DOI: 10.18727/0722-6691/5278

CUBES, the Cassegrain *U*-Band Efficient Spectrograph for the VLT

Stefano Cristiani[1]
Juan Manuel Alcalá[2]
Silvia H. P. Alencar[3]
Gerardo Avila[39]
Sergei A. Balashev[4]
Nate Bastian[5,6]
Beatriz Barbuy[7]
Umberto Battino[8]
Ariadna Calcines[9]
Giorgio Calderone[1]
Pamela Cambianica[10]
Roberta Carini[11]
Brad Carter[12]
Santi Cassisi[13]
Bruno Vaz Castilho[14]
Gabriele Cescutti[15]
Norbert Christlieb[16]
Robero Cirami[1]
Igor Coretti[1]
Ryan Cooke[17]
Stefano Covino[18]
Gabriele Cremonese[10]
Katia Cunha[19]
Guido Cupani[1]
André R. da Silva[20]
Vincenzo De Caprio[2]
Annalisa De Cia[21]
Hans Dekker[22]
Valerio D'Elia[23]
Gayandi De Silva[24]
Domenico D'Auria[2]
Valentina D'Odorico[1]
Marcos Diaz[7]
Paolo Di Marcantonio[1]
Alan Fitzsimmons[25]
Heitor Ernandes[7]
Chris Evans[26]
Mariagrazia Franchini[1]
Matteo Genoni[18]
Boris Gänsicke[27]
Clemens Gneiding[14]
Riano E. Giribaldi[20]
Andrea Grazian[10]
Camilla Juul Hansen[28]
Fiorangela La Forgia[29]
Marco Landoni[18]
Monica Lazzarin[29]
David Lunney[30]
Walter Maciel[7]
Wagner Marcolino[31]
Marcella Marconi[2]
Alessandra Migliorini[32]
Chris Miller[30]
Pasquier Noterdaeme[33,34]
Cyrielle Opitom[35]
Giorgio Pariani[18]
Bogumil Pilecki[20]
Silvia Piranomonte[11]
Andreas Quirrenbach[16]
Edoardo M. A. Redaelli[18]
Claudio B. Pereira[19]
Sofia Randich[36]
Silvia Rossi[7]
Ruben Sanchez-Janssen[30]
Walter Seifert[16]
Rodolfo Smiljanic[20]
Colin Snodgrass[35]
Omar Squalli[38]
Ingo Stilz[16]
Julian Stürmer[16]
Andrea Trost[1,15]
Eros Vanzella[37]
Paolo Ventura[11]
Orlando Verducci[14]
Chris Waring[30]
Stephen Watson[30]
Martyn Wells[30]
Duncan Wright[12]
Tayyaba Zafar[24]
Alessio Zanutta[18]

[1] INAF–Astronomical Observatory of Trieste, Italy
[2] INAF–Astronomical Observatory of Capodimonte, Napoli, Italy
[3] Department of Physics – ICEx – UFMG, Belo Horizonte, MG, Brazil
[4] Ioffe Institute, HSE University, Saint Petersburg, Russia
[5] Donostia International Physics Center, Guipuzkoa, Spain
[6] IKERBASQUE Basque Foundation for Science, Bilbao, Spain
[7] University of São Paulo, IAG, São Paulo, Brazil
[8] E.A. Milne Centre for Astrophysics, University of Hull, UK
[9] Centre for Advanced Instrumentation, Durham University, UK
[10] INAF–Astronomical Observatory of Padova, Italy
[11] INAF–Astronomical Observatory of Rome, Monte Porzio Catone, Italy
[12] Centre for Astrophysics, University of Southern Queensland, Toowoomba, Australia
[13] INAF–Astronomical Observatory of Abruzzo, Teramo, Italy
[14] LNA/MCTIC, National Astrophysics Laboratory, Itajubá, Brazil
[15] Department of Physics, Astronomy Section, University of Trieste, Italy
[16] Landessternwarte, Centre for Astronomy, Heidelberg University, Germany
[17] Centre for Extragalactic Astronomy, Durham University, UK
[18] INAF–Astronomical Observatory of Brera, Merate, Italy
[19] National Observatory, Rio de Janeiro, Brazil
[20] Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Warsaw, Poland
[21] Department of Astronomy, University of Geneva, Versoix, Switzerland
[22] Consultant Astronomical Instrumentation, Ottobrunn, Germany
[23] Italian Space Agency – Space Science Data Centre, Rome, Italy
[24] Australian Astronomical Optics, Macquarie University, Australia
[25] Astrophysics Research Centre, Queen's University, Belfast, UK
[26] European Space Agency, ESA Office, STScI, Baltimore, USA
[27] Department of Physics, University of Warwick, Coventry, UK
[28] Goethe University, Institute for Applied Physics, Frankfurt am Main, Germany
[29] Department of Physics and Astronomy, University of Padova, Italy
[30] STFC – United Kingdom Astronomy Technology Centre, Edinburgh, UK
[31] Valongo Observatory, Federal University of Rio de Janeiro, Brazil
[32] INAF–Institute of Space Astrophysics and Planetology, Roma, Italy
[33] French–Chilean Laboratory for Astronomy, Santiago, Chile
[34] Paris Institute of Astrophysics, CNRS-SU, France
[35] Institute for Astronomy, University of Edinburgh, Royal Observatory, UK
[36] INAF–Astrophysical Observatory of Arcetri, Firenze, Italy
[37] INAF–Astrophysics and Space Science Observatory, Bologna, Italy
[38] ESO
[39] Optical Lab, Baader Planetarium GmbH, Mammendorf, Germany

