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TARSIS, the 8 arcmin^2 IFU for the Calar Alto 3.5m telescope

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Abstract

TARSIS (Tetra-Armed Super-IFU Spectrograph) is a wide-field Integral-field Unit (IFU) with an 8-arcmin^2 field of view (FoV), adopted by the Calar Alto Observatory (CAHA) for its 3.5m telescope, currently in the preliminary design phase. It uses image-slicers to cover its FoV, feeding four spectrographs with a resolving power of R$\sim$1000, covering 320-520 nm (three spectrographs/quadrants/arms) and 510-810 nm (one quadrant), with a spaxel size of $\sim$2×2 arcsec^2. TARSIS will support the CATARSIS survey, a blind spectroscopic mapping of 16 galaxy clusters in the range $0.15 < z < 0.23$, out to their virial radii, using all CAHA 3.5m dark time over six years, beginning in 2028.

1 INTRODUCTION

As part of the Calar Alto Observatory's 2020 Call for "*New legacy proposals and instrumental concepts*", UCM and IAA-CSIC led a proposal for carrying out CATARSIS (Calar Alto

"*Tetra-ARmed Super-Ifu spectrograph*" Survey), a survey that aims at obtaining *blind*, deep spectroscopy of galaxy clusters and filaments at redshifts z∼0.15-0.23, down to a limiting magnitude of $m_{\mathrm{r,AB}}$=22 mag. CATARSIS will achieve high sensitivity to residual star formation in cluster galaxies by reaching the UV atmospheric cutoff at ∼320 nm. It will also deliver large samples of background galaxies, including numerous spectroscopically confirmed intermediate-redshift Lyman-α emitters (LAEs).

The scientific goals of CATARSIS led to the design of TARSIS, a new instrument for the CAHA 3.5m telescope. Following two successful selection processes, including a competitive feasibility study, TARSIS was chosen in May 2022 as the new-generation CAHA 3.5m instrument, with CATARSIS as its primary science target. The Conceptual Design phase concluded in 2023, and we are now in the Preliminary Design phase. TARSIS first light is scheduled for 2028.

TARSIS offers an unprecedentedly wide FoV, blue optimization, and intermediate resolving power. It will cover a 2.8×2.8 arcmin^2 FoV with four image slicers, each spanning 1.36×1.36 arcmin^2. It provides a combined 320-810 nm spectral range with a spaxel size of 2.05×2.05 arcsec^2 and a resolving power of R∼1000. Figure 1 shows the preliminary optomechanical design and subsystems. We describe below the TARSIS subsystems: image slicers, spectrographs, detectors, control, data reduction pipeline, and science tools. A description of the CATARSIS survey is provided in Sánchez-Blázquez et al. as part of these proceedings.

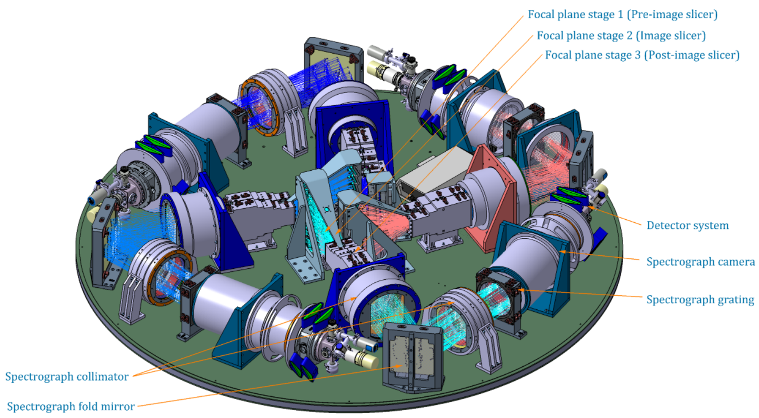

Figure 1: TARSIS in the Cassegrain focus of the CAHA 3.5m telescope, The four spectrographs and the different subsystems are labelled.

2 TARSIS subsystems

This section describes the main TARSIS subsystems: the Focal Plane (including rotator, slicers, and optics), four Spectrographs and Detectors, Control, and Scientific Software. TARSIS and CATARSIS are integral to one project, with TARSIS expected to serve as Calar Alto's workhorse instrument for years, even post-CATARSIS.

