The **SCAO** module for **ANDES**, the high resolution spectrograph for the ELT

**Paolo Di Marcantonio**
ANDES PM, INAF-OATs
European Extremely Large Telescope (ELT) will be the largest ground-based telescope at visible and infrared wavelengths

- **Flagship science cases:** the detection of life signatures in Earth-like exoplanets and the direct detection of the cosmic expansion re-acceleration (both require high resolution spectroscopy)

**High resolution spectroscopy**

- Interdisciplinary (from Exoplanets to Stars, to Cosmology and Fundamental Physics)
- Successful ESO tradition (UVES, FLAMES, CRIRES, X-shooter, HARPS, ESPRESSO)
- More than 30% of ESO publications can be attributed to its high-resolution spectrographs.
ANDES (ArmazoNes high Dispersion Echelle Spectrograph) is the high-resolution, high-precision, modular, fiber fed, optical-infrared spectrograph for the ESO/ELT (European Southern Observatory/Extremely Large Telescope) thought to study astronomical objects that require highly sensitive observations.

- Simultaneous spectral range 0.4-1.8 µm (0.37-2.4 µm goal)
- Spectral resolution ~100,000 (also 150,000 possible)
- Interchangeable, observing modes: seeing limited & SCAO+IFU module
- Sensitivity: 1h, 10σ, AB = 21.7
ANDES history

- ESO commissioned two phase-A studies for high-resolution spectrographs, CODEX and SIMPLE, in the framework of “ESO instrumentation roadmap for ELT construction proposal” (successfully completed in 2010)

- HIRES initiative: merging of CODEX and SIMPLE with a preparation of community white paper (2013)

- HIRES Phase A study: started 2016, successfully concluded beginning 2018

- the “waiting-for-approval phase”: new partners (USA and Canada) joined the (existing) consortium, modified baseline design adopted, new organisation of consortium developed, preparation of agreements

- ESO Council approves HIRES Construction (December 2021)

- New name adopted: ANDES (ArmazoNes high Dispersion Echelle Spectrograph)

- Start of the construction phase with SAR (System Architecture Review) completed on 18th of October 2023
A subset of ANDES science cases

- Exoplanets (characterisation of Exoplanets Atmospheres: detection of signatures of life)
- Protoplanetary Disks (dynamics, chemistry and physical conditions of the inner regions)
  - Stellar Astrophysics (abundances of solar type and cooler dwarfs in galactic disk bulge, halo and nearby dwarfs: tracing chemical enrichment of Pop III stars in nearby universe)
  - Stellar Populations (metal enrichment and dynamics of extragalactic star clusters and resolved stellar populations)
  - Intergalactic Medium (Signatures of reionization and early enrichment of ISM & IGM observed in high-z quasar spectra)
  - Galaxy Evolution (massive early type galaxies during epochs of formation and assembly)
  - Supermassive Black Holes (the low mass end)

- Fundamental Physics (variation of fundamental constants - $\alpha$, Sandage Test)

Community White Paper: Maiolino et al. 2013, ArXiV:1310.3163
- **Exoplanets and Circumstellar disks** (characterisation of exoplanets atmospheres, detection of signatures of life and dynamics, chemistry and physical conditions of disks)

  - In reflected light, ANDES can detect Proxima b planet in 7 nights at 8 sigma level

  - In transmitted light, ANDES can detect Trappist 1 & 2
    - H₂O (1.3-1.7 µm) in 2 transits,
    - H₂O (0.9-1.1 µm) in 4 transits
    - CO₂ in 4 transits
    - O₂ in 25 transits

  ...
Therefore, taking into account these driving requirements, the SCAO WFS is a pyramid WFS with tip/tilt modulation equipped with ADC, optical pupil derotator (k-mirror) and two translation stages to provide the field patrolling. The pyramid WFS has been selected as the one providing the highest performance for high contrast applications.
SCAO Performance – contrast estimation

The WG1 wish is: contrast 1.0E-3 for I=8  @14mas 1600nm

3 scenarios considered

1. High piston
   Phase A design: no correction of M4 petal piston (differential piston error 200nm RMS)

2. Low piston
   Phase A + phasing sensor (25nm residual piston error)

3. Low piston + Lyot coronograph
   (work ongoing by OCA team)

Expected contrast profiles, DL means Diffraction Limit.