CUBES, the Cassegrain *U*-Band Efficient Spectrograph, aims to bring a unique capability to ESO's Very Large Telescope: an ultraviolet eye on the Universe to complement the Extremely Large Telescope, a super-efficient (> 40%) spectrograph with a spectral coverage of 300–405 nm in the present design and two resolution modes, 20000 and 7000. An option of a fibre link to the Ultraviolet and Visual Echelle Spectrograph is foreseen that will provide the capability of simultaneous optical high-resolution

spectroscopy at $\lambda > 420$ nm. The CUBES design is able to address a treasure trove of scientific cases, from Solar System science to cosmology.

Introduction

Looking to the future of ESO's Very Large Telescope (VLT) there is a long-standing aspiration for an optimised ultraviolet spectrograph (Barbuy et al., 2014; Pasquini, 2014).

ESO's Extremely Large Telescope (ELT), with its 39-metre primary mirror, will be unprecedented in its light-gathering power, but, owing to the choice of protected silver (Ag+Al) for the mirror coatings (excluding M4), its performance drops significantly below 400 nm when compared to bare aluminium. Alternative coatings are under investigation, but in the short–medium term we can assume that the performance of the ELT in the ultraviolet (UV)–blue range will be limited. Indeed, during the Phase A study of the Multi-Object Spectrograph for Astrophysics, Intergalactic-medium studies and Cosmology (MOSAIC) instrument (Evans et al., 2016) it was concluded that a blue-optimised instrument on the VLT could potentially be competitive with the ELT at wavelengths shorter than 400 nm.

Motivated by this, in 2018 we revisited (Evans et al., 2018) the Phase A study undertaken in 2012 of the Cassegrain *U*-band Brazilian-ESO Spectrograph. That study investigated a $R \sim 20\,000$ spectrograph operating at 'ground-based UV' wavelengths (spanning 300–400 nm) to open-up exciting new scientific opportunities compared to the (then) planned instrumentation suite for Paranal Observatory (Barbuy et al., 2014; Bristow et al., 2014).

In January 2020 ESO issued a Call for Proposals for a Phase A study of a UV spectrograph to be installed at a Cassegrain focus of the VLT, with the goals of high-efficiency (> 40%) and intermediate resolving power (~ 20 000) in the ground-based UV domain (305–400 nm requirement, 300–420 nm goal). In May 2020 the Cassegrain *U*-Band Efficient Spectrograph (CUBES) Consortium, led by INAF, was selected to carry out the study.

