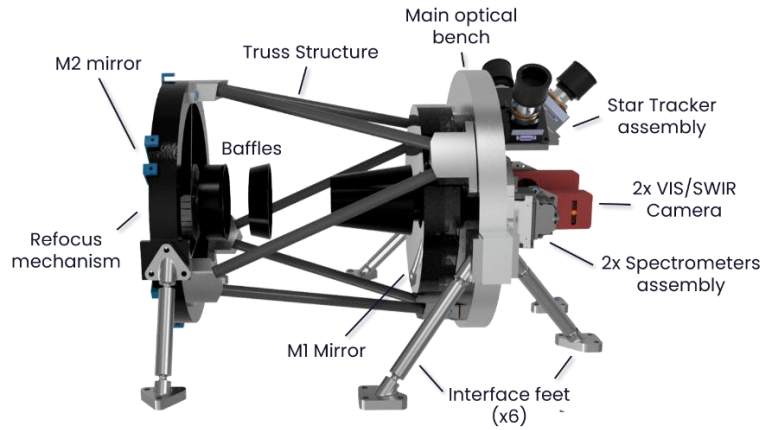


Figure 1. CALHYS payload overview.

4. OPTICAL DESIGN

4.1 Front telescope

The front telescope images a 5 m ground sample over the 10 km swath onto a $16\ \mu\text{m}$ slit pixel, with a 1:0.6 demagnification between slit and focal plane array. It must deliver a telecentric image space and an acceptance F-number above F/4.2 to match the spectrometer. A trade-off retained a Ritchey-Chretien form with a refractive field corrector, which is markedly more compact than an equivalent TMA or Korsch for this limited field of view. The corrector, three spherical fused-silica lenses, restores telecentricity and corrects residual field curvature and astigmatism at the edge of the field while keeping chromatic aberration controlled. The resulting telescope has a 1280 mm focal length, a 260 mm aperture (F/4.9), and a 1.65 degree diameter field of view. Centered surfaces keep manufacturing and alignment simple and affordable. A tolerance analysis based on the thermo-mechanical model shows that an M2 refocus mechanism is needed to compensate ground-to-orbit and hot-to-cold temperature differences and CFRP water desorption under vacuum.

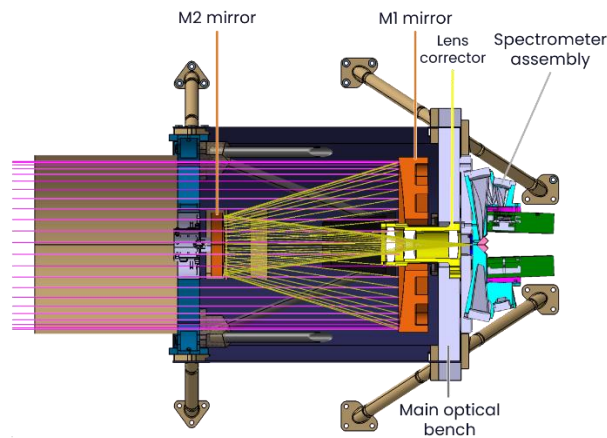


Figure 4. Optical layout of the front telescope: F/4.9 Ritchey-Chretien with a three-lens fused-silica field corrector providing a telecentric image space.

4.2 Spectrometer

Each spectrometer relies on a customized Offner-Chrisp layout incorporating a 0.6x slit demagnification. The 21 mm slit is spectrally re-imaged across 125 bands by a broadband spherical diffraction grating operating in order $m = -1$, ruled on a convex substrate [3], [6]. Two freeform mirrors, SM1 and SM3, are the key elements that achieve the compact form factor while correcting distortion; their departures from the best-fit sphere remain modest, so no manufacturing or testing difficulty is expected. The stop sits at the grating vertex, and the system is telecentric in object and image spaces. The demagnification lowers the working F-number, frees the volume needed to accommodate the COTS camera module, lowers the sensitivity to slit-related deviations and adds flexibility for straylight mitigation and mechanical accommodation. Together, these patented AMOS innovations reduce the spectrometer volume by approximately a factor of four with respect to an equivalent-performance Offner-Chrisp design.

