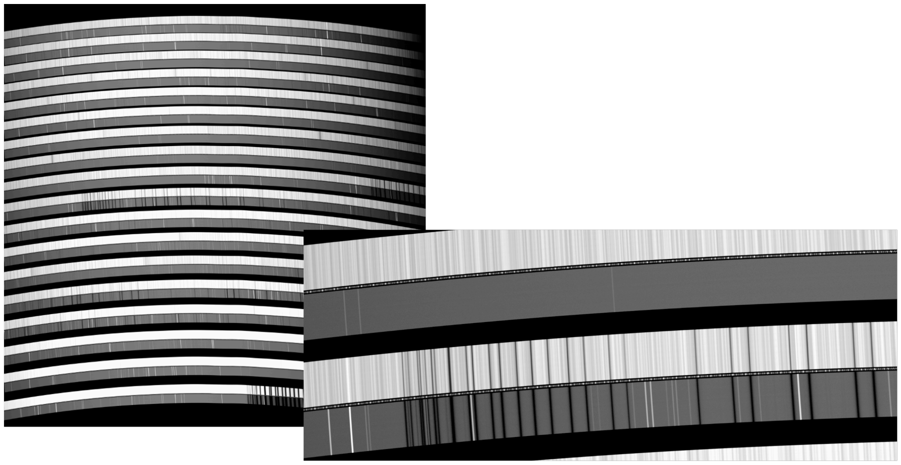

Figure 11. Left: ANDES Simulated RIZ (R Band) science spectrum obtained with the E2E simulator.

- Red Spectrograph (RIZ). The RIZ module has 2 cameras: R and IZ, with one scientific detector each.
- Infrared Spectrograph (YJH). The IR module has 3 cameras, Y, J and H, with one scientific detector each.
- K band Spectrograph (K). The K band module is an option under study has one camera, with one scientific detector.

All spectrographs have a fixed configuration, i.e. no moving parts, allowing to fulfil the requirements on stability. They include a series of parallel entrance slits consisting of linear micro-lens arrays each optically coupled to the fibre bundles. The split in wavelengths between the spectrographs is influenced, among other parameters by the optical throughput of the different types of fibres available on the market; therefore, the different modules can be positioned at different distances from the focal plane of the telescope (see Fig. 9 for more details).

The entire ANDES software (control and science tools) has been developed with the final goal of providing the astronomer with high level products as complete and precise as possible in a short time (within minutes) after the end of an observation while guaranteeing a smooth operation of the instrument at the Telescope when it will be offered to the community. This will maximize the overall efficiency and the scientific output making ANDES truly a "science-grade products generating machine" following the philosophy adopted already for ESPRESSO. Already in this phase ANDES-specific science tools have been developed: the ETC and the End-to-End simulator.

The ETC is able to compute for a compact (extended) source the limiting magnitude (surface brightness) achievable at a given wavelength, in a given exposure time and at a given signal to noise ratio. Moreover, this tool can compute the signal to noise ratio achievable at a given wavelength, in a given exposure time and at a given magnitude or surface brightness. Fig. 10 shows the expected performance of ANDES in the cases of compact and extended sources. The ANDES ETC can be, at the time of writing, easily accessible at the address andes.inaf.it.

The End-to-end (E2E) simulator has been used to perform full end-to-end simulations in order to evaluate the effect of technical choices on the science goals: an example is shown in Fig. 10, which shows a simulated ANDES raw data frame from the RIZ spectrograph (R band). E2E results coupled with the science requirements have also driven the identification of the main features of both DRS (Data Reduction Software) and DAS (Data Analysis Software), along with the Operation and Observation preparation tools.

The ANDES DRS is the data reduction library for both visible and near-infrared parts of the spectrograph and it will be in charge to produce fully calibrated, science calibrated spectra starting from the RAW data secured by ANDES. The concept of DAS is instead modelled around the successfully experience of the ESPRESSO DAS as a set of self-standing modules ("recipes") performing interdependent operations. For both, a fully integrated approach based on ESO standard tools like CPL with ESORex and fully compliant with the ELT Dataflow.

