OPTICAL SPECTROSCOPY WITH ADAPTIVE OPTICS: THE AVES SPECTROGRAPH FOR THE VLT

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ABSTRACT. The combination of Adaptive Optics (AO) and echelle spectroscopy opens up new possibilities for optical spectroscopy both in the area of very high resolution (several ∼100,000) of relatively bright objects and of medium-resolution spectroscopy (R∼15,000) of faint background limited objects. We discuss the latter possibility by referring to a specific instrument (AVES-IMCO) that we propose to built for the secondary port of the AO module NAOS at the VLT.

1. Introduction

The light concentrating power of Adaptive Optics (AO) provides great advantages not only for imaging (as is widely recognized) but also for spectroscopy. By narrowing the slit to match the AO improved image size, we can increase the spectral resolution and reduce the sky and detector background while retaining, at the same time, most of the light from the source. By taking advantage of AO, more compact spectrographs can be built which have either higher resolving power than non-AO spectrographs of comparable size (e.g. Ge et al. 1998) or reach fainter magnitudes than non-AO spectrographs of similar resolution in sky- or detector-limited observations (Pasquini et al. 1998, Pallavicini et al. 2000). A spectrograph optimized for a small image will be unique for observations which are limited by the sky and detector background and for which an increase in resolution is crucial for the science but cannot be achieved with the desired signal. Moreover, an AO spectrograph is ideally suited for observations of crowded fields where it is important to reduce the contamination by nearby objects. Note that for AO spectroscopy there is no need of a high Strehl ratio (which would be difficult to reach in the optical domain in any case), but simply of a high encircled energy to assure that most of the light from the source falls inside the slit. The potential of AO in optical spectroscopy has not yet been fully exploited but it will likely represent one of the key elements in the development of next generation optical spectrographs.

In this paper, we present the scientific motivations and a preliminary design of an Adaptive Optics Visual Echelle Spectrograph (AVES) for use at the Nasmyth AO focus of the Very Large Telescope (VLT). This study originated from an early suggestion (Pasquini et al. 1998) for a compact low-cost AO spectrograph for possible use at the VLT, but also at other large telescopes with AO capabilities. We have developed the original concept with specific regard to the Nasmyth Adaptive Optics System (NAOS,

TABLE I
Summary of AVES-IMCO characteristics

Spectrograph F/ratio	F/3.2	average
Pupil Size	5 cm	
Grating	echelle	63.5 blaze, 79 lines/mm
Resolving Power	15,600	with 0.3 arcsec slit
Sampling	2.5 pixels	0.12 arcsec/pixel
Crossdisperser	prism	double pass
Spectral Coverage	500-1000 nm	in one exposure
Order Separation	27 to 49 pixels	decreasing towards red
Spectro performances	S/N>10 for V=22.5	seeing 0.6" 2h int.
	S/N>4 for V=24.0	seeing 0.6" 2h int.
Imaging F/ratio	F/45	
FOV	5 arcseconds	
Image scale	9 mas/pixel	
Occulting masks	3	
Broad Band Filters	V,R,I plus open	
Narrow Band Filters	>5	
Imager performances	20 mas at 800 nm	seeing 0.6"
ADC	yes	adjustable
Detector	2K×2K, 15 μm pixel	frame transfer

Rousset et al. 1998) of unit UT4 (*Yepun*) of the VLT, where the spectrograph can be mounted as parallel instrument of NAOS (the main focus of NAOS being used by the CONICA instrument). In addition, in the course of this study we realized that imaging and coronograph functions could be implemented in the same instrument, with only a limited increase in complexity well justified by the improved scientific capabilities. An AO imager/coronograph in the optical will be unique at the VLT and will complement the IR observations of CONICA by providing a complementary wavelength range as well as better angular resolution and better detectors. The new design combines both spectrographic and imaging/coronograph functions in one instrument that we have named AVES-IMCO (Adaptive-optics Visual Echelle Spectrograph and IMager/COronograph). The main instrument characteristics are summarized in Table I.

A design study of AVES-IMCO is being carried out by a Consortium of four Italian Institutes, with the support by researchers at ESO as external consultants (B. Delabre, N. Hubin, L. Pasquini). The Institutes involved are the Osservatorio Astronomico di Palermo (OAPA), where the Project Office is located, the Osservatorio Astronomico di Brera (OABR), which is responsible for the optomechanical design, the Osservatorio As-

tronomico di Trieste (OATS), which is responsible for the instrument control electronics and software, and the Osservatorio Astrofisico di Catania (OACT), which is responsible for the detector and associated control electronics. The suggestion to add imaging and coronograph capabilities, and the specifications for them, came from the Laboratoire d'Astrophysique – Observatoire de Grenoble (LAOG) which has later joined the project, providing also the expertise for the crucial interface to NAOS. LAOG is acting on behalf of a consortium of French institutes also responsible for NAOS. An AVES-IMCO Science Team, including representatives from all participating institutions, is responsible for the identification of the primary scientific objectives of the proposed instrument and for elaborating the observational programme that we intend to carry out with the instrument.

In the following sections we will present first the scientific motivations for building an instrument like AVES-IMCO for the VLT and then we will discuss the design and expected performances of the instrument. Only a brief summary of the relevant issues are presented in this paper. For details we refer to the project technical documentation.

