# SIMPLE: a high-resolution near-infrared spectrograph for the E-ELT

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## ABSTRACT

SIMPLE is an optimized near IR echelle spectrograph for the E-ELT assisted by adaptive optics. It delivers a complete 0.84-2.5μm spectrum in one exposure with resolution up to R=130,000, nearly diffraction limited pixel scale and limiting magnitudes down to JHK~20. Its most prominent science cases include the study of the intergalactic medium in the early Universe (z>6) and of the atmospheres of exo-planet transiting nearby low mass stars.

**Keywords:** near-infrared, spectrograph, high spectral resolution, high-spatial resolution

## 1. INTRODUCTION

High resolution infrared spectroscopy is one of the youngest branches of astronomical research with a huge scientific potential. It is opening new windows in our understanding of several hot topics of modern stellar and extragalactic astrophysics, and it will have a major impact in the JWST and ALMA era and beyond.

Quantitative spectroscopy of key absorption lines in intrinsically red (cool stars and planets), or reddened (proto-planetary disks, stellar populations in the inner Galaxy) or red-shifted (high-z Universe) requires a spectral resolution R~100,000 over the 0.8-2.5 μm spectral range. However, high spectral resolution of faint objects at optical and near infrared wavelengths can only be performed by using large telescopes. At a resolution of R=100,000 the sky and thermal backgrounds are quite low, even in most of the K band. Since the targets (either compact sources or sub-structures) are typically smaller than the spectrometer entrance aperture (a few times the diffraction limit), regardless of the telescope size, the limiting flux observable with a given S/N scales with the *square* of the telescope aperture. This implies a limiting magnitude about *3.5 mag* fainter than any other current or planned near-IR high-resolution spectrometer at 8-10m telescopes.

This huge jump in sensitivity will place a near IR high resolution spectrometer at the E-ELT at the forefront in the astronomical context of the next two decades. The only potential competitor is a similar instrument at another ELT, and indeed according to the instrumental plans available on the WEB sites of TMT and GMT, TNT-NIRES and GMT-NIRS are high resolution IR spectrographs under study. However, a 42m E-ELT can still provide 0.7 and 1.6 deeper limiting magnitudes (only considering the telescope aperture) than a 30m TMT and 20m GMT, respectively.

In particular, SIMPLE has two big promises: i) characterize the atmosphere of exo-planets and detect signatures of life; ii) detect the signature of the “first light” sources in the early Universe, i.e. Population III stars. We claim that SIMPLE is the best instrument capable of pursuing such goals in the ELT era.

While truly unique in terms of performance, capabilities and scientific expectations, SIMPLE is a relatively compact instrument exploiting known technologies, which translates into a relatively low risk and low cost facility, perfectly suitable for the E-ELT first light and expected to deliver major scientific results from the early operation phase on.

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## 2. SCIENCE HIGHLIGHTS

The following scientific cases take advantage of the large collecting area of E-ELT and of the high spectral resolution of SIMPLE. These targets are unresolved and benefit of the AO system to concentrate their light into the slit.

**Exo-planets atmospheres and signatures of life.** By measuring the (differential) spectra of low mass stars during the transit of an exo-planet, SIMPLE will allow the detection and characterization of their atmosphere (see Figure 1), and possible signatures of life. High spectral resolution studies can be performed on planetary systems with cross-sections exceeding $3\text{x}10^{-4}$, i.e. on *i)* planets with extended atmospheres (>100 km) down to the Earth-size, *ii)* massive planets (super-Earths, Neptunes) with less expanded (<50 km/s) atmospheres. Small planets with more normal atmospheres (ocean, Earth /Venus like) are most challenging but the chemical composition of their atmospheres can still be investigated by applying a suitable rebinning of the individual molecular lines in their high resolution spectra.