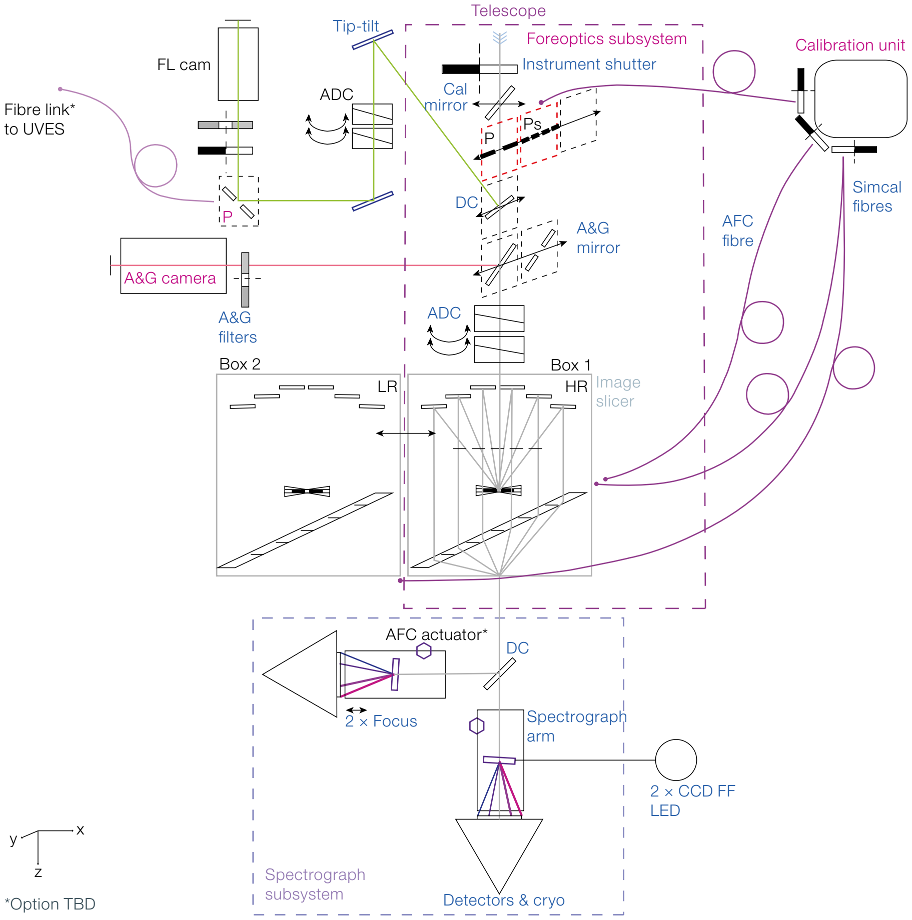


Figure 1. Functional scheme of the CUBES system (in which the light path goes from top to bottom). The following abbreviations are used: DC — dichroic; P — alignment pinhole; Ps — series of pinholes to measure spatial resolution along the slit; AG — acquisition and guiding; AFC — active flexure compensation system; FL — fibre link; ADC — atmospheric dispersion corrector. Optional modules (to be decided in Phase B) are marked with a trefoil sign (Zanutta et al., 2022).

The CUBES project completed its Phase A conceptual design study in June 2021 (Zanutta et al., 2022). After endorsement by the ESO Council at the end of 2021, Phase B started in February 2022 with the signature of the Construction Agreement between ESO and the leading institute of the CUBES Consortium, opening the detailed design and construction phase.

Science cases for CUBES

The CUBES science cases span a broad range of contemporary astrophysics across Solar System, Galactic, and Extra-Galactic science, and are driving the design of the instrument. An overview of CUBES science is given in Evans et al. (2022) and detailed presentations of specific science cases can be found in Opitom et al. (2022: cometary science), Giribaldi & Smiljanic and Smiljanic, da Silva & Giribaldi (2022: Beryllium abundances), Ernandes et al. (2022: nucleosynthesis), Alcalá et al. (2022: accretion and outflows in young stars), Ali & De Propris (2022: stellar populations in galaxies), D'Odorico (2022: the cosmological and galactic missing baryon problems), Balashev & Noterdaeme (2022: molecular hydrogen in absorption at high redshifts).

Instrument concept

The science cases of interest for the CUBES community have been used to identify the Top Level Requirements (TLR) in Phase A and effectively contribute to the design trade-offs, via the use of software tools developed in the study — the exposure time calculator (ETC), and the end-to-end (E2E) simulator (Genoni et al., 2022) — both in Phase A and in the current Phase B. Key TLRs identified for the development of the instrument conceptual architecture and design, were as follows.