The ANDES control software on the other side is responsible to control all the vital functions of the instrument like motors, sensors, lamps and to manage the execution of the scientific exposures according to the given observation mode. It will also implement all the needed interfaces towards external subsystems (telescope, scheduler, archive). During this phase a detailed requirement analysis have been conducted in order to identify main ANDES requirements leading to a quite detailed software architecture design and network architecture. The proposed architecture and solution for the current phase is fully based on the latest available version of ELT IFW framework. Moreover, also the main templates for ANDES observing mode, calibration and maintenance have been identified.

4. THE ANDES CONSORTIUM ORGANIZATION

The ANDES Consortium is composed of institutes from Brazil, Canada, Denmark, France, Germany, Italy, Poland, Portugal, Spain, Sweden, Switzerland, United Kingdom and USA. The full list of institutes is presented in Tab. 2. Overall, the consortium includes 35 Institutes from 13 Countries. All Consortium members are listed as authors of this paper.

The large number of institutes involved in the Consortium reflects the large scientific and technical interest in a high-resolution spectrograph for the ELT in the astronomical community worldwide. In particular:

- the Consortium includes the large majority of the high-resolution community in the ESO member states and reflects the large scientific and technical interest in a high-resolution spectrograph for the ELT;
- most Consortium Institutes have a proven expertise in building high-resolution spectrographs; overall the consortium includes most of the institutes that built the high-resolution spectrographs for ESO telescopes;
- the Consortium can count on a large number of specialized technical and scientific staff as well as on world class laboratories and technical facilities.

The ANDES Organization Breakdown Structure and the names of the key persons in the project are shown in Fig. 12.

The consortium is represented by the Principal Investigator who has the ultimate responsibility of the project and is the formal contact point between ESO and the Consortium. The Steering Committee (SC) is the ultimate decision-making body of the Consortium and the source of guidance and strategic decision making, in particular it approves all decisions significantly impacting the financial and human resources allocated to the Project. It is composed of one representative per Partner. The Executive Board (EB) provides regular advice to the PI and the SC on all technical and scientific matters, in order to ensure the fulfilment of the scientific objectives of the Project. It is a strong but hands-off high-level overview committee. Together with the PI prepares proposals for the decisions of the SC. With a loose analogy we could associate the PI to the Prime Minister, the EB to the Government, and the SC to the Parliament.

The Project Scientist leads the development of the science program and top-level requirements, working in close contact with the Project Manager (and his team) who takes the responsibility to manage the overall project. The project manager is supported by a System Engineer and the system team (composed by the Software System Engineer and System Architects) who are in charge to supervise the overall system design. SE and SSE work in close contact with the Instrument Scientist (and her team) who makes sure that the adopted technical solutions match the foreseen instrument scientific needs. The PI, PM, SE, SSE, PS and IS form the Project Office which ultimately and collegially encompass all programmatic activities of the project.

Technical work is organized following a modular approach where ANDES is seen as composed by the 8 subsystems described in Sec. 3: Front end, Fiber Link – Integral Field Unit, [U]BV spectrograph, RIZ spectrograph, YJH spectrograph, K spectrograph, Single Conjugated Adaptive Optics module, Calibration Unit, Software. For each subsystem, a subsystem Project Manager and a subsystem System Engineer have been appointed with similar responsibilities of the PM and SE even though limited to the subsystem level.

All matters that concerns science cases and GTO scientific programme for ANDES are responsibility of the PS and the Science Team (ST). The ST is organized in four Working Groups (WGs): WG1- Exoplanets