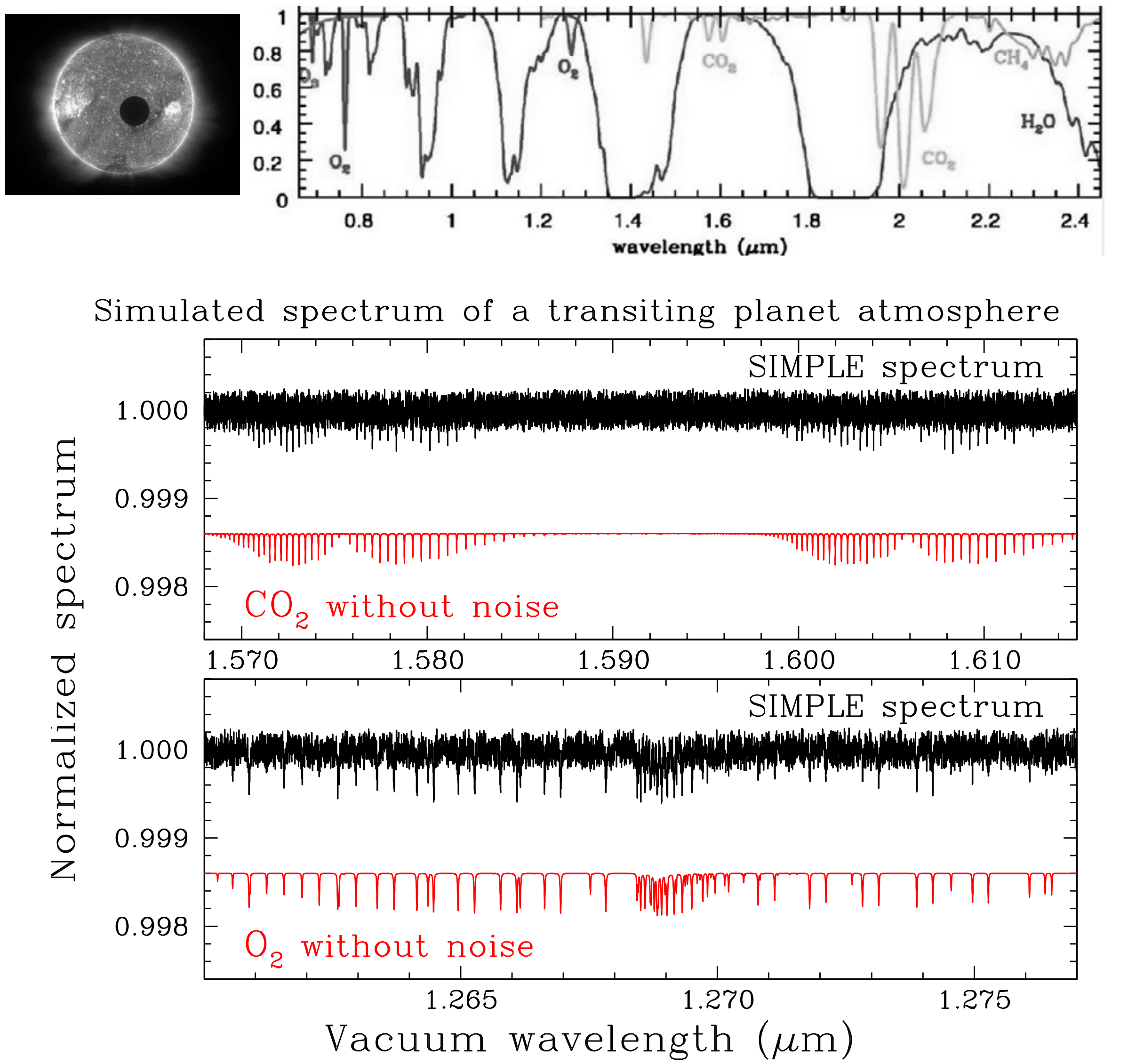


**Figure 1**.Top panel: near IR spectrum of an Earth-like atmosphere. Bottom panel: expected J band spectra of the $O_2$ lines and H band spectra of $CO_2$ for a transiting planet with an atmosphere cross section of $6\text{x}10^{-4}$.

A number of surveys are specifically dedicated to the search of transiting exo-planets and strong synergies are also expected with e.g. Kepler, EPICS and CODEX for planets search and classification, and with METIS, which can provide complementary information from mid-IR spectra. A potential competitor is JWST, but according to simulations, SIMPLE outperforms JWST because of the much larger telescope aperture of the E-ELT and of the higher spectral resolution for measuring the intrinsically narrow lines.

**Early nucleo-synthesis in the inner Galaxy**. SIMPLE will also allow us to determine for the first time the chemical abundance patterns of the atmospheres of the main sequence stars in the inner Galaxy. Such spectra will provide direct information on the chemical enrichment and overall nucleo-synthesis in the central Bulge at the early epoch of the Galaxy formation. Optimal targets for this science will be provided by VISTA, JWST and MICADO.

**First light sources.** The huge jump in sensitivity delivered by SIMPLE will provide high S/N spectra of QSO and GRB around, or beyond the re-ionization epoch, which will allow us to trace the early chemical enrichment and dust content of proto-galaxies along their line of sight by exploiting the associated absorption lines. The SIMPLE promise is to trace for the first time the Population III chemical fingerprint (see Figure 2). Targets for this science (mostly QSO at z>6.5) will be provided by ongoing and planned near-IR surveys (VISTA, PanSTARRS, Euclid/SNAP). While SIMPLE will be unique to detect the chemical fingerprint of first light galaxies in absorption, JWST and other ELT instruments (HARMONI and EAGLE) will provide complementary information by searching for Population III emission (continuum and emission lines).