2. Science case

2.1. Why building AVES-IMCO

An intermediate resolution optical spectrograph capable of observing objects as faint as V=22.5 at S/N>10, and as faint as V=24 for radial velocities, opens to spectroscopic investigations a large number of astrophysical problems, ranging from distant galaxies to solar-system objects, which can only partially be addressed, if at all, with the instruments available at present at the VLT and elsewhere in the world. Moreover, the implementation of imaging and coronograph functions in the same instrument further enlarges the range of science topics that can be tackled effectively, and sometimes uniquely, with the proposed instrument. The scientific objectives of AVES-IMCO include, among others:

- Spectroscopy of high-redshift star forming galaxies
- Absorption lines of intervening objects in QSOs
- Imaging and coronographic observations of Lyman-break galaxies and Damped Lyα galaxies
- Imaging of the host galaxies of QSOs at intermediate redshifts and of nearby AGNs
- **Chemical abundances of main-sequence stars in the galactic Bulge, in the Halo and in the cores of Globular Clusters**
- **Chemical abundances of turn-off stars in the Magellanic Clouds and other galaxies of the Local Group (e.g. Sagittarius)**
- Spectroscopy of both hot and cool supergiants in external galaxies up to distances of 3 Mpc

- Radial velocities of eclipsing and pulsating variables down to V=24 (e.g. eclipsing binaries and Chepheids in the Magellanic Clouds and bright Cepheids up to the distance of the Virgo cluster)
- Imaging and spectroscopy of newborn massive stars in compact HII regions in the Magellanic Clouds
- **Imaging and coronography of young stellar objects, protoplanetary disks, jets and circumstellar regions**
- Imaging and spectroscopy of faint galactic objects like very-low mass stars, brown dwarfs, magnetically active stars in young open clusters and star forming regions, and optical counterparts of X-ray binaries
- Imaging and spectroscopy of solar-system bodies including planets, asteroids and Kuiper belt objects

In the above list we have put in bold size the scientific objectives that we consider of primary importance for the spectroscopic and imaging capabilities of AVES-IMCO and for which there is a strong scientific interest within our Consortium. These topics form the core of our observational programme. We stress however that other scientific objectives are no less important and they can make AVES-IMCO a quite attractive instrument for the scientific community at large.

The small image size provided by NAOS will be a clear advantage in the observation of crowded fields (like globular clusters and distant open clusters) to reduce the contamination by nearby objects. Observations in crowded fields have the additional advantage of mitigating the intrinsic limitation of current NGS AO systems which require a bright ($V< 15-16$) reference star sufficiently close ($< 10-15$ arcsec) to the target for optimum AO correction (and within ~ 1 arcmin with degraded AO performances).

The AVES-IMCO instrument will provide a spectrographic mode with sensitivity higher (by nearly 3 magnitudes) than presently available for UVES at the VLT and nearly 2 magnitudes more than expected for GIRAFFE, and will have higher resolution (by at least a factor 3) than FORS1/2. Performance estimates discussed later in this paper demonstrate that the AVES-IMCO spectrographic mode will bring many investigations currently possible only at low resolution into the domain of intermediate/high resolution (R$\approx$16,000). This will allow breakthroughs in several fields, both galactic and extragalactic.

We stress that AVES-IMCO, independently of the additional improvement provided by the AO correction, **is an intrinsically very efficient spectrograph**, with an efficiency comparable to that of the ESI spectrograph at Keck (which has similar, although slightly lower, resolution). Fig. 1 shows a comparison of the expected efficiency of the AVES spectrograph (including telescope, AO transmission, spectrograph optics and detector) with the measured efficiencies of ESI (Sheinis et al. 2000) and of UVES (ESO Web pages) as well as with the expected efficiency of GIRAFFE at the VLT (ESO Web pages). In addition to its high *intrinsic* efficiency, AVES-IMCO will profit from the advantage of the AO correction, which is crucial in the observation of faint sky-limited objects.

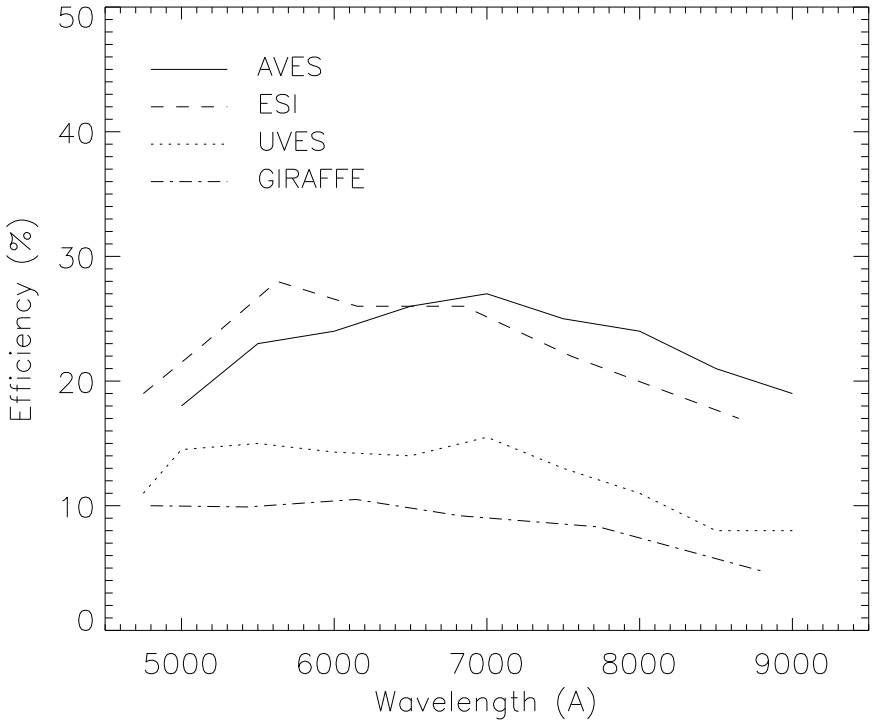

Fig. 1. Comparison of the total efficiency of the AVES spectrograph with those of ESI at Keck and of UVES and GIRAFFE at the VLT

Furthermore, AVES-IMCO will provide imaging capabilities in the optical with diffraction limit (20 mas at 800nm) when using bright reference objects. This translates into typical linear resolutions of 3 AU at 150 pc or 100 AU at 5 kpc. The angular resolution of AVES-IMCO will be higher than that of HST and CONICA. The advantage over HST is that AVES-IMCO will be fed by an 8m telescope rather than the 2.4m telescope of HST. An advantage of optical over IR observations is the much lower sky level. Moreover the optical detectors have generally higher quantum efficiency and lower noise than the IR detectors. These factors amply balance the fact that the Strehl ratio provided by NAOS is lower in the optical than in the IR. **For all the above reasons AVES-IMCO will be a necessary complement of CONICA**.