- Spectral range: CUBES shall provide a spectrum of the target over the entire wavelength range of 305–400 nm in a single exposure (goal: 300–420 nm).
- Efficiency: The efficiency of the spectrograph, from slit to detector (included), shall be > 40% for 305–360 nm (goal > 45%, with > 50% at 313 nm), and > 37% (goal 40%) between 360 and 400 nm.
- Resolving power (*R*): In any part of the spectrum, *R* shall be > 19 000, with an average value > 20 000, where *R* is defined as the full width at half maximum (FWHM) of unresolved spectral lines of a hollow cathode lamp in the spectral slice.
- Signal-to-noise (S/N) ratio: In a 1-hour exposure the spectrograph shall be able to obtain, for an A0-type star of $U = 17.5$ mag (goal $U \geq 18$ mag), a S/N = 20 at 313 nm for a 0.007 nm wavelength bin. For different wavelength bins, the S/N ratio shall scale accordingly.

An important development in the Phase A study was the potential provision of a second (lower) resolving power (with $R \sim 7000$), to enable background-limited observations of faint sources where spectral resolution is less critical. We have also investigated a potential fibre feed to the Ultraviolet and Visual Echelle Spectrograph (UVES), to provide simultaneous observations at longer wavelengths. This broadens the scientific capabilities of CUBES (by significantly enhancing the cases related to, for example, transients) while also offering operational efficiencies for many cases where observations at longer wavelengths are required to support the UV analysis.

Figure 1 shows the present functional scheme of the CUBES system that envisages the following.

- A calibration unit that provides the light sources necessary to register frames for flat-fielding, wavelength calibration, alignment, the options of simultaneous wavelength calibration and active flexure compensation (AFC) if required.
- A foreoptics (first-stage transfer optics) subsystem that includes an atmospheric dispersion corrector (ADC) and acquisition and guiding functionalities.
- Two image slicers (to enable different spectral resolutions).
- Two arms, both equipped with transmission gratings with a high groove density and working at first order, and cameras. Each arm has its own detector cryostat, which comprises a 9k or 10k CCD as detector, readout electronics, and cryo-vacuum components (both hardware and specific control electronics).
- Instrument control electronics, based on programmable logic controllers complying with the latest ELT electronics standard, to control all the functions in the instrument, excluding the scientific detector system and its associated cryostat and vacuum controller.
- Instrument software comprising control software (based on the ESO's