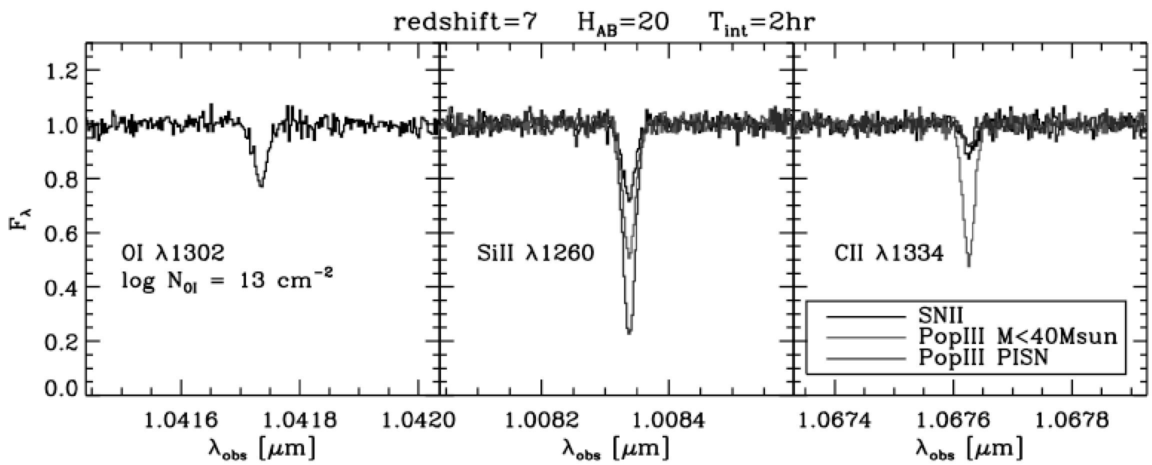


**Figure 2.**SIMPLE 2hr simulation of absorption systems at z=7 in the foreground of a quasar with $H_{AB}$=20, for different abundance patterns of the intervening proto-galaxy. The black line is for abundances typical of SNe II; the red line is for abundances expected from Population III stars with masses M<40 $M_{\odot}$, while the blue line is for abundances from Population III Pair Instability SNe.

The following science cases will also benefit of spatially resolved spectroscopy at the diffraction limit of the E-ELT.

**Virgo stellar clusters**. SIMPLE will allow us to characterize for the first time chemical composition and mass of globular clusters in external galaxies out to the Virgo galaxy cluster, which will be used as tracers of galaxy formation and chemical enrichment, in environments and systems different from our own Galaxy. For the massive clusters, which will turn out to be extended up to a few hundreds *mas*, dynamical studies will also become possible. Strong synergies are expected with JWST and MICADO to identify the best targets and characterize their photometric properties.

**Solar system moons.** SIMPLE can map the surface and atmospheric stratification of the molecules with an unprecedented resolution of a few hundred meters in various moons of the Solar system. Strong synergies are expected with METIS, which will provide complementary information on the physical parameters.

**Proto-planetary disks.** SIMPLE will probe the inner structure of proto-planetary disks and trace the early phases of planet formation. JWST, Herschel, ALMA & METIS will provide complementary information of the outer regions.

Other areas where SIMPLE will provide extremely important contributions, and likely breakthroughs, are *i*) the nucleo-synthesis of evolved red giant and supergiant stars, *ii*) the origin of cool-star mass-loss linked to the fate of low- and intermediate-mass stars, *iii*) the origins of stellar magnetic fields, *iv*) the dynamics of the accretion phases in star formation, *v*) the origin and evolution of stars in the neighbourhood of the Galactic center, *vi)* relativistic effects around the super-massive black hole, *vii*) the initial mass function in starburst galaxies.

Finally, an E-ELT with a near IR high resolution spectrograph is also a powerful facility for the detection of exo-planets (and in particular rocky planets) around low mass stars.

If during the first period of E-ELT operation, the LTAO/MCAO system will not be available, a number of SIMPLE science programs can be nonetheless performed using the SCAO-WFS onboard the instrument, which operates with bright (JH<13) targets. Among them we emphasize the study of exo-planet atmospheres, solar system moons, spectro-astrometry of proto-planetary disks, chemistry and magnetic fields of cool stars.

## 3. THE INSTRUMENT CONCEPT

The scientific requirements of SIMPLE yielded an instrument concept which includes and optimizes two distinct observing modes, namely

*1) Single-object* - This mode must deliver the full 0.84-2.50 μm spectrum in a single exposure, providing the highest possible sensitivity, spectral quality and stability.