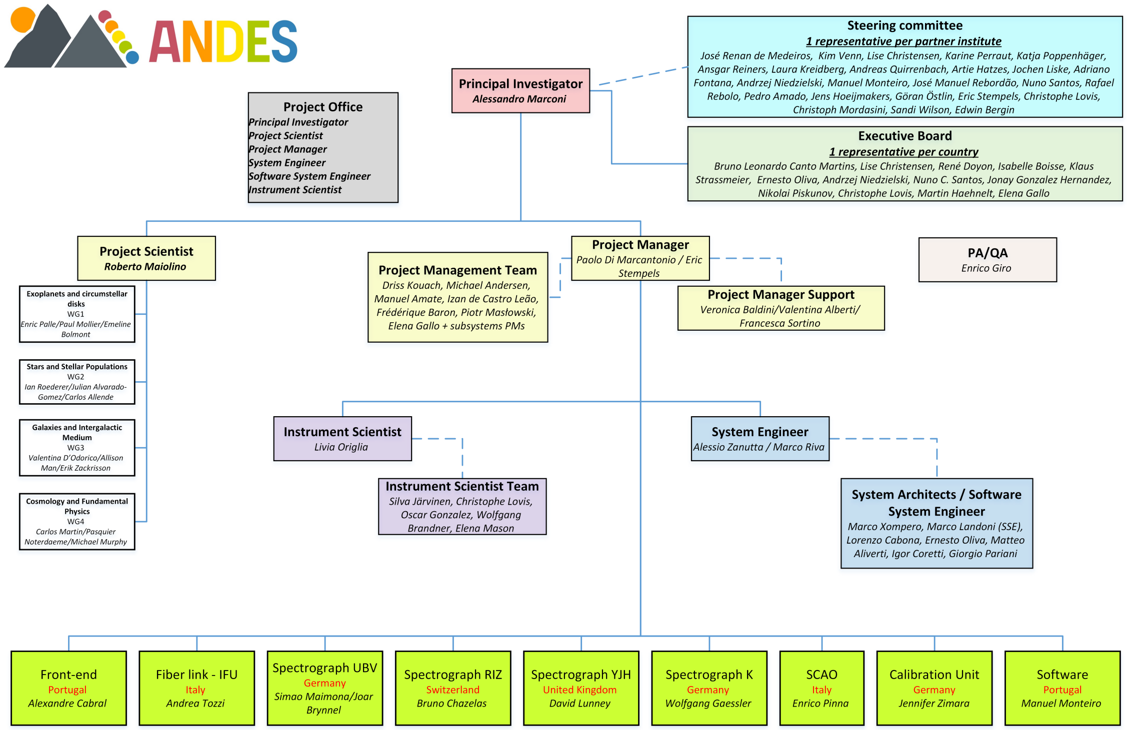

Figure 12. ANDES Consortium organization breakdown structure. ANDES logo by Alexis Lavail (Uppsala)

and Circumstellar disks, WG2 - Stars and Stellar populations, WG3 - Galaxies (formation and evolution) and Intergalactic Medium, WG4 - Cosmology and Fundamental Physics. Each WG is led by a chair, assisted by co-chair(s) and composed by a number of scientists from the participating countries selected by appointment from the PI, following indications of the EB and of the PS and ultimately approved by the SC.

The Consortium is assisted by a follow-up team from ESO, composed of a Project Manager, an Instrument Scientist and a System engineer which provide all the necessary information and support to design and build an instrument which is compliant with ELT standards and with the scientific needs of the ESO community.

Communication and Outreach. The ANDES Consortium recognizes the important of Communication and Outreach both internally and externally to the Consortium. This is why a Communication and Outreach WG has been established which includes at least one representative per major subsystem/country. In this intial phase sof the project, the WG activity is focused to plan an internal communication, while in a more advanced stage it will develop different strategies to communicate results and milestones to external stakeholders. The website has a crucial role in this strategy and for that the WG has recently restyled the webpage (andes.inaf.it) where ANDES is presented in its fundamental outlines: scientific cases, technical design, consortium and team, followed by useful tools (internal documents, exposure time calculator, access to restricted clouds, and so on), publications and conferences, the news section.

5. COST ESTIMATES AND SCHEDULE

The current estimate of the overall hardware costs is around 45 MEUR in hardware (including the K band and excluding contingencies). Contingencies have been evaluated at subsystem level using different margins according to the considered components (usually 5-10%). Then a 5% contingency at system level can been applied. We have considered a contingency lower than 20% because the proposed baseline design is based on proven technical solutions and can benefit on heritage from ESPRESSO and other similar instruments developed by Consortium Partners. The FTEs required to complete the project are estimated, to be approximately 650 when including contingencies. The FTEs will be compensated with 65 nights of GTO, while the hardware costs will be compensated with a number of GTO nights still to be agreed, but with a minimum of at least 60. These GTO nights will be used for joint Consortium science programs.