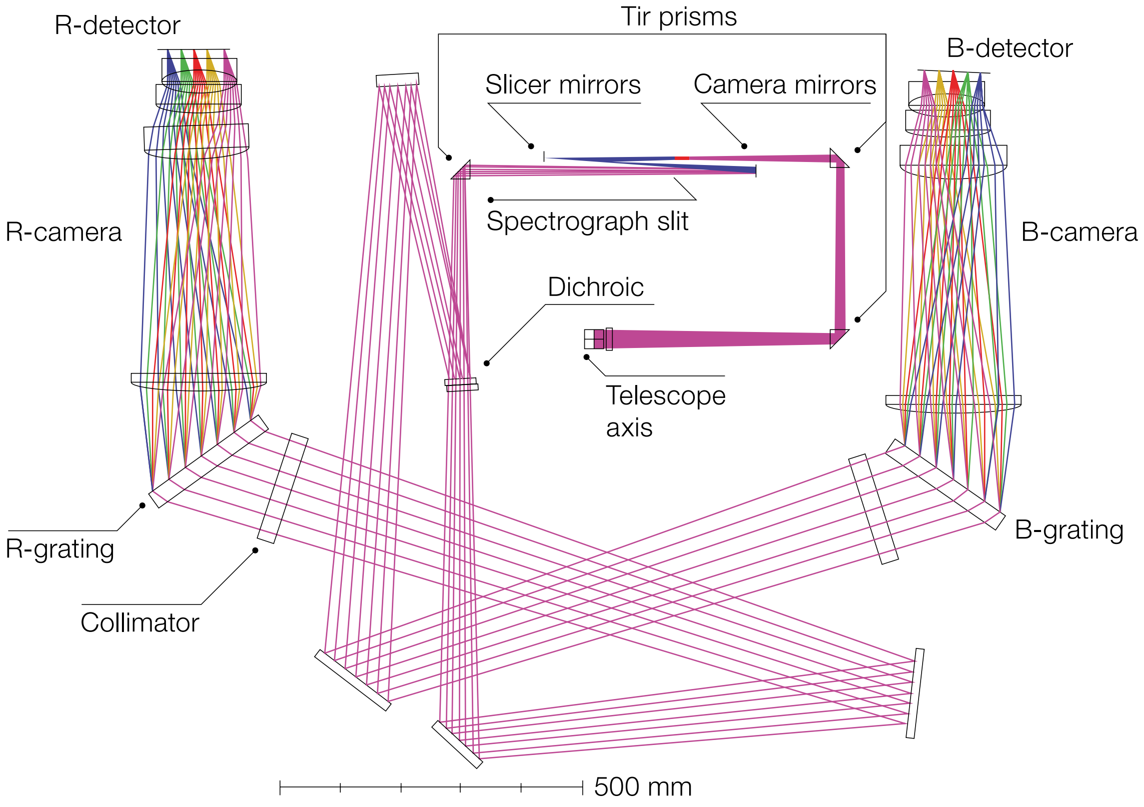


Figure 2. Early optical end-to-end model of the CUBES spectrographs. The light from the foreoptics enters at the prism marked "telescope axis". Note: the four-lens camera shown here has now been replaced by a three-lens camera and a flat CCD window. The tilt of the detector plane is clearly visible.

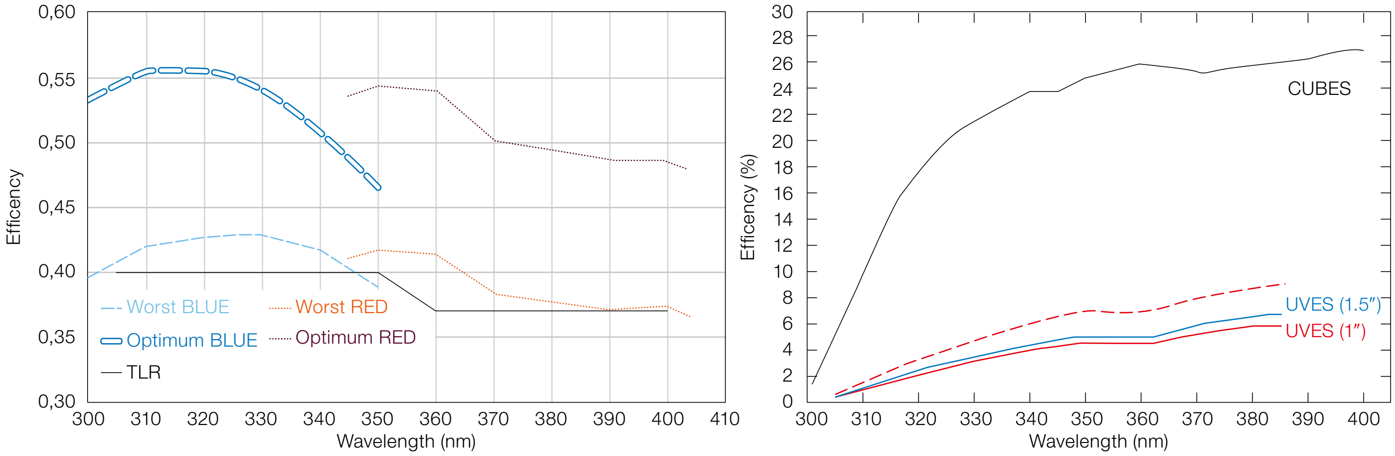


Figure 3. Left: Calculated detective quantum efficiency of the two arms of CUBES (BLUE and RED) for worst and best scenarios. The black line indicates the formal top-level efficiency requirement. The throughput was calculated from the telescope focus, including detector quantum efficiency and slicer vignetting. Right: Comparison of predicted CUBES efficiency (including telescope and atmosphere) with the predicted efficiency in the central wavelengths of the UVES echelle orders, using the ESO Exposure Time Calculator. The dashed red line shows the anticipated gain in performance (a factor of 1.5) resulting from a possible UVES upgrade.

ELT Instrument Control Software Framework), and data-reduction and simulation tools (Calderone et al., 2022).

- A fibre-link unit provides the option of simultaneous observations with UVES (in its red band at 420–1100 nm, via relay optics feeding optical fibres (1 object, 3 sky) subtending a 1-arcsecond aperture and approximately 40 metres long to transmit light from the Cassegrain focus of Unit Telescope 2 to the Nasmyth platform.

Optics

Using two lens doublets and a number of folding prisms (not shown in Figure 1), the foreoptics relays a field of view of 6 × 10 arcseconds at the telescope focus to the entrance plane of the spectrograph. Direct-vision ADC prisms in the parallel beam between the doublets provide atmospheric dispersion correction over the range 300–405 nm for zenith angles of 0–60°. By inserting a dichroic just below the telescope focal plane, light redward of 420 nm may be directed to the UVES fibre feed. During acquisition, the object field is directed by a 45-degree mirror to the acquisition and guiding CCD which is equipped with a set of photometric filters. After acquisition the mirror is moved to pass the centre of the field to the spectrograph.