*2) Long-slit* - This mode does not require full spectral coverage but must provide optimized image quality along the slit with a spatial sampling of 9*mas*/pix or smaller.

The second observing mode unambiguously defines the type and parameters of the instrument, which are those we adopt for SIMPLE.

The first observing mode can be obtained using two fundamentally different instrumental concepts, namely:

- An "AO-assisted" spectrometer, such as the one we propose.
- A "seeing-limited/GLAO-assisted" spectrometer, with an entrance aperture of 0.5" to maximize the light power collection at all wavelengths.

We performed a detailed analysis of the relative performances of these two types of instruments and came to the following conclusions.

The AO-assisted instrument performs better in the following cases and for the following reasons.

- Observations in the K-band of any type of object, because of the good performances of the AO-correction and because of the thermal background, which becomes the dominant source of noise for the much larger aperture of the GLAO instrument.
- Observations of relatively faint sources at $\lambda$>1μm, because the main source of noise is the read-out of the detector and the light in the seeing-limited/GLAO-assisted spectrometer is spread over a much larger number of pixels than in the AO-assisted spectrometer.

The seeing-limited/GLAO-assisted spectrometer performs better in the following cases.

- Observations in the I-band of any type of object, because of the relatively poor performances of the AO-correction at $\lambda$<1μm and because of the lower noise of the CCD detectors that can be used at these wavelengths.
- Spectroscopic observations at very high s/n ratio (>300) in the H, J, Y bands. The gain in limiting magnitudes is modest (0.2mag) in the H band, while it becomes more important in the J (0.7mag) and Y (1.2mag) bands.

Therefore, the best approach to optimize the performances at all wavelengths and observing conditions would be building two separate instruments, namely:

- A cryogenic, AO-assisted spectrometer covering the whole spectral range. This instrument is relatively compact and similar to those designed for smaller-size telescopes.
- A refrigerated seeing-limited/GLAO-assisted spectrometer operating to $\lambda$<1.4μm (refrigerated to −20 ºC) or to $\lambda$<1.8μm (refrigerated to −80 ºC). This instrument has an aperture-resolution product 20 times larger, implying much higher complexity, risks and costs.

The scientific cases are compatible with the performances that the AO-assisted instrument can achieve. We do not identify any strong scientific reason that could make the seeing-limited/GLAO-assisted spectrometer preferred relative to the AO-limited instrument. Therefore, the solution we propose is a relatively simple (hence the name) instrument that consists of a canonical cross-dispersed echelle spectrometer whose slit-width is a few times the diffraction limit at the longer wavelengths (K band). In other words, the design is independent on the telescope diameter [1]. With this approach the instrument can be developed using standard, low-risk and relatively low-cost technologies. We note in particular that the extension to the bluest wavelengths (0.84μm) comes virtually for free, i.e. it does not add any complication or risk relative to an instrument optimized over the "canonical" 1.0-2.5 μm near-infrared wavelengths range.

### 3.1 Observing modes

The spectrometer is a single channel system with fixed, all-mirrors optics. The collimated beam has a diameter of Ø180mm and the disperser is a commercial R2 echelle grating. Therefore, the required resolving power of R=130,000 is achieved with a slit width of 27*mas*, equivalent to $2.5\cdot\lambda/D$ in the K-band. The pixel scale in the spatial direction is 9*mas*, it can be expanded to 3*mas*/pix using anamorphic optics in the pre-slit system. The spectrometer covers the whole wavelengths range in one exposure because it employs prisms as cross-dispersers. It delivers a complete cross-dispersed spectrum on a linear mosaic of three $4k^2$ array. The slit-length in this mode is limited to 0.45", to avoid orders overlap.

The long-slit mode requires a dedicated order-sorter device, which we have designed and included in the pre-slit system. Simulated spectra in the two modes are displayed in Figure 3. The slit length is 4" with 9*mas*/pix sampling or 1.3" with the expanded pixel scale of 3 *mas*/pix.