In the following we will discuss more extensively the spectroscopic and imaging capabilities expected for AVES-IMCO and we will present examples of "key projects" (both for spectroscopy and for imaging) that we consider as important scientific drivers for AVES-IMCO. These examples, while do not exhaust the list of scientifically interesting programs that could be carried out with AVES-IMCO, are sufficient to show that the demand for an instrument with the capabilities of AVES-IMCO at the VLT is fully justified.

2.2. Spectroscopy

A considerable amount of spectroscopic data has been gathered in the last two decades on nearby disk stars and relatively bright (V<15) field halo stars, using mainly 4m class telescopes. This has allowed us to grasp some basic facts about the chemical evolution of the Galaxy, however we have so–far only scratched the surface of a very complex and fascinating phenomenon. The turn-off stars of the nearest globular clusters, such as NGC 6397 and 47 Tuc, are now within the capabilities of UVES and FLAMES+GIRAFFE at the VLT and some data have already been collected and more will be collected in the near future. However for the majority of globular clusters, as well as for the Galactic Bulge, the distant Halo (at $20-30$ Kpc), not to speak of the external galaxies, to observe **late-type main-sequence stars** with a resolution and S/N suitable for abundance determination is beyond the present or future planned capabilities of VLT, or of any other 8m class telescope.

When observing stars fainter than ∼22nd magnitude with any conventional spectrograph under Paranal median seeing conditions the signal from the star becomes comparable to the sky background, so that there is little hope of improving the situation by using larger diameter telescopes (not currently available) or more efficient detectors (possibly available in the next five to ten years). By its clever use of adaptive optics AVES-IMCO will allow us to overcome this limitation, pushing the VLT nearly to its diffraction limit and opening up to our investigation the main-sequence and turn-off stars of the Galactic Bulge, of many Globular Clusters, of the distant Halo and of several Local Group galaxies. In this respect the scientists using AVES will have the possibility of achieving a major breakthrough in the subject, which would not be possible with any other available or planned instrument.

The performances expected from AVES-IMCO in its spectroscopic mode indicate that a S/N > 10 can be reached in 2 hours for a V=22.5 star. The gain with respect to GIRAFFE at the VLT (which has a similar resolution) should be nearly two magnitudes, due both to higher intrinsic efficiency of the spectrograph and to the reduction of the sky/detector background (Pasquini et al. 2000) The gain should be nearly 3 magnitudes with respect to UVES, which however operates at a higher resolution, i.e. for typically brighter sources.

The Keck Observatory built for its second unit (Keck II) a spectrograph with performances somewhat similar to AVES, but not optimized for AO: ESI (Echellette Spectrograph and Imager) provides in echellette mode a resolution of 10,000, thus in the domain of AVES spectrographic mode, albeit somewhat lower than the resolution of AVES. The instrument was commissioned in December 1999 and is now operating on a routine basis (Sheinis et al. 2000). However since ESI is not fed by an AO system for targets "faint enough that read-out noise is significant, the night sky emission will be bright enough to dominate the read-out noise in any case" (ESI Web pages). Thus AVES-IMCO should be superior to ESI for all such objects.

It is important to stress that an instrument with the capabilities of ESI in terms of its combination of intermediate resolution and high efficiency is not available at present or foreseen among VLT instruments. AVES-IMCO can fill this gap, in addition of providing further advantages (due to its use of AO) both for spectroscopy of background limited

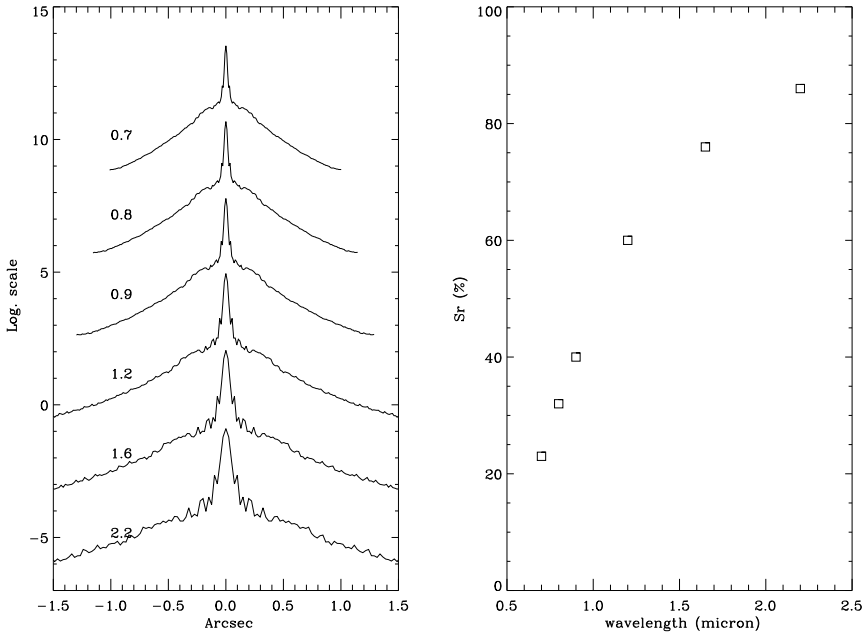

Fig. 2. Simulated NAOS PSF at various wavelengths ranging from 0.7 to 2.2 microns (left) and Strehl ratio as a function of wavelength (right). Case of an 11th mag star and seeing 0.85". PSFs are diffraction limited, eventhough the Strehl decreases, as expected, with wavelength.