At the magnified telescope focal plane produced by the foreoptics (scale 0.5 mm arcsec^{-1}), one of two user-selectable reflective image slicers decomposes the rectangular field of view into six slices. Six camera mirrors, one for each slice, re-image the slices on an output slit mask. By using optimised dielectric coatings and careful mask alignment, the slicer efficiency is expected to be > 90% (goal 94%) The output slit mask has six slitlets, corresponding to six slices, each one measuring 0.25 × 10 arcseconds on the sky for the high-resolution slicer (R = 20 000) and 1 × 10 arcseconds for the low-resolution slicer (R = 7000). Further slit mask apertures are illuminated by a ThAr fibre source for simultaneous calibration and/or use by the AFC system.

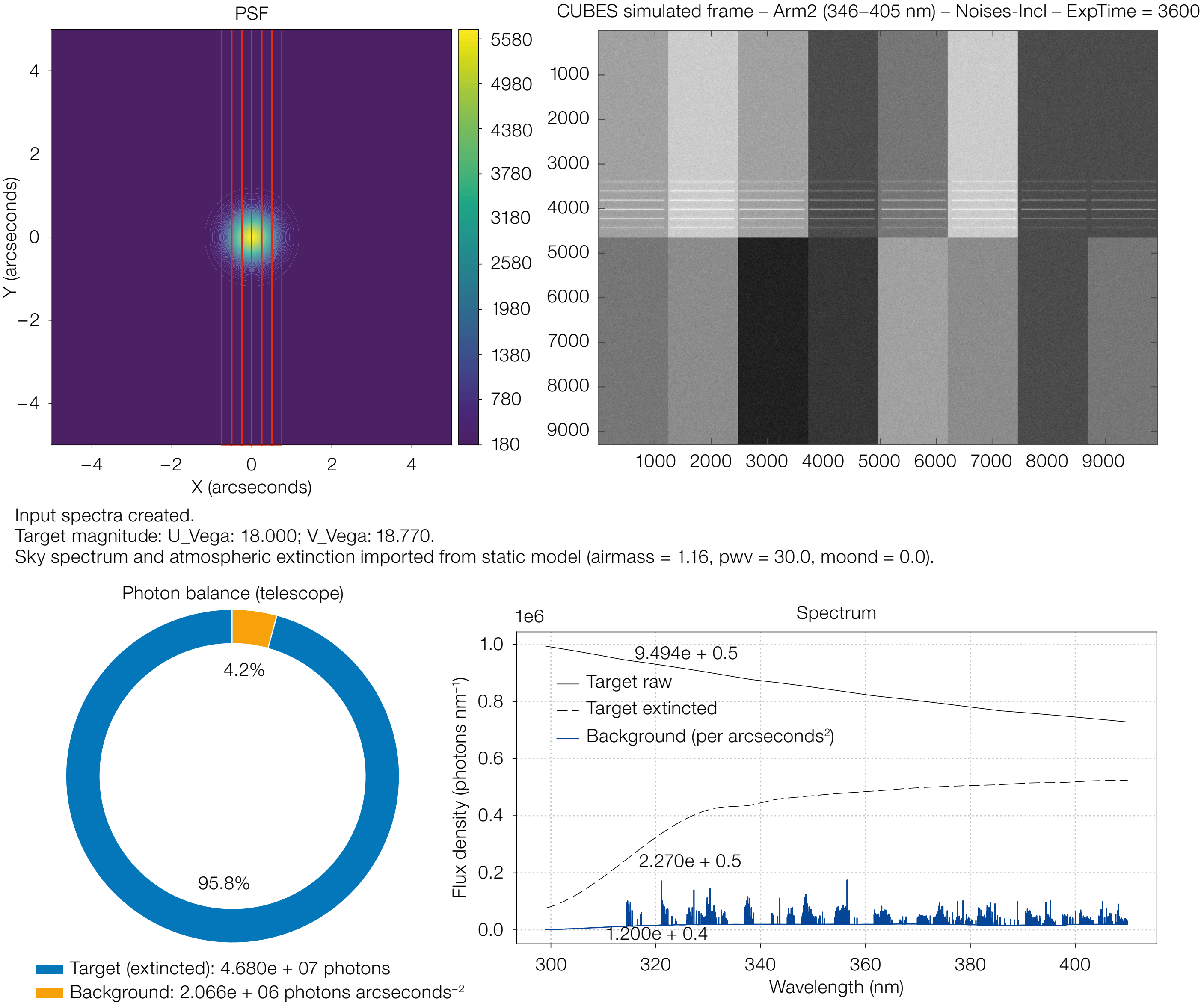
In order to achieve a high (> 20 000) resolution without the efficiency losses associated with crossdispersed echelles, CUBES uses state-of-the-art first-order dispersing elements. Binary transmission gratings produced by electron-beam microlithography and an atomic layer deposition overcoat have been identified as a suitable technology (Zeitner et al., 2022). Their theoretical average diffraction efficiency, based on rigorous coupled-wave analysis, is > 90%. A first prototype, funded by the Fundação de Amparo à Pesquisa do Estado de São Paulo, was produced and tested as early as 2018; further prototyping activity is underway and a test and characterisation report will be presented at the Preliminary Design Review.