The current Project schedule foresees that ANDES will be available at the telescope in 2032, but the we could adopt a more aggressive schedule to send a module at the telescope as early as 2030/2031, if needed. Indeed, a more aggressive schedule could be adopted to minimize the risk that the key ANDES science cases are harvested by high-resolution spectrographs at other 30m-class telescopes (e.g., G-CLEF at GMT). It is worth mentioning that the Consortium will do subsystem reviews in October/November 2024, in order to have a PDR in June 2025 and minimize delays.

6. CONCLUSIONS

The ANDES baseline design is that of three ultra-stable and modular fibre-fed cross dispersed echelle spectrographs providing a simultaneous spectral coverage of 0.4-1.8 μm (goal 0.35-2.4 μm) at a resolution of 100,000 with several, interchangeable, observing modes ensuring maximization of either accuracy, throughput or spatially resolved information. Overall, the studies conducted so far have shown that the ANDES baseline design can address the 4 top priority science cases, being able to provide ground-breaking science results with no obvious technical showstoppers.

The construction of ANDES includes the majority of the institutes in ESO member states with expertise in high resolution spectroscopy and will require an estimated 45 MEUR in hardware (including the K band and excluding contingencies) and about 650 FTEs. Contingencies are expected to be low (5-10%) because the proposed baseline design is based on proven technical solutions and can benefit on heritage from HARPS and ESPRESSO and other previous high-resolution spectrographs, e.g. PEPSI at the 11.8m LBT, SPIRou, CARMENES and GIANO. The construction (including Phase B) will last about 8-10 years. Therefore, with Phase B concluding in 2025, ANDES (or at least one of its modules) could be at the telescope in 2031/2032.

Overall, ANDES is an instrument capable of addressing ground-breaking science cases while being almost (telescope) pupil independent, as it can operate both in seeing and diffraction limited modes; the modularity ensures flexibility during construction and the possibility to quickly adapt to new development in the technical as well as science landscape.

We conclude by summarizing the highlights of the ANDES project, formerly known as HIRES, from Phase A through Phase-B1.

- The Phase A study has been conducted by an international consortium including the majority of the institutes in ESO member states expert in high resolution spectroscopy. During Phase A the consortium was composed of 30 institutes from 12 countries, and a grand total of about 200 people have contributed to the study. The Consortium is now composed of 33 institutes in 13 countries, with almost 300 people contributing to the project.
- The Phase A study started on March 22, 2016 and has been completed in one and a half years, with the datapack delivery to ESO on October 6, 2017.
- The ANDES Construction has been officially approved by the ESO Council in December 2021.
- Phase-B1 started in September 2022 and was concluded with the System Architecture Review (SAR) in October 2023.
- The science priorities which have been identified for prioritizing the Top Level Requirements of the instrument are:
  1. the detection of the signatures of life through the study of exoplanet atmospheres in transmission
  2. the variation of the fundamental constants of Physics
  3. the detection of the signatures of life through the study of exoplanet atmospheres in reflection

4. the direct detection of the Cosmic acceleration through the measurement of the Sandage effect

Many other ground-breaking science cases are made possible with the TLRs inferred from 1 to 4. These TLRs has then drive the Technical Specification which has been officially issued by ESO.