objects and for diffraction limited imaging in the optical. It appears therefore that AVES-IMCO at the VLT will be highly competitive in its spectroscopic mode with instruments anywhere in the world and will be significantly more sensitive than any other optical spectrographs at the VLT, allowing us to carry out programs (such as the study of the chemical evolution of the Galaxy and of Local Group galaxies by means of accurate abundance determination of late-type main-sequence stars) which are not possible at present with any other VLT instrument.

2.3. Imaging

The past years have demonstrated the tremendous progress in the knowledge of astrophysical objects when observing at sub-arcsecond resolution. NAOS on the VLT will provide diffraction limited images down to the optical domain (Fig. 2). Direct imaging and spectroscopy in the 0.5 to 1 micron domain with AVES-IMCO will certainly improve the scientific output of NAOS.

Observations at optical and near-IR wavelengths are complementary in deriving color

information on science objects and in deriving spectral energy distributions, constraints on the nature, on physical and optical properties of emitting or scattering sources, and on relative astrometry of visible counterparts. Moreover it is possible to observe prominent emission lines of astrophysical interest in the optical, such as Hα, OI, SII and others.

Observing at optical wavelengths provides the following specific advantages:

- better angular resolution at shorter wavelengths (e.g. 20 mas at 0.8μ) than in the near IR, eventhough the image quality is not optimized for visible observations. Access to $\simeq$ 20 mas resolution certainly allows another quantitative stepforward in several fields of astronomy through access to smaller details in extended objects, better separations of multiple systems, and access to more distant objects.

- very good performances of the optical detectors in terms of sensitivity (typically 5 e- noise with CCDs instead of typically 50 e- noise with SBRC detectors), and the relative insensitivity to sky emission and to thermal background. This translates directly into improved detection limits and higher dynamics.

- overall improved observing efficiency in comparison to observations at H band or longwards, since no time is spent on the sky. This is interesting when the scientific aim does not require a given observing wavelength.

Besides, a parallel instrument working at optical wavelengths can provide spectroscopy at intermediate resolution, an observing mode that is not provided by CONICA.

Diffraction limited observations with NAOS are expected to provide important information in a number of astrophysical domains as reviewed in the NAOS Science Analysis Report (Lagrange et al. 1998). The NAOS Science Analysis Report reviews the science that can be done mainly in the 1$-$5 μm spectral range. Some science is common but **there is a specific and significant gain that can be obtained by observing at optical wavelengths**. This gain can be obtained in many different areas ranging from solar system objects to imaging of young stellar objects and protoplanetary disks, from the study of double and multiple stellar systems to imaging of Active Galactic Nuclei and QSO host galaxies.

3. Instrument description

AVES is a compact cross-dispersed echelle spectrograph designed to operate at magnification one with a slit of 0.3 arcsec and AO correction, providing a spectral resolution R$\sim$16,000. The same optical component acts as collimator and camera. A front optics adapts the F/15 output beam of NAOS to the F/3.2 required by the AVES spectrograph and combines also an imaging optics which acts both as a coronographic imager and for target acquisition in the spectrographic mode. A schematic view of the optical design of the spectrograph and of the front optics is given in Figure 3. The spectrograph is accomodated on the exterior of NAOS, while most of the fore-optics is attached to a plate inside NAOS.

The switching between the two modes of operation (imaging and spectroscopy) is obtained by means of two mechanisms, one internal and one external to NAOS. Both modes of operation share the same atmospheric dispersion compensator (ADC) and

pre-slit optics. The ADC is made of 2 counter-rotating prisms. In order to save surface losses the same ADC prisms are used as lenses. A first doublet in combination with the first ADC prism provides a real image of the telescope pupil, suitable for ADC location. The second prism, located just after such pupil, provides an F/20 real image where the coronographic masks and the slits for spectroscopy will be inserted.

After the intermediate F/20 focus a toggling mechanism inserts either the direct imaging or the spectroscopic lenses. The direct imaging lens consists of 2 doublets and a folding mirror, which provides an image of sky on the AVES CCD. These doublets change the F/20 into F/45 providing a plate scale of 9 mas per pixel. A filter wheel accomodates several narrow and broad filters for imaging. The spectroscopy fore-optics consists instead in a pupil relay lens and an imaging triplet. The entrance slit (F/15) is re-imaged on the focal plane of the spectrograph with the adequate F/ratio (F/3.2).

Dispersion and cross-dispersion are obtained via an echelle grating 79 l/mm blazed at 63 deg (R2) and a Schott SF4 prism with 52 deg apex angle. The spectrograph will be operated between order 22 and order 44 providing a full coverage of the $504 - 1045$ nm wavelength range.

Some features need to be emphasized. Since high efficiency is a primary requirement, the wavelength coverage is limited to above 500 nm to ensure that optimal coatings are used. The selected echelle grating (R2 79 l/mm, silver coated) is probably one of the most efficient echelle ever produced. Another key feature is that the full spectral range is covered in one exposure. There are no movable parts inside the spectrograph (except for alignement and focussing and for switching between the operating modes) and the whole instrument is less than 60 cm in length (w/o cryostat) to be easily accomodated on the external side of the NAOS structure.

A 3D-layout of the AVES-IMCO instrument mounted on NAOS is reported in Figure 4. An overall view of the AVES-IMCO instrument is shown in Fig 5.