As shown in Figure 2, the light coming from the slit mask is folded by a total internal reflection prism and then reaches a dichroic which splits the light by reflecting the blue-arm passband (300–352.3 nm) and transmitting the red-arm passband (346.3–405 nm), exceeding the 305–400 nm TLR. The layout of the two arms is similar but the individual components and separations are different so as to achieve the required dispersion, magnification and image quality for the 2 passbands, using only fused silica. The f/20 collimator is a single lens. The spectrograph camera is composed of three aspheric, tilted and decentered lenses.

The large CCDs (9k × 9k or 10k × 10k) are tilted to compensate for the change in refractive index of silica with wavelength. The CCDs are cooled with Stirling coolers and controlled by ESO's 2nd-generation detector control system (NGC2).

Mechanics

CUBES requires a fairly large beam diameter of 160 mm. Consequently, the instrument envelope is also rather large compared to other Cassegrain instruments (such as X-shooter, with its 100-mm beam diameter). Scaling classical instrument designs to the required size of CUBES would exceed the mass limit of



Input spectra created.
Target magnitude: U_Vega: 18.000; V_Vega: 18.770.
Sky spectrum and atmospheric extinction imported from static model (airmass = 1.16, pwv = 30.0, moond = 0.0).

Figure 4. Top left: Simulated image of the target point spread function (PSF) on the (high-resolution) slicer focal plane, with the slice boundaries superimposed in red. Top right: Simulated raw frame for Arm 1. The six "science" slices as well as the SimCal traces are located on the upper half of the detector. The lower "AFC" half is automatically read and analysed every few minutes to measure and if necessary, actively maintain the position of a faint ThAr spectrum on the CCD (the need for SimCal and/or AFC is under study in Phase B). Bottom: Results for a flat input spectrum of U = 18 mag, computed with the Basic Version E2E, assuming an integration time of 3600 s. The integrated flux from the target and the sky is computed assuming the collecting area of the primary mirror of a VLT Unit Telescope and a detector integration time of 3600 s. At left, the photon balance between the target and the sky background and at right, the spectra of the target (with extinction) and background. See Genoni et al. (2022) for details.

2500 kg for VLT Unit Telescope Cassegrain instruments; a lightweight construction principle has therefore been adopted, making use of modern composite materials. The optical layout was optimised such that all optical elements of the spectrograph from slit to detector lie in a single plane, so all spectrograph optics can be mounted on a single optical bench of size 1.3 × 1.7 m. This is arguably the most stable configuration since the dispersion direction of CUBES is parallel to the stiff surface plane of the optical bench. A general focus of the mechanical design is, in fact, to minimise the effects of gravitational bending of the instrument.

In the current design, the CUBES main mechanical structure is divided into three main components: 1) a telescope adapter, that provides a stiff connection between the Cassegrain telescope flange and the optical bench assembly; 2) an optical bench that provides a stable platform for the spectrograph optics as well as for the foreoptics; and 3) an assembly to provide support for auxiliary equipment such as electronic racks, the calibration unit and vacuum equipment. This support frame is detached from the optical bench to mitigate the contribution of flexure. We are currently planning to use steel for the telescope adapter and the support frame, and a carbon-fibre-reinforced polymer (CFRP) for the optical bench. The optomechanics are currently intended to be made of aluminum alloys, for example $AlSi_40$, to improve the specific stiffness and lower the coefficient of thermal expansion (CTE) mismatch between the optomechanical parts and the CFRP bench.