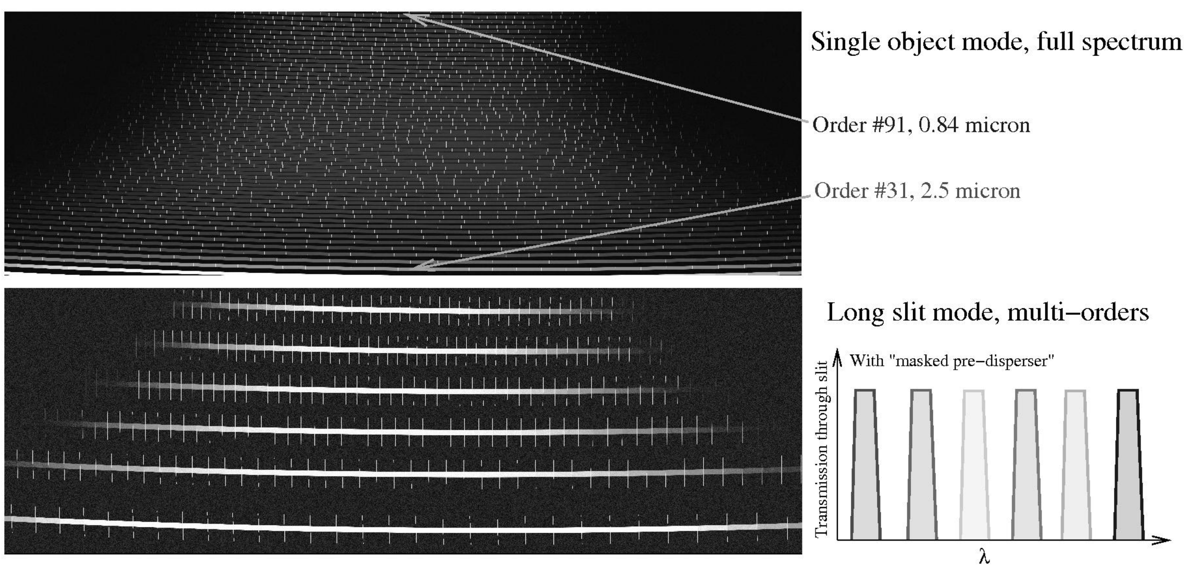


**Figure 3**.Simulated SIMPLE spectra in the single-object configuration (top panel) and in the long-slit mode (bottom panel). The focal plane detector is a linear mosaic of three $4k^2$ array detectors

Four slits of different widths, namely 27*mas* (R=130,000), 36*mas* (R=100,000), 54*mas* (R=67,000) and 72*mas* (R=50,000), are available to the observer. The slits are at a fixed position inside the spectrometer and are selected by sliding a dekker/mask, which is also used to switch between the long-slit and full-spectrum modes. The dekker unit is the only moving part at cryogenic temperatures.

### 3.2 Adaptive optics

The spectrometer requires a good level of adaptive optics correction to concentrate the light into the slit and maximize throughput. To properly quantify this requirement we define the "slit efficiency parameter" (SLE), which measures the fraction of light falling within the 27*mas* x 54*mas* aperture used to extract the spectrum in the baseline observing mode with R=130,000. The effect of SLE on the instrument performances is estimated as follows. Using the same instrument on telescopes with different diameters ($D_{TEL}$), the magnitude of a compact object that can be observed with a given S/N ratio in a given integration time scales as:

$$m_{lim} = \text{constant} + 2.5\ \log_{10}(SLE) + 5.0\ \log_{10}(D_{TEL})$$

This relationship has general validity, i.e. it does not depend on what is the predominant source of noise (detector *vs.* background *vs.* photon-noise of the object). Therefore, it implies that SIMPLE on the E-ELT with a poor AO correction (SLE<0.03) would achieve similar limiting-magnitudes as the same spectrometer mounted on the VLT. Therefore, to take proper advantage of the telescope area, the minimum requirement is SLE>0.1 over most of the wavelengths range.

The values of SLE predicted with different types of AO corrections are plotted in Figure 4. This shows that LTAO/MCAO matches the requirements, while GLAO is unable to concentrate enough light, even using a 3x image-slicer. The right-hand panel of Figure 4 also shows that on-axis SCAO correction with 84x84 sub-apertures provides much higher values of SLE, while SCAO with 42x42 sub-apertures provides performances similar to LTAO/MCAO. More details on the SCAO mode, including magnitude limits, can be found in [2].