2.1 Focal Plane

To maximize its field of view, TARSIS employs four image slicers: three for blue-optimized spectrographs and one for a red-optimized spectrograph. Light is distributed through four pick-off mirrors arranged like a hipped roof, each covering 1.36×1.36 arcmin^2 and separated by 4.1 arcsec gaps (2 spaxels). Additionally, three mirrors in front of the pick-offs can rotate around the optical axis to adjust for different Position Angles (PA) on the sky, as shown in Figure 2.

A pre-image slicer optical system is required to ensure a relatively slow beam reaches the slicers, minimizing vignetting and optimizing the allocated space at the CAHA 3.5m Cassegrain focus. Each arm's optical system reimages the light from F/10 at the pick-off mirrors to F/20 at the image slicer mirrors. The blue (red) pre-image slicer consists of two triplets (doublets) and a fold flat mirror.

The image slicers, designed following Bertin-Winlight's fully reflective concept [1], include two sets of optical components: slicer mirrors and reimaging mirrors (see Figure 3). The slicer mirrors divide the light from each quadrant into 40 slices, directing it to two rows of reimaging mirrors. These mirrors create two stepped parallel curved pseudo-slits spaced to allow projection with a half detector difference. The slicers relay the focal plane from F/20 to F/9, with the mirrors arranged in two parallel rows to produce output stepped pseudo-slits. Each pseudo-slit contains 20 slices, maximizing multiplexing and FoV, the key design objective of TARSIS. The gap between projections is optimized to minimize vignetting, measuring 2.3 mm at the detector (or 155 pixels).

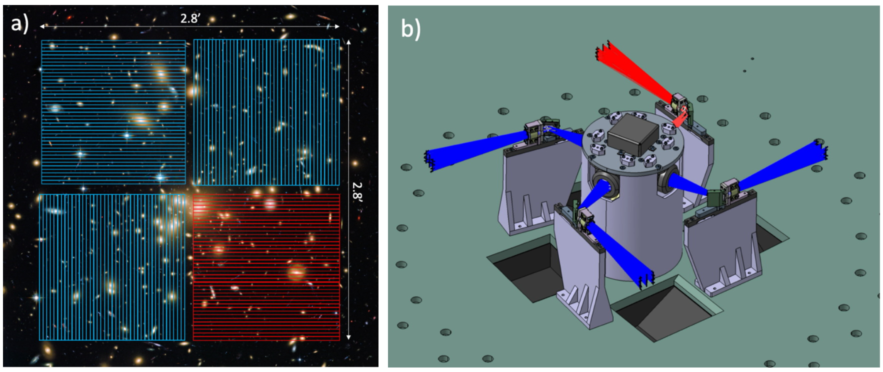

Figure 2: a) TARSIS layout. The four image slicers are shown. We show the 40 slices feeding the red spectrograph in red while the three sets of 40 slices each that feed the three blue spectrographs are shown in blue. b) Pre-image slicer opto-mechanical assembly design. The four pick-off mirrors are located inside.

A highly curved focal plane is provided at the image slicer exit. We use an optical relay system (or post-image slicer) to flatten the focal plane and to provide a faster beam (F/3) and a nearly telecentric exit pupil (see Figure 3). There are total of eight post-image slicers (one per pseudo-slitl). The post-image slicers, both the red and blue ones, have 9 lenses that are all made or either Fused Silica or CaF_2 to maximize throughput at these wavelengths.

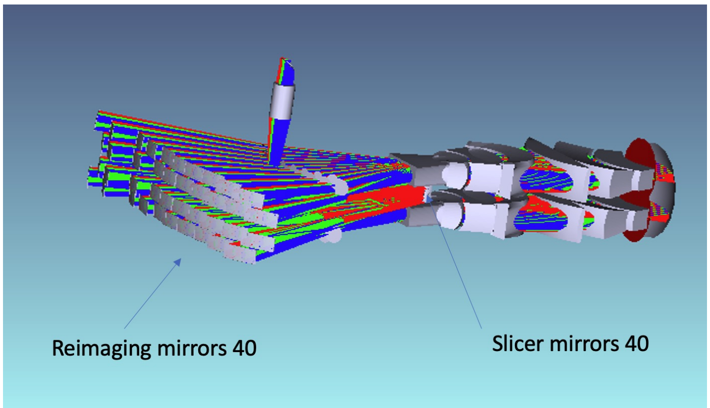

Figure 3: Image slicer optical layout. The pre- and post-image slicer components are also shown.