I=8 → SR=0.22
I=14 → SR=0.20

I=8 → SR=0.59
I=14 → SR=0.54

One point on the curve on the right corresponds to the average of the flux in all the pixels sitting on the white circle on the left picture.
ANDES Key scientific objectives I

(Palle et al. in prep)

(labels mark exoplanets in our rocky-HZ ‘golden sample’)

Paolo Di Marcantonio - RTC4AO 2023
ANDES Key scientific objectives I

(Palle et al. in prep)
ANDES key scientific objectives II

- **Stars and Stellar Populations** (abundances of solar type and cooler dwarfs in our and nearby galaxies, tracing chemical enrichment of Pop III stars in nearby universe, early chemical enrichment)
Galaxies (formation and evolution) and Intergalactic Medium (signatures of reionization and early enrichment of IGM observed in high-z quasar spectra, evolution of massive early type galaxies during epochs of formation and assembly)

The Inter-Galactic Medium:
- tracing the chemical enrichment of the universe (e.g. Pop III SNe)
- High spectral resolution (R>50-100x10^3) and broad spec. cov. (opt+NIR)
Cosmology and Fundamental Physics (variation of fundamental constants, Sandage Test)
Fundamental Physics: variation of the fundamental constants

More science cases, see “Community White Paper: Maiolino et al. 2013, ArXiV:1310.3163”
ANDES Science Prioritisation

- **Priority 1**: Exoplanet atmospheres via transmission spectroscopy (potential detection of bio-signatures)
  - TLR 1: $R > 100,000$, 0.5-1.8 $\mu$m; drive the ANDES baseline design
    - Enables: reionization of Universe; characterization of Cool stars
    - Doable: detection and investigation of near pristine gas; 3D reconstruction of the CGM; Extragalactic transients
- **Priority 2**: Variation of the fundamental constants of Physics
  - TLR 2: blue extension to 0.37 $\mu$m
    - Enables: Cosmic variation of the CMB temperature, Determination of the deuterium abundance; investigation and characterization of primitive stars
- **Priority 3**: Exoplanet atmospheres via reflection spectroscopy (potential detection of bio-signatures)
  - TLR 3: SCAO+IFU
    - Enables: Planet formation in protoplanetary disks; characterization of stellar atmospheres; Search of low mass Black Holes
    - Doable: characterization of the physics of protoplanetary disks
- **Priority 4**: Redshift drift (Sandage test)
  - TLR 4: $\lambda$ accuracy 2 cm/s, stability 2 cm/s
    - Enables: Mass determination of exoplanets (Earth-like objects)
    - Doable: Radial velocity search for exoplanets around M-dwarf stars
Combination of ANDES science cases requires $R \approx 100,000$, $0.35 < \lambda < 2.4 \mu m$, many different observing modes, and several other challenging TLRs which lead to a fiber-fed, modular instrument:
ANDES architecture

- Front End (FE)
- Fiber Link (FL)
- SCAO module
- Calibration Unit (CU)
- (U)BV Spectrograph
- RIZ Spectrograph
- YJH Spectrograph
- (K Spectrograph)
- Software
ANDES concept: deployment
ANDES concept: deployment
Front-end: old design

- Front End structure preliminary design: Arms management
Front-end: new design

- Top View:
  - SLArm 1
  - IFU
  - SCAO
  - SLArm 2

- Side View:
  - Dichroics translation only
  - SLArm 1&2
  - IFU
  - SCAO
### Science operations

#### Seeing Limited Observing Mode

<table>
<thead>
<tr>
<th>observing mode</th>
<th>FE</th>
<th>FL</th>
<th>along the spectrograph slit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SL_UNI</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>[U]BV+RIZ+YJH</td>
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<td></td>
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<td></td>
<td>two identical apertures simultaneously illuminated by target and sky, or target and wavelength calibration. If needed, beam-switching of the two apertures can be performed.</td>
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<tr>
<td><strong>SL_UNI_TS</strong></td>
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<tr>
<td>Target + Sky</td>
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<tr>
<td><strong>SL_UNI_TC</strong></td>
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<td></td>
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<tr>
<td>Target + Wavelength Calibration</td>
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</table>

#### IFU+SCAO Observing mode

<table>
<thead>
<tr>
<th>Observing mode</th>
<th>FE</th>
<th>FL</th>
<th>along the spectrograph slit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IFU_SCAO</strong></td>
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<td></td>
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<tr>
<td>[U]BV+RIZ+YJH</td>
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<tr>
<td>IFU of maximum 61 spaxels. 4 spaxel scales in the 5-100 mas range are foreseen. Off-axis guiding out to 3 arcsec is also possible.</td>
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<tr>
<td><strong>IFU_SCAO</strong></td>
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<tr>
<td>YJH</td>
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<tr>
<td>input PSF on microlenses array and fibre bundle. fibre bundle after fiber2fiber couplers.</td>
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<td>4 segments (S1, S2, S3, S4), one per each hexagonal annulus around the central spaxel, + the central spaxel (S).</td>
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Other ANDES subsystems
The SCAO subsystem is aimed to provide the adaptive optics correction to the IFU feeding the YJH spectrograph and, in the case of its implementation, to the IFU feeding the K-band spectrograph. The possibility to feed the RIZ spectrograph is currently under evaluation.