Mecanically, the AVES-IMCO instrument consists of two principal subsystems, one internal and the other external to NAOS. The internal subsystem (Figure 6) supports the needed pre-focal plane functions such as the atmospheric dispersion compensator (ADC), the slits, the coronographic masks and the filters. An Internal Exchange Mechanism (IEM) allows switching between the F/45 Imaging/Coronographic mode and the F/3.2 spectroscopic mode. The IEM is made of two tubes in which the lenses are mounted by means of aluminum clamps to a common shaft on which a motor provides a 180 deg bi-directional movement.

The external subsystem (see Figure 7) consists of a carbon-fiber base-plate which acts as an optical bench lodging all the opto-mechanical components of AVES-IMCO that are located outside the NAOS structure. The high stiffness (the Young Modulus of Carbon-fiber material is commonly higher then 300 GPa, to be compared to the Aluminum Alloy Young Modulus which is about 70 Gpa) and the low weight (1.8 g cm^{-3}) make carbon-fiber a very good material for the base-plate. The base-plate is fixed to NAOS by means of 3 supports made of aluminium and screwed on the fixation points.

The main components fixed on the base-plate are the spectrograph mechanics, the External Exchange Mechanism (EEM) and the cryostat. The spectrograph mechanics consists in the supports for the grating and the prism with related adjustment system for

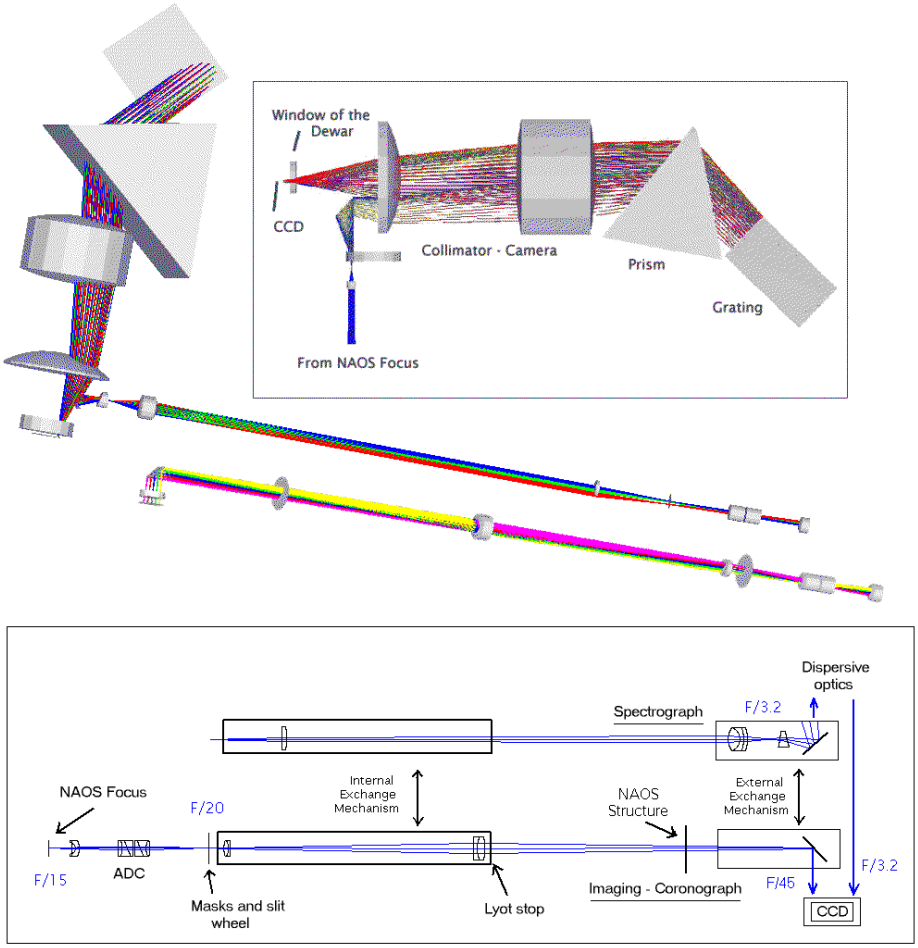

Fig. 3. Optical design of the AVES-IMCO spectrograph and imager-coronograph

alignment. The camera/collimator optics will be mounted in an internal tube suspended through retaining spheres to an external tube attached to the base-plate. Such a support system is provided with a translation adjustment that allows a focal correction by sliding the lenses inside the external tube. The adjustment is made by means of a micrometer screw connected to a pivot.

Purpose of the EEM is to alternatively deviate the beam directly to the CCD in imaging/coronographic mode or to the spectrograph in spectroscopic mode. A movable trails is mounted on steel rectified rods fixed by means of 4 aluminum supports to the base-plate. The movement of the EEM is ensured by a system made of motor, toothed belt and a pulley. The toothed belt is connected to the movable plate. During operation