2.2 Spectrographs

Each TARSIS spectrograph re-images two curved pseudo-slits onto a flat focal plane equipped with a single 4k $\times$ 4k detector. The spectrographs are all collimator-camera systems with a reduction factor from F/3 to F/1.5. The angle between the collimator and camera is fixed but varies for the blue (12.9 Å) and red (13.2 Å) spectrographs (see Figure 4). Located between the collimator and the camera, the pupil houses the Volume Phase Holographic (VPH) dispersing element.

The blue collimator consists of six Fused Silica and CaF_2 lenses, while the blue camera contains nine lenses, with all but one made of the same materials. The red collimator has four lenses, and the red camera comprises seven lenses made from different glasses and CaF_2. To prevent contamination between the pseudo-slits, we make use of band-pass filters in all four arms.

Both the blue and red spectrographs feature a double grating, designed by Wasatch Photonics, consisting of two gratings with slanted lines at varying angles. This configuration allows light from one slit to be efficiently diffracted by one grating while passing undiffracted through the second, which only diffracts light from the second slit. The VPHs in the blue spectrographs have 542 lines per mm, centered at 420 nm, covering 320-520 nm. The red spectrograph's VPH has 370 lines per mm, centered at 660 nm, with a range covering 510-810 nm. Additionally, we evaluated a high-resolution red VPH with 720 lines per mm, covering 590-730 nm at double the resolution of the nominal red VPH. We note that this high-resolution configuration is not part of the CATARSIS survey baseline.

2.3 Detectors and cryogenics

The four cameras of TARSIS project light onto four flat Charge-Coupled Device detectors (CCD model 231-84 from Teledyne), each with an active area of 61.4×61.4 mm^2 (4096×4096 15-μm pixels). Certain regions of these detectors are intentionally left unilluminated to prevent contamination between pseudo-slits and to accommodate tolerances related to lines-per-mm, detector positioning, and the effective lengths of collimators and cameras. Of the four CCDs, one is optimized for red wavelengths, while three are tailored for the blue.

Extreme sensitivity at the blue end of the spectrum is a key design goal for TARSIS. We selected the Teledyne NBB© blue-enhanced antireflection coating for the blue detectors, yielding a quantum efficiency (QE) of 70% at the bluest wavelength of 320 nm. The blue detectors will be fabricated from standard silicon, approximately 15 μm thick, providing excellent blue response. A Deep-Depletion CCD, about 40 μm thick, has been selected for the red detector, which efficiently absorbs red photons, maximizing quantum efficiency (QE) and minimizing fringing. At the upper limit of the TARSIS bandwidth (810 nm), this red detector achieves a QE of 85% with the Teledyne ML15© antireflection coating.

The readout noise for the CCD231-84 can be as low as 2.1 e^- root-mean-square (RMS) at very slow readout speeds. With the dual-amplifier configuration, we anticipate a readout noise of about 3-3.5 e^- RMS for a 60 s readout time. This configuration is preferred over the faster quad-amplifier due to potential cross-talk in between amplifiers in the latter case.