The main elements involved in the SCAO subsystem are:

- Wavefront Sensors: AO WFS and phasing WFS
- Real Time Computer (RTC)
- Deformable Mirror (DM): the ELT M4 - not part of the SCAO itself.
SCAO functional scheme
**Fixed FE benefits for SCAO**

- Gravity invariant:
  - Simplified requirements and test for devices (stages)
  - Simplified interfaces (proximity electronics, cabling, etc)
  - Improved stability

- Improved mass budget

- Improved volume budget

**SCAO-IFU technical source (telescope simulator)**

Volume and mass on fix FE allows for technical source for SCAO+IFU non-spectral calibration (yellow box)
A preliminary design to control the ANDES SCAO module foresees the adoption of HEART, the Herzberg Extensible Adaptive Real-time Toolkit. Under study possible customization to fit the HEART Soft Real-time into the ESO RTC toolkit.

See talk of J. Dunn: *HEART On-Sky Results and Soft-Realtime Functionality*

- WFS type: modulated pyramid WFS
- WFS camera: ALICE 240x240 pixels
- WFS on chip binning: 2x2, 3x3, 4x4 (TBC)
- WFS signal: pixel map / slopes
- AO loop frame rate: 500Hz
- Deformable Mirror: ELT-M4/M5
The ANDES Consortium is composed by 24 institutes from 13 countries.

- **Brazil**: Federal Univ. of Rio Grande do Norte
- **Canada**: Univ. De Montreal, Herzberg Astrophysics Victoria
- **Denmark**: Univ. Copenhagen, Univ. Aarhus, Danish Tech. Univ.
- **France**: LAM Marseille, LAGRANGE Nice, IPAG Grenoble, IRAP/OMP Toulouse, LUPM Montpellier
- **Germany**: AIP Potsdam, Univ. Göttingen, Landessternwarte Heidelberg, MPIA Heidelberg, Thüringer Landesternwarte Tautenburg, Univ. Hamburg
- **Italy**: INAF Istituto Nazionale di AstroFisica (Lead) (Arcetri, Bologna, Brera, Padova, Trieste)
- **Poland**: Nicolaus Copernicus Univ. in Toruń
- **Portugal**: Instituto de Astrofísica e Ciências do Espaço, CAUP and FCIências
- **Spain**: Inst. Astrofísica de Canarias (IAC), Inst. Astrofísica de Andalucía (IAA - CSIC), Centro de Astrobiología (CSIC-INTE) Madrid
- **Sweden**: Uppsala Univ., Lunds Univ., Stockholm Univ.
- **Switzerland**: Univ. de Genève, Univ. Bern
- **United Kingdom**: Univ. of Cambridge, UK Astronomy Technology Centre, Heriot-Watt Univ.
- **USA**: Univ. of Michigan
Project organisation: members

Over 230 (scientific and technical) people contributing to ANDES, see author list of recent SPIE paper (Marconi et al. 2022, SPIE)
## Schedule

### Project timeline

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<th>Project phases</th>
<th>Milestones</th>
<th>Duration</th>
<th>Name</th>
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<td><strong>Phase B</strong></td>
<td>KM.1</td>
<td>T0</td>
<td>Kick-off (KO)</td>
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<td></td>
<td>KM.2</td>
<td>T0 + 9 months</td>
<td>System architecture completion (SAR)</td>
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<td></td>
<td>KM.3</td>
<td>T0 + 22 months</td>
<td>Preliminary design completion (PDR)</td>
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<td></td>
<td>T0 + 26 months</td>
<td>Funding review (FR)</td>
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<tr>
<td><strong>Phase C</strong></td>
<td>KM.4</td>
<td>T0 + 48 months</td>
<td>Final design completion (FDR)</td>
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<tr>
<td><strong>Phase D</strong></td>
<td>KM.5</td>
<td>T0 + 80 months</td>
<td>Integration readiness completion (IRR)</td>
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<td>KM.6</td>
<td>T0 + 88 months</td>
<td>Test readiness completion (TRR)</td>
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<td></td>
<td>KM.7</td>
<td>T0 + 108 months</td>
<td>Preliminary acceptance Europe completion (PAE)</td>
</tr>
<tr>
<td><strong>Phase E</strong></td>
<td>KM.8</td>
<td>T0 + 120 months</td>
<td>Provisional acceptance Chile completion (PAC)</td>
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<tr>
<td><strong>Phase F</strong></td>
<td>KM.9</td>
<td>PAC + 2 years</td>
<td>Final acceptance completion (FAC)</td>
</tr>
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</table>
ANDES is a challenging instrument in several aspects: it is actually a *multi-instrument* composed by several modules (subsystems) where each one is an instrument by itself already exceeding dimensions of current largest spectrographs of such kind, worldwide.

At the project management level main challenges are represented by its *large consortium*, the needs of *huge efforts and funds’ investments* for its construction within a not negligible time frame to reach on-sky operations.

In order to master ANDES complexity, a *modular* approach has been adopted both at project and system level: 9 major subsystems have been identified with their own project managers and system engineers which are responsible for their respective subsystems and, at the same time, are also part and support the project manager and system engineer at the system level.