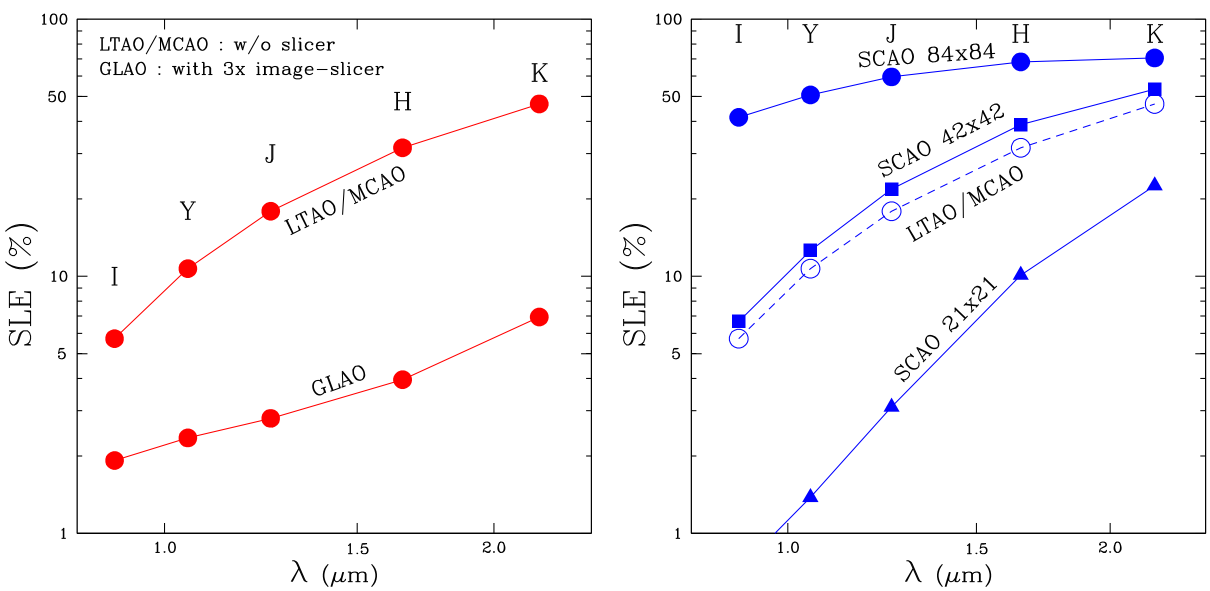


**Figure 4.** Predicted values of SLE (fraction of light falling in the spectrometer aperture) for different types of AO corrections. The numbers for LTAO/MCAO and GLAO are based on the simulated PSFs made available by ESO for the E-ELT-ETC. The numbers for SCAO are discussed in [2].

Figure 5 shows the predicted light distribution along the slit for LTAO/MCAO correction. The contribution of the PSF wings at >100 *mas* from the slit center is negligible even at the shortest wavelengths. This implies that the slit of SIMPLE (450*mas* in the full-spectrum mode) is long enough for proper object nodding and sky subtraction along the slit.

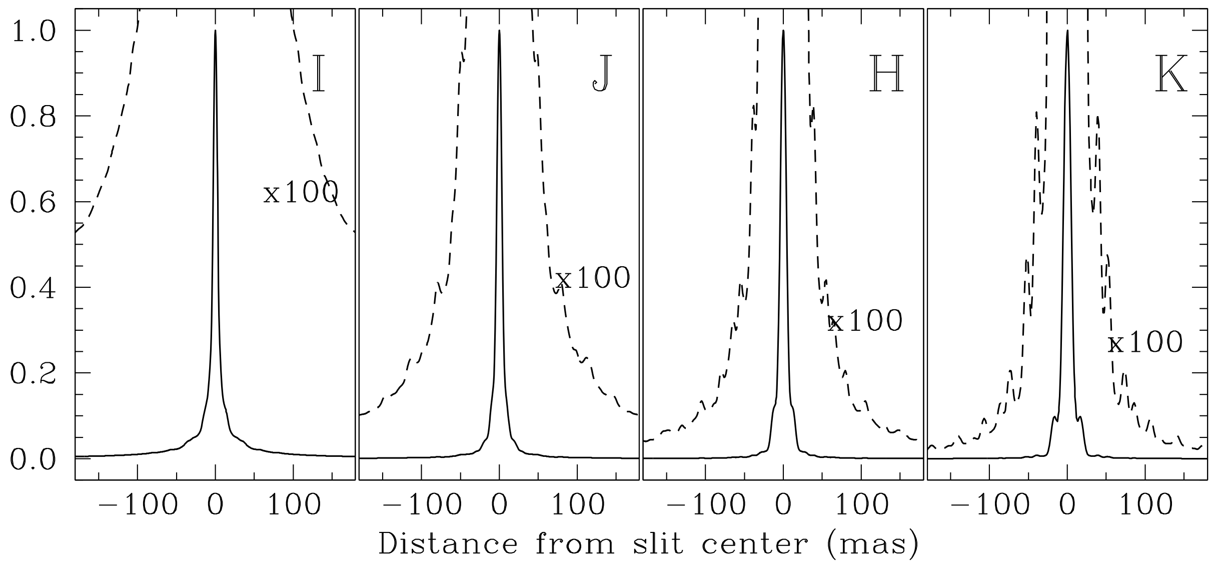


**Figure 5.** Predicted distribution of light along the R=130,000 slit, based on the LTAO/MCAO PSF computed for the E-ELT-ETC. The flux is normalized to unity at the peak. The dashed curves show the profile expanded by a factor of 100 to properly evaluate the amplitude of the wings.