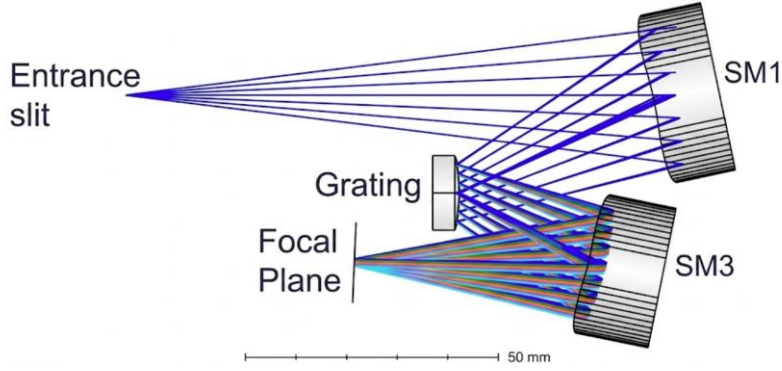


Figure 5. Optical layout of one spectrometer unit. The 0.6x slit demagnification opens room for the COTS camera module and lowers the F-number.

4.3 Straylight, ghosts and order sorting filter

A first-order straylight analysis of the front telescope was performed in FRED to size the baffles, ensuring that no direct ray reaches the focal plane without passing through both mirrors. Three baffles complement the main baffle: a front baffle blocking incidence beyond about 13 degrees, a lens-corrector baffle suppressing the M1-M2 double reflection, and an M2 plus intermediate baffle assembly, a configuration already proven on large-FoV survey astronomical telescopes, that stops light reaching the corrector without passing through the mirrors. Critical surfaces are coated with ultra-black paint. Two ghost mechanisms are addressed by heritage solutions: the slit-image ghost, intrinsic to Offner spectrometers because the slit is conjugate with the focal plane, is controlled by a sub-micron multilayer black coating qualified by CILAS on the CHIME slits and applied to the CALHYS slit without altering the aperture; and grating diffraction ghosts, which AMOS has characterized on its dual-blazed gratings and keeps to a low level. A thin order sorting filter in front of the sensor rejects the second- and third-order diffraction that would otherwise appear above 900 and 1350 nm, and broadband anti-reflection coatings on the corrector lenses limit double-reflection ghosts.

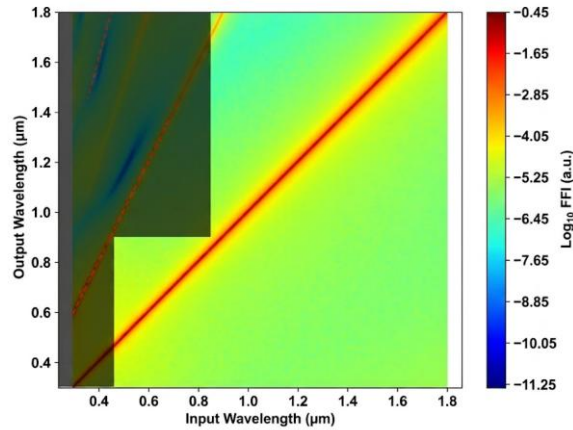


Figure 6. Computed grating spectral response matrix including straylight background from ruling error, the order sorting filter (dark spectral rejection region on the left) suppresses the spurious second and third orders and fully preserves the first order (diagonal response).