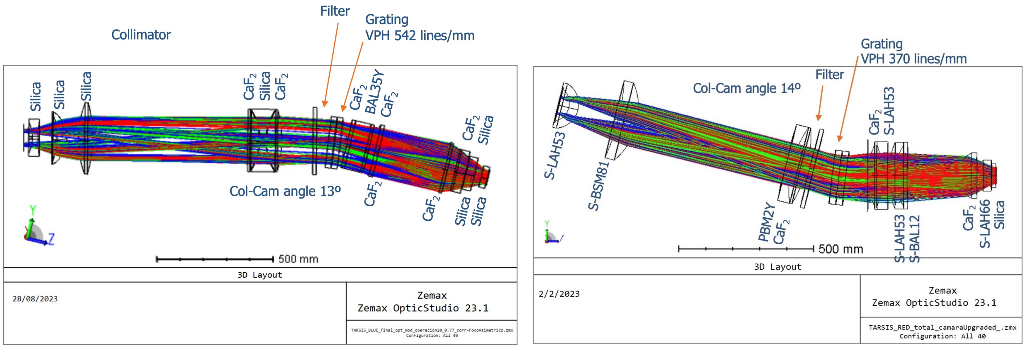

Figure 4: Left) Optical design of the blue spectrograph. The materials used are labeled. Right) Red-spectrograph optical design. The majority of blanks for all spectrographs have been received at CAHA and are manufactured by Ohara Corp. and Hilger Crystals Ltd.

To mitigate dark current effects, the CCDs must be cooled to ∼158 K and housed in a vacuum cryostat. For each of the four CCD heads, we will utilize the same MUSE instrument design [2] currently employed in the CARMENES instrument (shown in dark gray in Figure 5; [3]). Although this was initially designed for the ESO continuous flow cryostat, we opted for a *Stirling* system, specifically the Cryotel MT© cooler, featuring an AMETEK Inc.'s anti-vibration controller. This compact, closed-cycle cooler includes its own compressor (illustrated in light gray and yellow in Figure 5). The CCDs will be read out using STA Archon© controllers, which handle two CCDs each and will be synchronized via a serial cable.

2.4 Control system

The TARSIS Instrument Control System (ICS) encompasses hardware elements (Instrument Control Electronics or ICE) and a software management system (Instrument Control Soft-

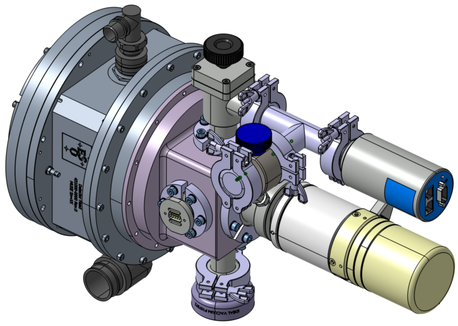

Figure 5: One of the cryostat assemblies used for each of four TARSIS arms.

ware, ICSW). Key subsystems integrated into the ICS include the Acquisition and Guiding System (A&G), Calibration Unit (CU), optical rotator for position angle adjustments (the Rotator), and the four TARSIS spectrographs with their corresponding detectors.

The A&G design features a Complementary Metal Oxide Semiconductor (CMOS) detector that primarily utilizes off-the-shelf components, except for the focusing mechanism, which requires external components to adjust one optical element along the longitudinal axis. This involves a motor and encoder. The CU comprises a power supply and shutter for each of the six calibration lamps and a mechanism for inserting elements into the optical path during calibration.

For the Rotator, a specialized rotary platform will be implemented to fit within the limited envelope space, equipped with a standard digital data interface managed through a dedicated ICS module.

The four CCD detectors will be operated via computers in the control room, communicating with two Archon© controllers through an Ethernet interface using optical fibers. Interface modules will convert the signals from the controllers to optical format, with detector shutters controlled by a common signal from the detector system. The Control System will monitor temperature readings from sensors throughout the instrument and manage interlocks. While the detectors will function in cryogenic conditions within four cryostats, their operation will be overseen by the detector system rather than the control system.

2.5 Scientific Software

TARSIS employs four spectrographs that operate across two spectral ranges, utilizing eight pseudo-slits that made up of 160 slices –half oriented horizontally and the other half vertically (see Figure 2). The complex task of matching the spectra registered on the four detectors with the sources in the large $\sim$8 arcmin^2 FoV of TARSIS necessitates of the development of robust software tools. Key functionalities include (1) optimizing observing strategies (see Figure 6), (2) processing raw data, (3) generating CATARSIS data products, (4) combining multiple observations to cover areas larger than TARSIS's FoV (see Section 3), and (5) efficiently managing the large data volumes produced.

These five critical aspects and their associated requirements are organized under a general *Scientific Software* work-package. The TARSIS team is developing several software tools and sub-packages, including the TARSIS Scheduler, Simulator, Exposure Time Calculator (ETC), Data Reduction Pipeline (DRP), Post-Processing, Quality Control (QC), Storage, High Performance Computing (HPC), and CATARSIS-specific scientific analysis tools.