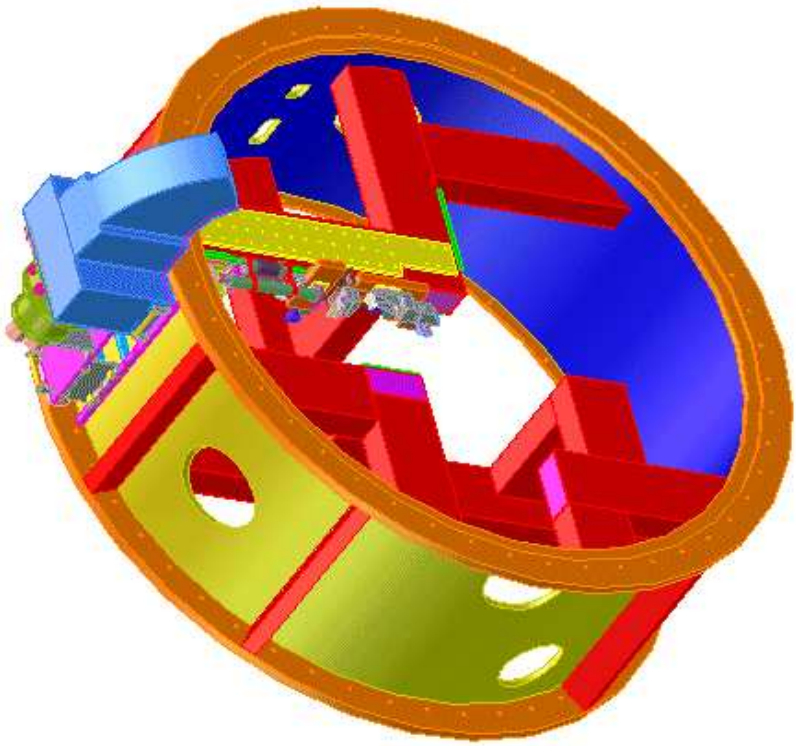

Fig. 4. 3D view of the AVES-IMCO instrument mounted on NAOS

the trail is maintained in place by means of permanent magnets that are over-written by electromagnets when the trail has to be moved, just as in the IEM. Two limit switches are used to control the activation of the electromagnets that release the trail.

The continuous flow cryostat (similar to the one adopted in many VLT instruments) is fixed on the base-plate by means of an aluminum flange. The calibration lamps and the shutter are instead mounted on the lower side of the base-plate.

The stability of the mechanical design has been tested by means of a Finite Element Analysis code. The most critical element is the base-plate which supports the heavier loads. The results of the analysis performed on the upgraded model guarantee the stability required.

AVES-IMCO needs to be equipped with its own calibration system both for imaging and spectroscopy. Since NAOS is very sensitive to thermal contamination the lamps for

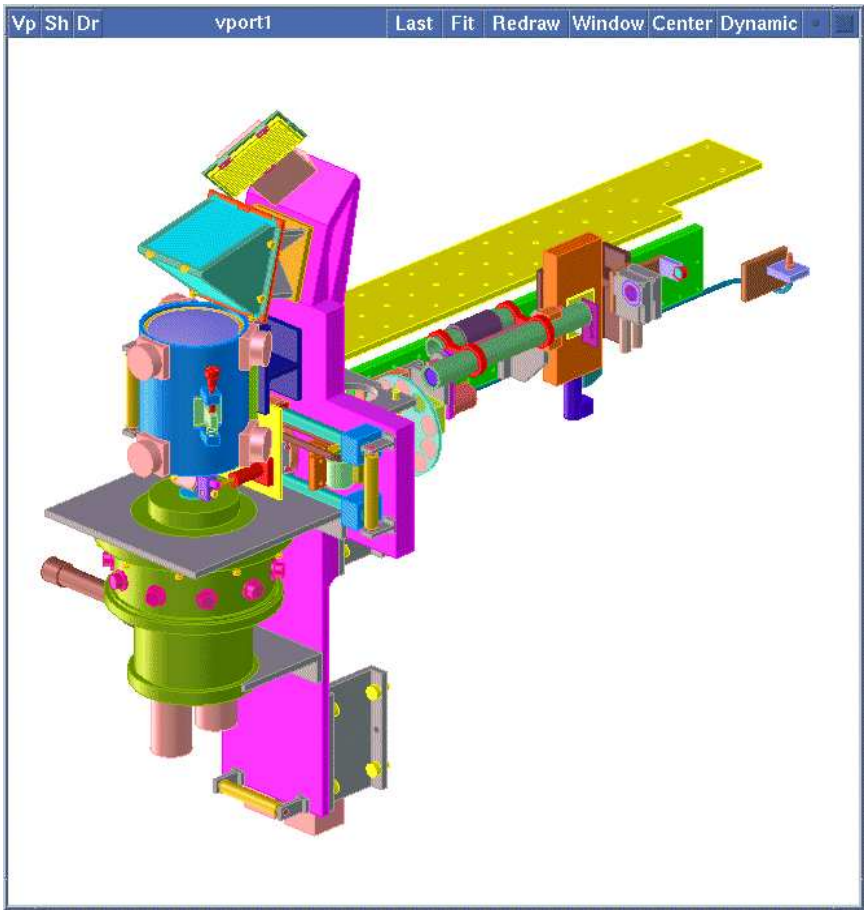

Fig. 5. Overall view of the AVES-IMCO instrument

calibration have to be positioned outside the NAOS structure. Two types of lamps are foreseen in the AVES-IMCO instrument. A ThAr lamp and a low voltage halogen quartz lamp. We plan to position the lamps in the lower side of the base-plate outside NAOS and transfer via fibers the light inside NAOS up to before the original F/15 focus, i.e. onto the mirror (governed by NAOS) that toggles the beam between CONICA and the parallel instrument.