5. PERFORMANCE ANALYSIS

The telescope MTF is diffraction-dominated, with a mean value of about 0.7 in the visible and 0.5 in the SWIR including the effect of the central obscuration. Lateral chromatic aberration keeps the centroid within 2.4 μm peak-to-valley over the full spectral range, about 1/7 of a pixel, which bounds its keystone contribution. At spectrometer level, the geometric spatial (sagittal) MTF at the 50 lp/mm Nyquist frequency ranges from 83% to 95% over the focal plane, and the spectral (tangential) MTF stays above 82%, broadening the spectral response function by only about 1.2 times the sampling interval. The design is strongly optimized against distortion: the smile is limited to 0.35 μm peak-to-valley, equivalent to a 0.2 nm variation of central wavelength across the swath, and the keystone to 0.5 μm , about 1/20 of the GSD. Both meet the smile and keystone requirements with comfortable margin.

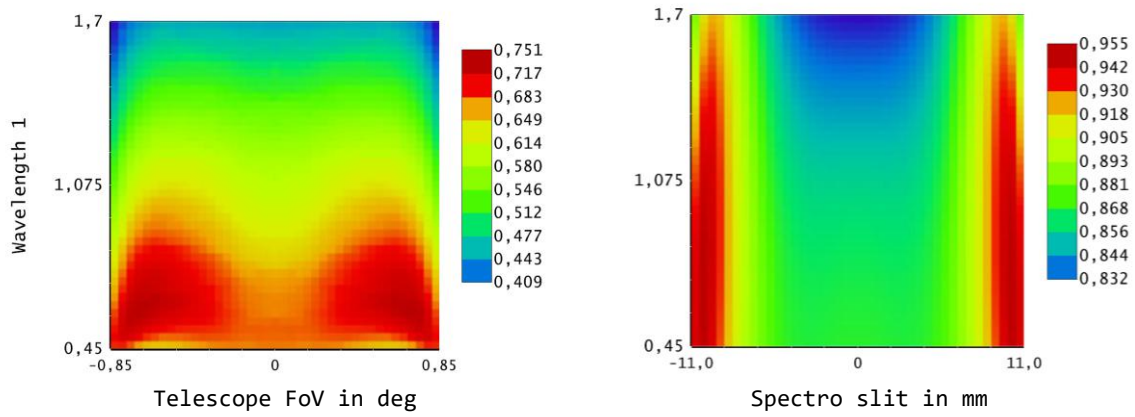


Figure 7. Modulation transfer function of the payload at Nyquist : telescope MTF versus field and wavelength (left) and spectrometer spatial MTF (right).

The grating throughput is broadened across 0.4 to 1.7 μm by an engineered dual-blazed groove profile, demonstrated on CHIME, that distributes the diffracted power evenly over the band while keeping the grating polarization sensitivity below 2%. Mirrors and grating use a UV-enhanced protected silver coating from CILAS, qualified by AMOS on nickel-plated AlSi mirrors, whose polarization sensitivity stays below 1% for the typical sub-30-degree incidence angles. Accounting for the four spectrometer reflections and the grating efficiency, the spectrometer transmits 30% to 50% of the incoming flux in the useful order, while the telescope throughput is about 0.7. Combined with the InGaAs quantum efficiency, which rises from 20% to 40% across the visible and is flat near 75% in the SWIR, the resulting signal-to-noise ratio is shot-noise dominated and rather uniform across the band, with a mean near 120 at the reference radiance (0.3 albedo, 30 degree SZA) for the 8.3 ms frame period. Should a specific science application require it, the grating efficiency can be tuned, for instance toward the red, with the model matching measured performance to better than 5%.