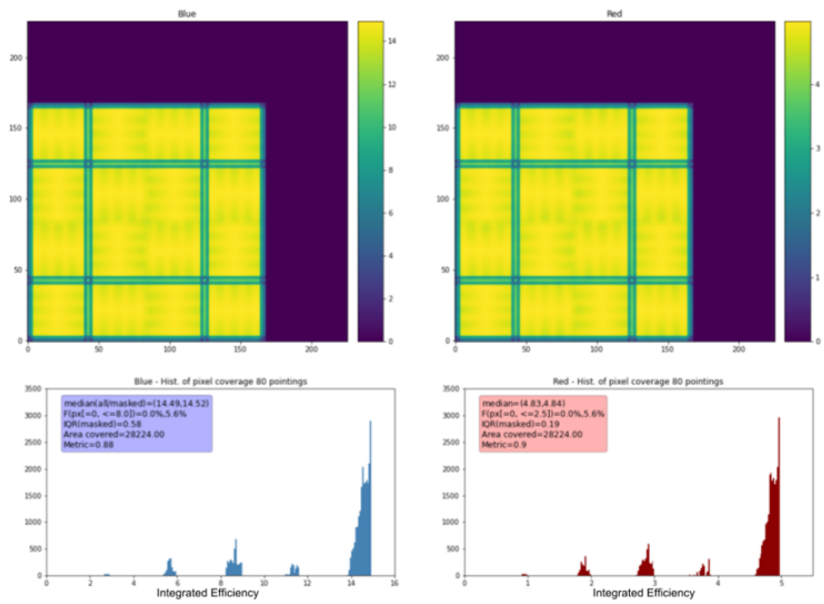

Figure 6: Left) Exposure maps (top) for the blue (left) and the red (right) spectrographs given an observing block with 4 pointings rotated by 90 degrees, which nicely covers the 4 quadrants (except for the gaps). The histograms (bottom) show that the blue integrations are 3× deeper than the red ones. Right) Exposure maps (top) with a gap-dithering strategy and resulting histograms (bottom). In this case, we use 4 sets of 5-dithering patterns (with an offset of 2 slices), separated by a FoV (82 slices).

The TARSIS Scheduler, illustrated in Figure 6, is essential for achieving uniform coverage of the CATARSIS footprint. Given the characteristics of the TARSIS field of view, including gaps and vignetting patterns introduced by the image slicers, careful planning of rotation, mapping, and dithering strategies is critical –especially for a ground-based instrument.

To optimize CATARSIS observations, an early implementation of both an ETC and a Simulator is key. The ETC will determine the total exposure time necessary to meet the CATARSIS's scientific goals, while the Simulator will generate raw TARSIS science and calibration images compatible with the Data Reduction Pipeline (DRP) and post-processing tools, facilitating their development.

The DRP aims to process individual exposures from CATARSIS observations, each lasting approximately 1920 seconds, to create products for post-processing. The expertise of the UCM team, known for their work on the EMIR [4], MEGARA [5], and FRIDA [6] pipelines for the GTC telescope, will be invaluable in this effort.

CATARSIS observations require more than simple individual exposures. They necessitate (1) combining four different orientations at a single sky position, (2) dithering between individual positions (to fill gaps and mitigate the impact of the slicers' vignetting pattern), and (3) mapping extended clusters and filaments. This allows to reach a total effective exposure time across the majority of each mapping area of 8 hours in the blue and 2.67 hours in the red. The TARSIS Post-Processing sub-package focuses on optimally combining these observations, which significantly impacts the Storage and High Performance Computing (HPC) components of the project. We will leverage the expertise of the CAB Virtual Observatory and UAL HPC groups.

As a legacy to the community, CATARSIS will provide a suite of data products: final data cubes from the TARSIS Post-Processing software and science-ready products such as emission-line maps, source catalogs, extracted spectra, Spectral Energy Distributions (SEDs), and various measurements from our 2D and 1D spectra. These products will resemble those provided by the MEGADES Survey [7] with the GTC MEGARA instrument and will assist in achieving the scientific objectives of CATARSIS, as described in Sánchez-Blázquez et al. as part of these proceedings.

Acknowledgments

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