### 3.3 Interface to the telescope

SIMPLE, to achieve all its science goals, must be fed by a LTAO/MCAO module. We performed a detailed trade-off analysis between the interfacing with the LTAO-module (ATLAS) and the MCAO-module (MAORY) and found them equivalently good. We have therefore developed a design that maximizes the flexibility of interfacing to the telescope.

The instrument is mechanically separated from the LTAO/MCAO module and collects the light far (~3m) beyond the F/17.7 focus. The alignment between the spectrometer and the AO module is monitored and corrected by a dedicated guider-module that uses an off-axis natural star within 30” of the scientific target. With this approach the instrument can be positioned on the Nasmyth platform at any focal station.

Figure 6 shows how the instrument can be interfaced to the lateral port of MAORY.

To further increase its flexibility, SIMPLE also includes an infrared SCAO-WFS that uses the light from the astronomical target when observing bright objects. This module, which is described in [2], is a sub-system of SIMPLE that will be built, tested and delivered together with the rest of the instrument. In case a LTAO/MCAO module will not be available at the beginning of E-ELT observations, SIMPLE can nonetheless be mounted at a “naked-focus” and operate as a first-light instrument for all those observations that can be performed with SCAO-WFS correction. Noticeably, these include the scientifically prominent program aimed at the detection of molecules in the atmospheres of planets transiting in front of their parent star.

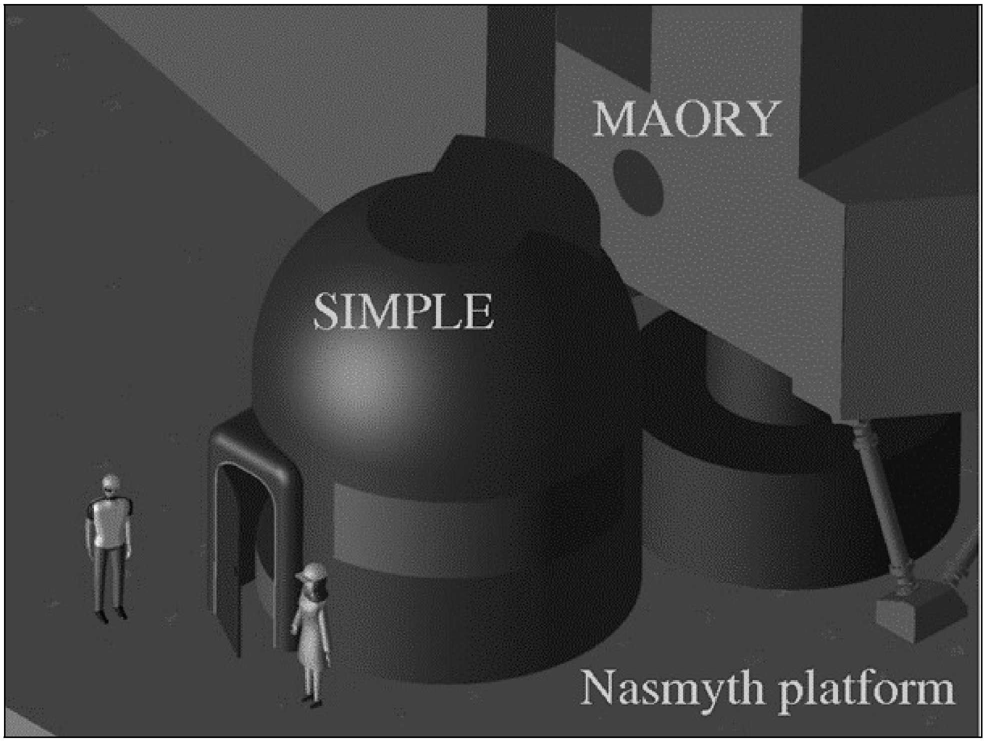


**Figure 6.** Illustration of SIMPLE interfaced to the lateral port of MAORY.

### 3.4 Instrument sub-systems

The instrument design is specifically focused to create sub-systems that are well separated both from the logical and physical point of view. They can be separately developed, built and tested minimizing the interactions with the other sub-systems, up to the final instrument integration.

This approach is particularly effective to distribute the work among different groups/partners/industries, to simplify the supervision tasks of the project office and to minimize risks. The main sub-systems of SIMPLE are summarized in Figure 7 and briefly described in the following.