AVES-IMCO motorized functions, calibration system and data acquisition for telemetry will be driven by a suitable control electronics (ICE). Such electronics is fully VLT compliant and is implemented with VME-based LCU connected via Local Area Network (LAN) to the Instrument Workstation (WS). The WS is used for instrument control and user interface while the LCU is used for real time control. The ICE consists of two main sections, namely the electronic boards controlling all the functions, located on board the instrument itself, and the Instrument Cabinet, hosting the LCUs, the power supplies

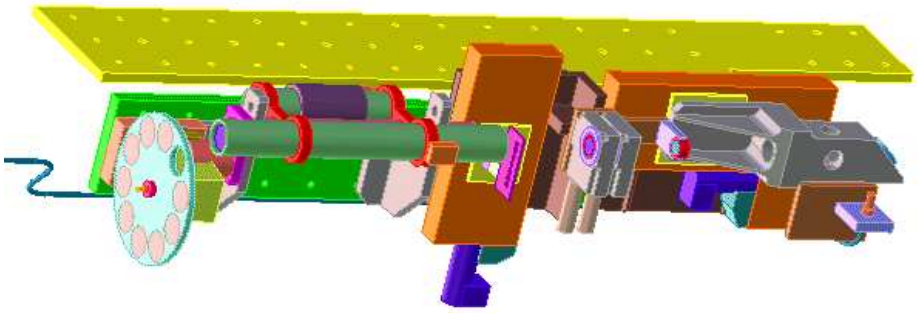

Fig. 6. Mechanical layout of AVES-IMCO internal subsystem

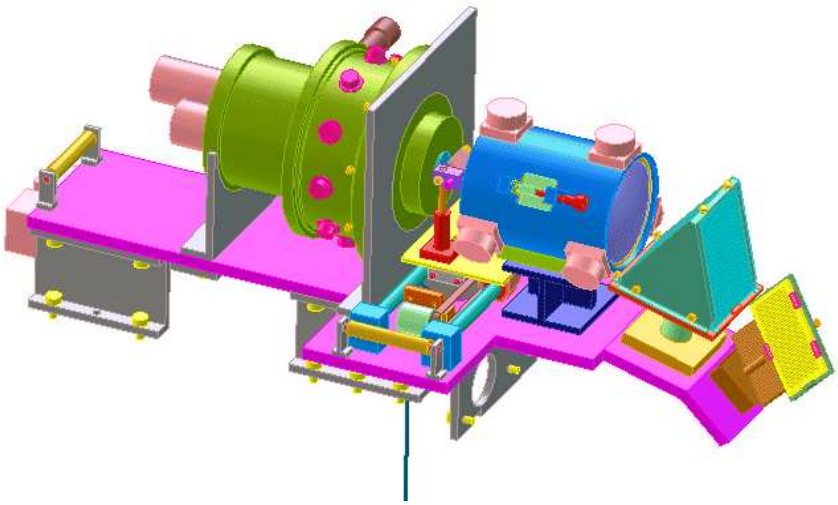

Fig. 7. Mechanical layout of AVES-IMCO external subsystem

and the rest of the controllers (lamps, sensors). The connecting cables, attached with proper connections located on the instrument, will reach the Instrument Cabinet via the cable-rotator.

The detector that will be used in the AVES-IMCO spectrograph is a 2K x 2K (13.5-15 μm pixel) CCD. Performance evaluation has been made of available CCDs to select the best suitable for our purposes. In this evaluation emphasis has been put on the red-oriented spectral range, the Q(E) and the uniformity of the response (fringing-free device). The most promising results of the search concern High Resistivity Deep Depleted CCDs. With respect to ordinary CCDs these devices provide enhanced sensitivity between 500 and 1000 nm, i.e. the AVES-IMCO working wavelength range. A viable solution is represented by the MARCONI A.T. 2048x4608 50 μm thick back-illuminated deep-depleted CCD which provides QE as high as 60% at 900 nm and 30% at 1000 nm. The Deep depletion technique together with the consolidated "fringe suppression" technique can easily be applied by MARCONI A.T. to a 2048x2048 device suitable for AVES, which in fact has been already quoted by MARCONI for the AVES Consortium. The dark current of this device (at -110^o) is 2-3 e^-/h and the max read-out noise is 3-4 e^- r.m.s. These numbers as well as those regarding PSF, non-uniformity, full well and charge transfer efficiency are almost identical to standard grade 1 thinned back-illuminated CCDs like the MARCONI A.T. 42-40-904; the only appreciable difference is the QE versus wavelength curve that privileges longer wavelengths.

As a base-line for the CCD controller we plan to use a modified version of the standard ESO FIERA controller, the modification consisting in the weight distribution to meet the stringent requirements imposed by ESO on the weight of the NAOS parallel instrument.

The AVES-IMCO software has necessarily to be fully VLT-compliant. This because it will have to be integrated in the complex environment governing VLT, NAOS and CONICA.

4. Expected performances

A preliminary study of the AVES spectroscopic performances (in terms of S/N ratio) has been made using an Exposure Time Calculator (ETC) developed for AVES in the IRAF environement.

Fig. 8 shows the SNR for stellar continuum (at 700 nm) as a function of visual magnitude V of a G2V type star and airmass=1 for 1h and 2h exposure times for a slit width ϕ=0.3". A V sky magnitude of 21.8 mag/arcs^2 has been assumed, RON of 3 e/pix (rms) and a dark current of 1e/pix/hour. A reference star of magnitude V=8 has been assumed but the results in terms of SNR and magnitude limit are only slightly dependent on the magnitude of the reference star down to V=16. In typical seeing condition $\Gamma = 0.65$", a SNR=8 is reached in 2 hour exposure with V=23; very low SNR (SNR=3.5 for 2h) can be reached for V=24 for G main-sequence stars. Sky brightness can be an important noise source for very faint targets. But when AO is operating, an improvement in SNR can be obtained because the AO will concentrate most of the light in a very small region (< 0.3") reducing drastically the background contribution of the sky. Fig. 9 shows the improvement due to the use of AO under the same conditions for

