Design Study of an Adaptive Optics Visual Echelle Spectrograph and Imager for the VLT

R. Pallavicini[a], L. Pasquini[b], B. Delabre[b], N. N. Hubin[b],
P. Conconi[c], L. Mantegazza[c], R. Mazzoleni[c], E. Molinari[c], F. M. Zerbi[c],
P. Molaro[d], P. Bonifacio[d], P. Santin[d], P. Di Marcantonio[d], M. Franchini[d],
G. Bonanno[e], P. Bruno[e], R. Cosentino[e], S. Scuderi[e], S. Catalano[e], M. Rodonò[e],
P. Caldara[a], F. Damiani[a], M. Comari[d], S. Monai[d], F. Passaretta[c]

[a]Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy

[b]ESO, Karl-Schwarzschild-St. 2, D-85748 Garching b. München, Germany

[c]Osservatorio Astronomico di Brera, Via Bianchi 46, I-23807 Merate (LC), Italy

[d]Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, I-34131 Trieste, Italy

[e]Osservatorio Astrofisico di Catania, Viale A. Doria 6, I-95125 Catania, Italy

ABSTRACT

We present a preliminary design study for an adaptive optics visual echelle spectrograph and imager/coronograph for use as parallel instrument of the Nasmyth Adaptive Optics System (NAOS) on unit UT3 (Melipal) of the VLT. The spectrograph is intended for intermediate (R$\sim$16000) resolution spectroscopy of faint (sky and/or detector limited) sources. It could be used for observations of late-type dwarfs in distant Galactic clusters and in galaxies of the local group as well as for spectroscopy of extragalactic objects like quasars and Lyman break galaxies down to a limiting magnitude of V = 22.5. The implementation of an imaging and coronograph mode increases the versatility of the instrument and its scientific objectives. The instrument takes advantage of Adaptive Optics at visible wavelengths (V, R and I bands) both for imaging and spectroscopy. With NAOS at the VLT, the light concentration in these bands will be above $\sim$ 60% of the flux in a 0.3 arcsec aperture for typical Paranal conditions. Simulations show that a gain of more than one magnitude with respect to comparable non-adaptive optical spectrographs will be possible for sky- and/or detector limited observations. In addition, the smaller diffraction limit in the optical than in the IR will allow a significant gain in imaging and coronography as well. Finally, the instrument will allow gathering unprecedented experience on the performances of AO at visible wavelengths, which will be fundamental for further development of AO systems, in particular for very large telescopes.

Keywords: Optical Instrumentation, Echelle Spectrographs, Adaptive Optics Instruments, Coronographs, VLT

1. INTRODUCTION

The light concentration power of Adaptive Optics (AO) provides significant advantages not only for imaging (as it is widely recognized) but also for spectroscopy. By narrowing the slit to match the image size, one 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 either have higher resolving power than non-AO spectrographs of comparable size[1] or reach fainter magnitudes than non-AO

Further author information: (Send correspondence to R. Pallavicini and L. Pasquini)
R. Pallavicini. E-mail: pallavic@oapa.astropa.unipa.it
L. Pasquini: E-mail: lpasquin@eso.org

spectrographs of similar resolution in sky- or detector-limited observations[2]. A spectrograph optimized for a small image is expected to give better performances than conventional spectrographs in generic observational conditions and will be unique for observations which are otherwise limited by the sky and detector background or for which an increase in resolution is crucial for the science but cannot be achieved with the desired signal. 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 a design study for an Adaptive Optics Visual Echelle Spectrograph (AVES) for possible use at a Nasmyth AO focus of the Very Large Telescope (VLT). This study originated from an early suggestion[2] for a compact low-cost AO spectrograph to be used at the VLT, but also on other large telescopes with AO capabilities. We have developed the original concept with specific regard to the Nasmyh Adaptive Optics System (NAOS)[3] of unit UT3 of the VLT, where the spectrograph could 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 added to the instrument, with only a limited increase in complexity. The new design therefore combines both spectrograph and coronograph functions in one instrument that we have provisionally called AVES-IMCO (Adaptive-optics Visual Echelle Spectrograph and IMager/COronograph).

This design study is being carried out by a Consortium of four Italian Institutes, in collaboration with researchers at ESO. The Institutes involved are the Osservatorio Astronomico di Palermo (where the Project Office is located), the Osservatorio Astronomico di Brera-Merate (which is responsible for the optomechanical design), the Osservatorio Astronomico di Trieste (which is responsible for the instrument control electronics and software) and the Osservatorio Astrofisico di Catania (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 whose participation in the project, and related responsibilities, are under negotiation at present. An AVES-IMCO Science Team, formed by representatives of all participating institutions, is responsible for the identification of the primary scientific objectives of the proposed instrument.