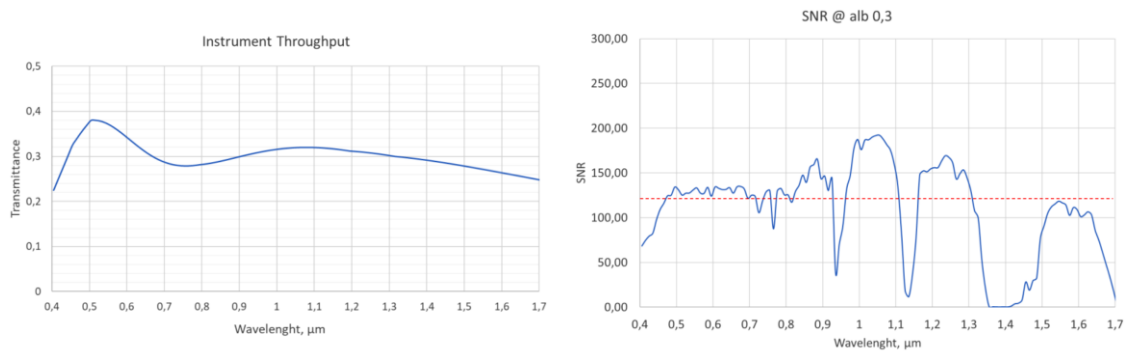


Figure 8. Radiometric performance: total instrument throughput (telescope and spectrometer) and computed signal-to-noise ratio over the spectral range at the reference radiance level.

At system level, the preliminary mass budget totals about 40 kg including roughly 20% margin, comfortably under the 50 kg allocation. The MTF budget, split into along-track and across-track contributions and combining optical design, manufacturing, alignment and detector terms, meets the 0.15 ACT and 0.20 ALT requirements before platform smearing. The radiometric budget, built from calibration-GSE, instrument and sensor contributions and assuming periodic in-orbit recalibration, supports the 5% absolute and 3% relative accuracy requirements. Table 2 summarises compliance against the key requirements.

Table 2. Summary of predicted performance against key requirements.

Requirement	Specification	Predicted	Status
GSD	5 m	5 m	Compliant
Swath	10 km	10 km (1 km overlap)	Compliant
Spectral range	0.45 to 1.7 μm	0.4 to 1.7 μm	Compliant (goal)
Smile	< 2 nm p-v	0.2 nm	Compliant
Keystone	< 1/5 GSD	1/5 GSD	Compliant

Requirement	Specification	Predicted	Status
SNR @ 0.3 alb, 30°SZA	> 120	~120 (mean)	Compliant
MTF (ACT / ALT)	0.15 / 0.20	Meets budget	Compliant
Polarization	< 3%	< 2%	Compliant
Radiometric (abs / rel)	5% / 3%	Within budget	Compliant
Mass	< 50 kg	~40 kg	Compliant
Power	< 50 W	< 50 W	Compliant

6. HERITAGE, DEVELOPMENT PLAN AND CONCLUSION

CALHYS carries heritage for every critical technology, substantially lowering the development risk. The front telescope is derived from the Aerospacelab ROSE design and reuses its flight-proven refocus mechanism. The spectrometer is a modified version of the architecture matured on the ESA CHIME programme, from which the dual-blazed grating technology and the slit black coating are inherited, while the patented demagnification was first introduced on ELOIS [4]. The detector is a space-qualified, commercially available COTS InGaAs module, and the payload computer (ICU and DPU) reuses the Aerospacelab PLC already flown on six satellites. AMOS contributes an extensive single-point-diamond-turning manufacturing heritage on aluminium mirrors and gratings, demonstrated on Sentinel-5p TROPOMI, Proba-V and Chandrayaan-2, and a series of ESA-supported miniaturised-spectrometer breadboards built and tested since 2013.