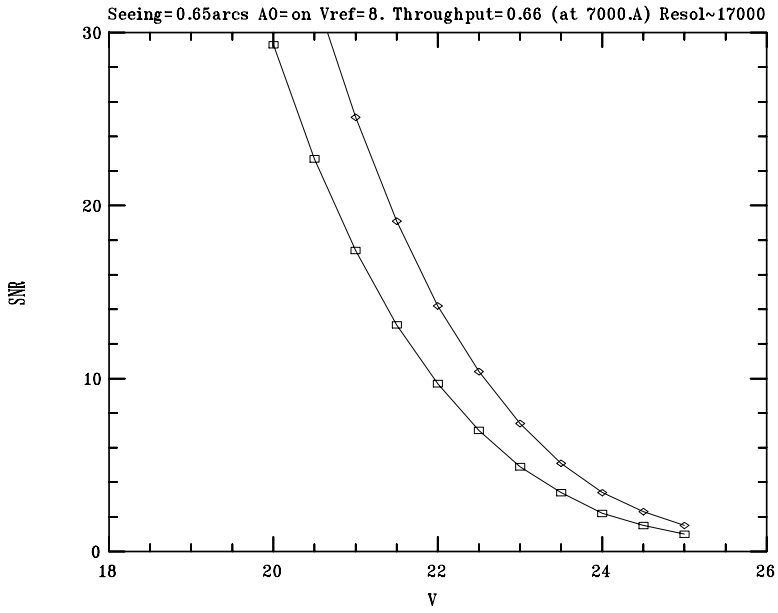

Fig. 8. SNR per resolution element expected from AVES (at λ=700 nm for G2V star) as a function of V mag for 1h exposure (squares) and 2h exposure (diamonds).

stars of different magnitudes and an exposure time of 2 hours.

To conclude, since a seeing of 0.65" is a median seeing at Paranal, the high efficiency of a spectrograph like AVES (not lower than 20% not including slit losses but including telescope reflectivity, AO module transmission, and spectrograph and detector efficiencies) guarantees a competitive instrument with respect to conventional spectrographs. All these considerations are strongly dependent on the assumptions used for the monochromatic PSFs when AVES works with the AO module. Anyway, also taking into accounts these limits, the preliminary results indicate that the nominal specification of achieving SNR >10 for V=22.5 at R$\sim$16,000 in 2 hours can be fulfilled. The gain introduced by the use of adaptive optics is about a factor of 2, but the higher intrinsic efficiency of the spectrograph in comparison to GIRAFFE and UVES ensures a gain of nearly 2 and 3 magnitudes, respectively, with respect to these other ESO instruments. With respect to ESI, which has an efficiency comparable to that of AVES, there is still an advantage (due to the use of AO) in the observation of background-limited objects.

5. Status of the project

The project is currently in the design phase which is expected to be completed by the end of year 2000 with a full documented Preliminary Design Phase (PDR). The design phase is being carried out with the financial support of CNAA in Italy and CNRS in

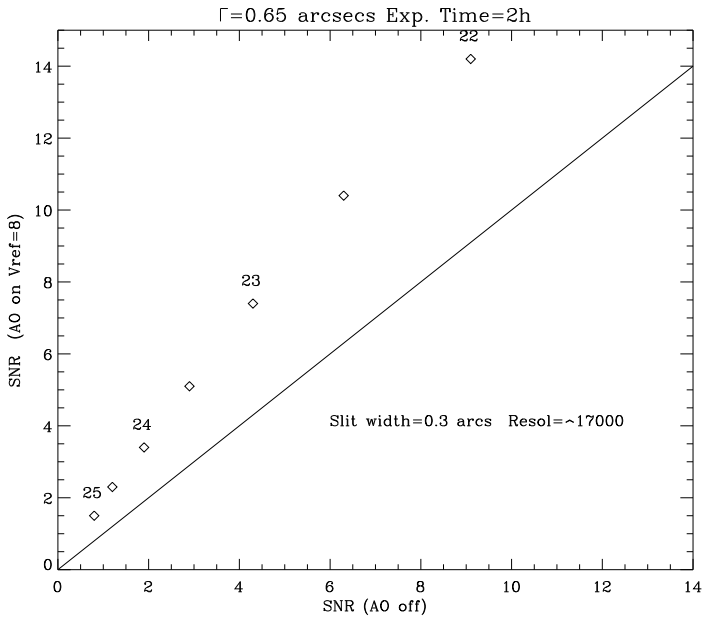

Fig. 9. SNR per resolution element expected from AVES (at λ=700 nm for G2V star) in 2h exposure in the case of AO-on and AO-off for stars of different magnitudes

France, with additional financial support from the participating Institutes. A formal proposal will be submitted to ESO as soon as the secondary port of NAOS will be made available to the community for use by a parallel instrument. If the proposal will be accepted by ESO, the construction phase is estimated to last 2 years after a Final Design Review (FDR) to be conducted under the supervision of ESO.

Table II summarizes the project milestones, for both the design phase and the following construction phase.

In brief, the proposed instrument will provide spectroscopic and imaging capabilities which are either not covered by other VLT instruments or are significantly superior to them at least in three areas: i) medium-resolution spectroscopy of faint background-limited objects, ii) spectroscopy of single objects in crowded fields and iii) diffraction limited imaging and coronography of extended objects in the optical domain. The compact low-weight design of AVES-IMCO is ideally suited for use as parallel instrument of the Nasmyth Adaptive Optics System (NAOS) at the VLT and will complement in a very effective way the existing VLT intrumentation package. Moreover, AVES-IMCO will be the first instrument at the VLT to explore the potential of Adaptive Optics for spectroscopy and imaging at visible wavelengths thus paving the road to future generations of optical instruments at very large telescopes.

TABLE II
Project milestones

MILESTONES	DATE
Kick-off	November 1998
End of conceptual design	June 1999
Addition of imaging capabilities	September 1999
PDR	September 2000
End of design phase	December 2000
FDR (after ESO approval)	early 2002 ?
Construction phase	FDR + 2 years

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