2. SCIENCE CASE

An intermediate resolution optical spectrograph capable of observing objects as faint as V=22.5 opens to spectroscopic investigations a large number of astrophysical problems, ranging from distant galaxies to solar-system objects. Moreover, the implementation of imaging and coronograph functions in one instrument further enlarges the range of science cases that could be addressed effectively, and sometimes uniquely, with the proposed instrument. The scientific objectives, include, among others:

- Imaging and spectroscopy of high-redshift forming galaxies
- Absorption lines of intervening objects in faint QSOs
- Chemical abundances of main-sequence stars in the Galactic bulge, in the halo and in the Magellanic Clouds
- Spectroscopy of hot stars and supergiants in Local Group galaxies and beyond
- Coronography of circumstellar disks and protoplanetary disks
- Imaging and spectroscopy of faint objects like very-low mass stars, brown dwarfs, magnetically active stars in clusters, and optical counterparts of X-ray binaries
- Imaging and spectroscopy of solar-system bodies including cometary nuclei and asteroids
- Radial velocities of eclipsing variables down to V=24 (e.g. Cepheids in Virgo cluster)

The small image size 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. Besides, observing at optical wavelengths provides better angular resolution (e.g. 20 mas at 0.8 μ) than in the near IR, eventhough image quality is not optimized for visible observations. This translates into typical linear resolutions of 3 AU at 150 pc or 100 AU at 5 kpc.

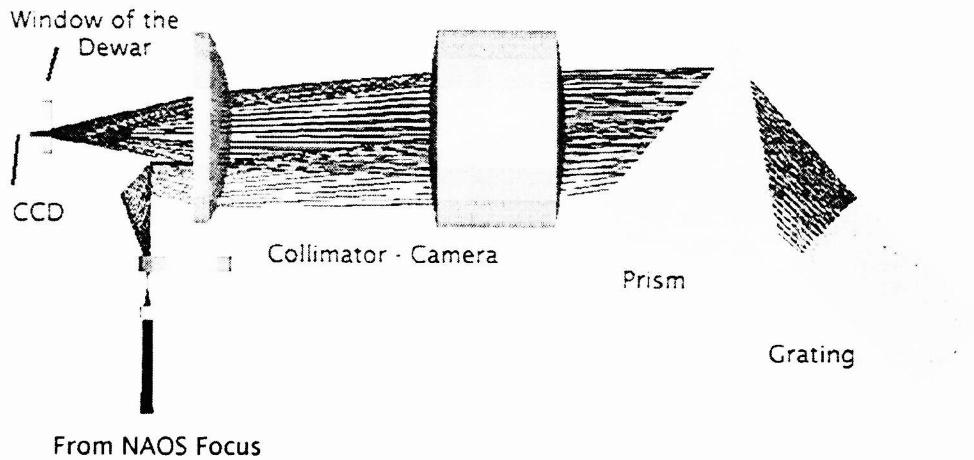

Figure 1. The optical design of the AVES spectrograph.

3. REQUIREMENTS

The scientific requirements for an intermediate-resolution AO spectrograph for faint sources have been identified as follows:

- Small entrance slit (at least 60% of the light in < 0.3 arcsec slit with a median Paranal seeing of 0.65 arcsec). The possibility of varying the slit width should be retained
- Spectral resolution: R$\sim$16,000 for a 0.3 arcsec slit
- High efficiency: $> 15\%$ (including slit losses, AO and telescope transmission)
- Red spectral region only (from 500 to 1000 nm)
- Coverage of full spectral range in one exposure
- Simple, compact design (small volume, low weight)
- Easy interface with other telescopes/foci with minor modifications (portability desirable, but not strictly required)
- Independent acquisition and calibration system
- High performances with respect to other VLT spectrographs (limiting magnitude at least one magnitude fainter than GIRAFFE at comparable resolution and at least 2 magnitudes fainter than the higher resolution UVES spectrograph)
- Addition of an imaging mode desirable to increase versatility of the instrument and to control accurately slit positioning

4. OPTICAL DESIGN

4.1. The AVES Spectrograph

The optical design of the AVES spectrograph is the same presented in Ref. 2 and is shown in Fig. 1. It is based on a prism crossdispersed, double-pass echelle spectrograph concept. The F/15 focus from the AO system is converted to F/3.2 by a relay system which in the actual configuration foreseen for use at the VLT (see discussion below) acts