*i*) the spectrometer, is the core of the instrument and it includes the slit and the optical elements necessary to collimate, disperse and re-focus the light onto the detector. It operates in a vacuum-cryogenic environment cooled by liquid nitrogen. It can be divided into two main modules, namely the cryostat and the optical bench carrying the spectrometer optics that consist of six aluminum mirrors (five aspheric and one flat), the echelle grating and the cross-disperser prisms;

*ii*) the pre-slit, which is refrigerated to $-30^{o}$C and includes a pupil stop, an acquisition camera and slit viewer and selectable sub-modules for the different observing modes, i.e. an ADC, a fibre scrambler, and a polarimeter;

*iii*) an infrared (1-2.1 micron) SCAO-WFS that uses the light from relatively bright (JH<13) targets. It includes a pupil-steering mirror, a viewing/tracking camera at an intermediate focus, a fast (up to 1kHz) modulation mirror, and two selectable cameras to switch between the 42x42 and 84x84 sub-apertures modes. The splitting between scientific-light (transmitted) and WFS-light (reflected) is made by means of selectable beam-splitters with parameters optimized for the different scientific cases.

*iv)* a calibration unit;

*v*) a re-imager and guider module, including a small (Ø360mm) telescope, which creates an intermediate F/36 focal image above the entrance of the pre-slit (see Figure 7).

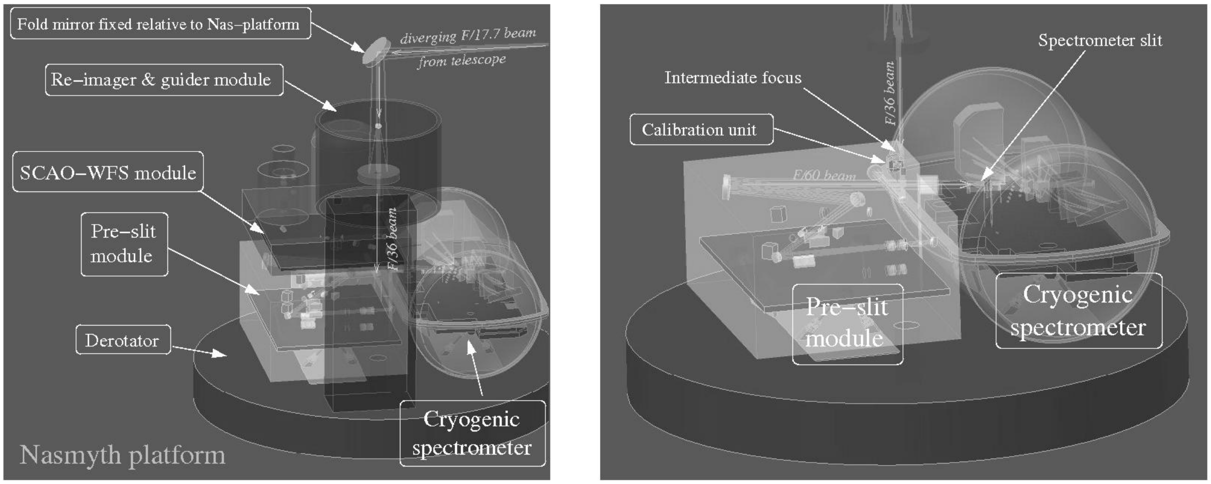


**Figure 7.** Left-hand panel: 3D view of SIMPLE identifying the main sub-systems and the optical path. Right-hand panel: closer view the pre-slit and cryogenic spectrometer identifying the main sub-modules.

The total instrument efficiencies are remarkably high, ranging between 20% (I band) and 40% (K band), because the instrument optics is mostly composed of mirrors whose high throughput is guaranteed by standard protected-Ag coating.

A dedicated exposure time calculator for the instrument was developed and made publicly available on the SIMPLE web page (*http://simple.bo.astro.it*). Limiting magnitudes for representative cases are summarized in Table 1 where one can see that Vega magnitudes of JHK~20-21 (S/N~10) and 17-18 (S/N~100) can be obtained with an on-source integration time of 2 hrs at the maximum resolving power R=130,000.

**Table 1**. Limiting Vega-magnitudes(1) for spectra at R=130,000(2) with on-source integration time=2hr.

| **Band (λ)** | **S/N values** | | | | | |
|---|---|---|---|---|---|---|
| | **10** | **20** | **50** | **100** | **300** | **$10^3$** |
| **I (0.90 μm)** | 19.6 | 18.7 | 17.5 | 16.4 | 14.3 | 11.7 |
| **Y (1.05 μm)** | 20.3 | 19.4 | 18.2 | 17.1 | 15.0 | 12.4 |
| **J (1.25 μm)** | 20.6 | 19.8 | 18.6 | 17.5 | 15.4 | 12.8 |
| **H (1.65 μm)** | 20.8 | 20.0 | 18.8 | 17.7 | 15.6 | 13.0 |
| **K (2.20 μm)** | 20.4 | 19.6 | 18.4 | 17.4 | 15.3 | 12.8 |

Notes
(1) S/N ratio is computed per spectral resolution element.
(2) The entrance aperture is 27 *mas* x 54 *mas*. LTAO/MCAO image correction is assumed.

## 4. REFERENCES


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