- The ANDES baseline design is that of a modular fibre-fed cross dispersed echelle spectrograph which has three ultra-stable spectral arms, [U]BV, RIZ and YJH, providing a simultaneous spectral range of 0.4-18 μm (goal 0.35-2.4 μm with an extension to the U band and additional spectral arm K) at a resolution of 100,000 with several, interchangeable, observing modes allowing observations both in seeing- and diffraction-limited modes.
- In particular, the seeing-limited mode will be quite unique among the ELT suite of instruments and will allow observations even in bad atmospheric conditions and/or with poor phasing of the ELT mirrors. It will also require simpler telescope operations.
- The proposed baseline design can fulfil the requirements of the 3 top science cases, with the goal of fulfilling also the 4th one.
- The modularity of the instrument ensures that several extensions can be added without affecting the instrument design or stability. The fibre-feeding ensures ultra-stable VIS and NIR spectrographs with no internal moving parts while, at the same time, allowing for many different observing modes.
- The total estimated cost of the baseline design is about 45 MEUR, excluding contingencies at the level of $\sim 10\%$, with an estimated 650 FTEs required to complete the project.
- The consortium will provide all the necessary funds for the construction of the instrument. ESO will compensate the consortium for hardware and FTEs costs with GTO on the ELT, which the Consortium will use for joinst science programs.
- The schedule proposed by the Consortium now foresees PDR in June 2025 with the final Preliminary acceptance in Chile in 2032, part of which could be anticipated to 2030/2031 if needed.
- Overall, ANDES should start operating as close to the ELT first light as possible and the studies conducted so far have provided several reasons for this:
  1. It allows ground-breaking science cases, and it should not be late compared to its competitors
  2. As an ELT instrument, it is relatively technically simple and has relatively low risks
  3. It is almost independent of the quality of the telescope pupil and it can operate in seeing-limited conditions
  4. It is a modular instrument and therefore it naturally allows a staged deployment.

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Table 2. Consortium Partners and Institutes

Country	Consortium Partners
Brazil	Board of Stellar Observational Astronomy, Federal University of Rio Grande do Norte, Natal
Canada	Observatoire du Mont-Mégantic and the Institute for Research on Exoplanets, Université de Montréal – COPL (Centre for Optics, Photonic and Laser), University Laval – Department of Physics & Astronomy, University of Victoria – Dunlap Institute + Dept. Astronomy & Astrophysics, University of Toronto – Quebec Artificial Intelligence Institute (Mila)
Denmark	Instrument Centre for Danish Astrophysics representing: – Niels Bohr Institute, København – Aarhus University – Danmarks Tekniske Universitet (DTU), Lyngby
France	Centre National de la Recherche Scientifique (CNRS) representing: – LAGRANGE, Observatoire de la Côte d'Azur, Nice – LAM (Laboratoire d'Astrophysique de Marseille), Marseille – IRAP (Institut de Recherche en Astrophysique et Planetologie), Un. Toulouse – IPAG (Institut de Planétologie et d'Astrophysique), Un. Grenoble Alpes – LUPM (Laboratoire Univers et Particules), Université de Montpellier – IAP (Institut d'Astrophysique de Paris) – LMD (Laboratoire de Météorologie Dynamique), Ecole Polytechnique
Germany	Leibniz-Institut für Astrophysik Potsdam (AIP) Institut für Astrophysik und Geophysik, Universität Göttingen (IAG) Max-Planck-Institut für Astronomie, Heidelberg Zentrum für Astronomie (ZAH), Universität Heidelberg Thüringer Landesternwarte Tautenburg (TLS) Hamburger Sternwarte, Universitẗ Hamburg (UHH)
Italy	Istituto Nazionale di Astrofisica (INAF), 'Leading Technical Institute'
Poland	Nicolaus Copernicus University in Toruń
Portugal	Instituto de Astrofísica e Ciências do Espaço, Porto Centro de Investigação em Astronomia/Astrofísica da Universidade do Porto Associação para a Investigação e Desenvolvimento de Ciências, Universidade de Lisboa
Spain	Instituto de Astrofísica de Canarias Consejo Superior de Investigaciones Científicas (CSIC, Spain) representing: – Instituto de Astrofísica de Andalucía (IAA) – Centro de Astrobiología (CSIC-INTA)
Sweden	Lund University Stockholm University Uppsala University
Switzerland	Département d'Astronomie, Université de Genève Physikalisches Institut, Universität Bern
United Kingdom	Science and Technology Facilities Council representing: – UK Astronomy Technology Centre – Cavendish Laboratory & Institute of Astronomy, University of Cambridge – Institute of Photonics and Quantum Sciences, Heriot-Watt University
USA	Department of Astronomy, University of Michigan