Performance

An E2E simulator and an ETC have been developed to help in the definition of the current baseline design as well as in the scientific evaluation of the various observing modes (Genoni et al., 2022). The E2E provides different scenarios for the efficiency of the various components, as shown in Figure 3, and can be run in different versions according to the needs and users (for example, it can be accessed by the user in a Jupyter notebook), Figure 4 gives example of some of its outputs. For the ETC a webpage has been established through which the CUBES science community was able to test the key science cases.

Project organisation

The CUBES consortium is currently composed of institutes from five countries:

- Italy: INAF — National Institute of Astrophysics (consortium leader)
- Brazil: IAG-USP — Institute of Astronomy, Geophysics and Atmosphereic Sciences (primary Brazil partner) and LNA — National Astrophysical Laboratory (secondary Brazil partner)
- Germany: LSW — Landessternwarte, Heidelberg University Centre for Astronomy
- Poland: NCAC — Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences
- UK: STFC-UKATC — UK Astronomy Technology Centre, (primary UK partner) and Durham University Centre for Advanced Instrumentation (secondary UK partner)

CUBES adopts the standard project phasing for ESO instruments which is based on the stage-gate paradigm. Important decision points are project milestones (gates of the project) which mark the transition to a new stage when successfully completed. The entry into force of the Construction Agreement was on 15 February 2022 with expected Construction, commissioning, and Preliminary Acceptance Chile stage to be reached in 77 months, permitting the instrument to be ready for science observations in 2028.

Public engagement

CUBES offers opportunities for ambitious research programs and some of the scientific topics are related to the hottest open questions in modern astrophysics. Considering the promising discovery capabilities of the project, and the remarkable research and development behind the technology, we see crucial importance in adequately communicating the project to the lay public. Dissemination of science and technology is a fundamental part of our project and we have since the beginning defined a work package devoted to outreach. During phase A we have mainly communicated the progress of our project and the main scientific topics. We have prepared a webpage[1] that is also a useful tool for the project as a whole, and maintain profiles in various social media platforms, i.e. Facebook[2], Twitter[3], and YouTube[4]. A series of short video interviews with some of the people in the CUBES consortium have been prepared and made available on the web. As the project matures, specific activities (conferences, popular science papers, etc.) are foreseen.

Acknowledgements

BB acknowledges the FAPESP grant 2014/18100-4. ARS, RG, and RS acknowledges support by the Polish National Science Centre through project 2018/31/B/ST9/01469.

We gratefully acknowledge support from the German Federal Ministry of Education and Research (BMBF) through project 05A20VHA.

References

Alcalá, J. M. et al. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09832-1
Ali, S. S. & De Propris, R. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09849-6
Balashev, S. & Noterdaeme, P. 2022, arXiv:2203.15582
Barbuy, B. et al. 2014, Ap&SS, 354, 191
Bristow, P. et al. 2014, Proc. SPIE, 9147, 914709
Calderone, G. et al. 2022, Proc. SPIE, 12189, 81, arXiv:2209.07294
D'Odorico, V. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09859-4
Ernandes, H. et al. 2022, Exp Astron, https://doi.org/10.1007/s10686-021-09829-2
Evans, C. J. et al. 2016, Proc. SPIE, 9908, 99089J
Evans, C. J. et al. 2018, Proc. SPIE, 10702, 107022E
Evans, C. J. et al. 2022, Exp Astron, in press
Genoni, M. et al. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09844-x
Giribaldi, R. E. & Smiljanic, R. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09850-z
Opitom, C. et al. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09853-w
Pasquini, L. 2014, Ap&SS, 354, 121
Smiljanic, R., da Silva, A. R. & Giribaldi, R. E. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09845-w
Zanutta, A. et al. 2022, Exp Astron, https://doi.org/10.1007/s10686-022-09837-w
Zeitner, U. D. et al. 2022, in Exp Astron, https://doi.org/10.1007/s10686-022-09840-1

Links

[1] CUBES homepage: https://cubes.inaf.it/home
[2] The CUBES channel on facebook: https://www.facebook.com/profile.php?id=100057094524211
[3] The CUBES channel on Twitter: https://twitter.com/VLT_CUBES
[4] The CUBES channel on YouTube: https://www.youtube.com/channel/UCZqdt1MnWDUgLcYqjBTFsUA