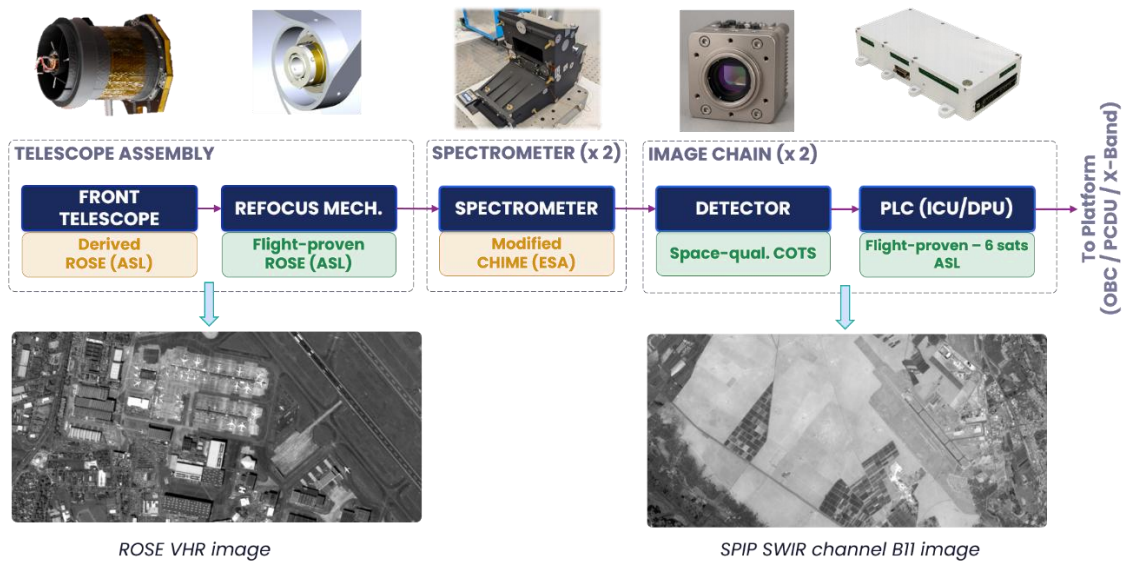


Figure 9. Building blocks with heritage: front telescope and refocus mechanism (ROSE / Aerospacelab), spectrometer and grating (CHIME, ELOIS), COTS InGaAs detector, and PLC (Aerospacelab, flown on six satellites).

The implementation phase is planned to start with a kick-off in early 2027, followed by SRR and PDR in 2027, breadboard and spectrometer verification together with the engineering and qualification of the detector and order sorting filter, a structural and thermal model and a delta-qualification of the PLC, CDR in 2028, and protoflight-model AIV leading to delivery in early 2030.

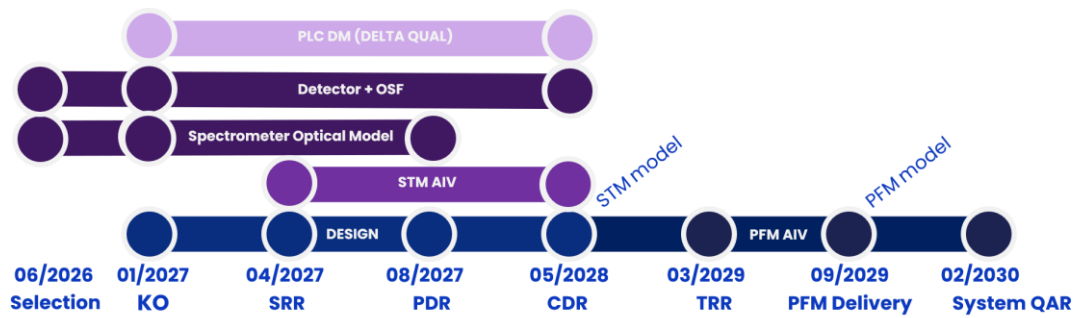


Figure 10. Indicative implementation schedule from kick-off (early 2027) through PDR, CDR and protoflight delivery (early 2030).

In conclusion, the CALHYS consolidated design meets the radiometric, spectral and spatial requirements of the HiBiDiS science case while remaining within a sub-50 kg and sub-50 W envelope. By combining a compact Ritchey-Chretien telescope with twin staggered-slit, freeform Offner-Chrisp spectrometers and a single broadband InGaAs detector, the payload delivers a 5 m GSD over a 10 km swath across the full VNIR-SWIR range, a factor of six finer than current operational hyperspectral missions. Supported by mature, flight-proven building blocks from AMOS and Aerospacelab, CALHYS demonstrates a credible and low-risk path toward high-resolution hyperspectral Earth observation from small satellite platforms, and a new capability for monitoring biodiversity and ecosystem function from space.

7. ACKNOWLEDGEMENTS

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