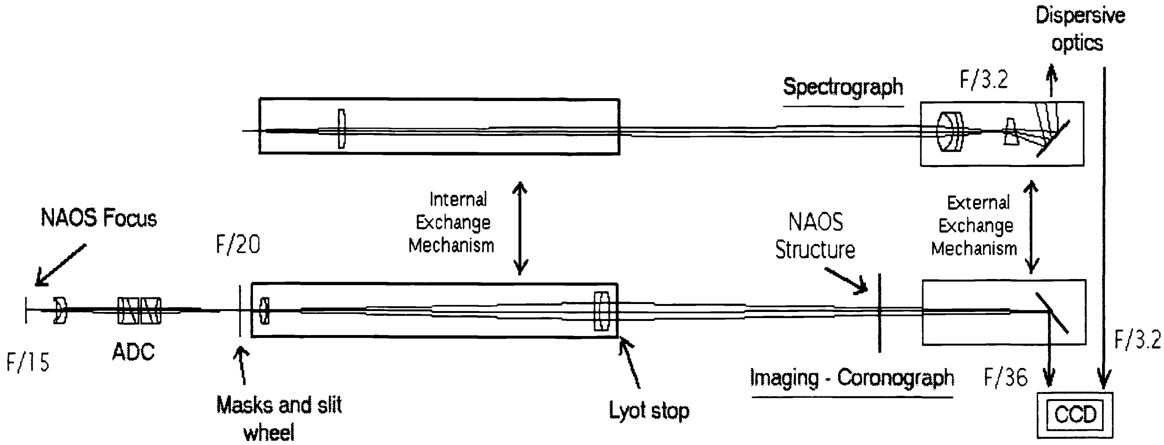

Figure 2. The relay system from the AO focus to either the AVES spectrograph or the imager/coronograph.

either as a focal reducer to feed the spectrograph or as a imaging/coronograph system which converts the F/15 focus to F/36. Exchange mechanisms, both internal and external to NAOS, are used to switch between the spectrographic and imaging functions, as shown in Fig. 2. Note that in the current design the relay system is specific for use with the NAOS AO system at the VLT. However, by simply changing the focal reducer, the AVES spectrograph could easily be mounted on another telescope (e.g. on the LBT) or moved to another VLT focus with AO capabilities.

The main characteristics of the spectrograph are the following:

- classical design, prism cross-dispersed, Littrow
- entrance slit width 0.3 arcsec, with the possibility of chosing slits of different sizes
- collimator and camera aperture F/3.2
- beam size 5 cm
- R2 79 gr/mm echelle, R $\sim$ 16,600 with a 5 cm beam and 0.3 arcsec wide slit ($\lambda/\delta\lambda \sim 41,500$ per pixel)
- sampling: 2.5 pixels (F/3.2 camera for 15 μm pixel, 0.12 arcsec/pixel)
- full spectral coverage from 500 nm to 1000 nm in one exposure
- order separation (with SF4 prism and an apex angle of 50 degrees): $\sim$27 pixels (3.2 arcsec) between the reddest orders, $\sim$49 pixels (5.9 arcsec) between the bluest
- detector: 2K $\times$ 2K CCD chip with 15 μm pixels (with frame transfer, only half used)

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 gr/mm) is probably one of the most efficient echelle ever produced. Another key feature is that the full spectral range is covered in one exposure. On the other hand, the spectrograph has no multi-object capability. 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.

4.2. The Relay System

Since NAOS provides an F/15 focus for the parallel instrument, it is necessary to extract the focus from inside of the NAOS structure and reduce it to F/3.2 to feed the spectrograph. A simple focal reducer is sufficient for that. However, a relay system can be designed which performs as an imager, thus greatly enhancing the instrument versatility. Fig. 2 shows a possible design for the relay system which includes also a coronograph function. There is no need of a slit viewer for the spectrograph in this design but a number of motorized functions need to be implemented inside and outside of the NAOS structure to switch between the two main instrument functions (imaging and spectroscopy).

The preslit optics is common to the two observing modes. The light from the F/15 NAOS focus is reimaged by a pupil relay lens and by a relay optics (two doublets + an atmospheric dispersion corrector ADC) to the F/20 position of the mask and slit wheel. The FOV is 5 arcsec, but can be increased to 10 arcsec. After the mask-slit wheel (which can accomodate several masks for imaging and slits for spectroscopy) an exchange mechanism internal to NAOS allow switching between the two modes. In the imaging mode an optical system of two doublets transforms the F/20 focus into an F/36 beam. Since the optics is rather slow a Lyot stop can be positioned on the exit surface of the second doublet. A flat mirror is than used to bring the light on the detector. In the spectrographic mode, the F/3.2 focus to enter the spectrograph is formed by a singlet attached to the internal exchange mechanish after the slit and by a triplet positioned outside of the NAOS structure. The external exchange mechanism accomodates, in the spectrograph mode, the triplet, an off-axis lens and a flat mirror, whereas in the imaging-coronograph mode it accomodates only a flat mirror.

We are exploring at present the possibility of eliminating the internal exchange mechanism by adopting a common optical path for the imaging and spectrographic functions. If proven feasible without degrading the optical performances, this would simplify considerably the optomechanical design of the whole instrument, by maintaining only a simple sliding mechanism outside of the NAOS structure to switch between the imaging and spectrographic modes.

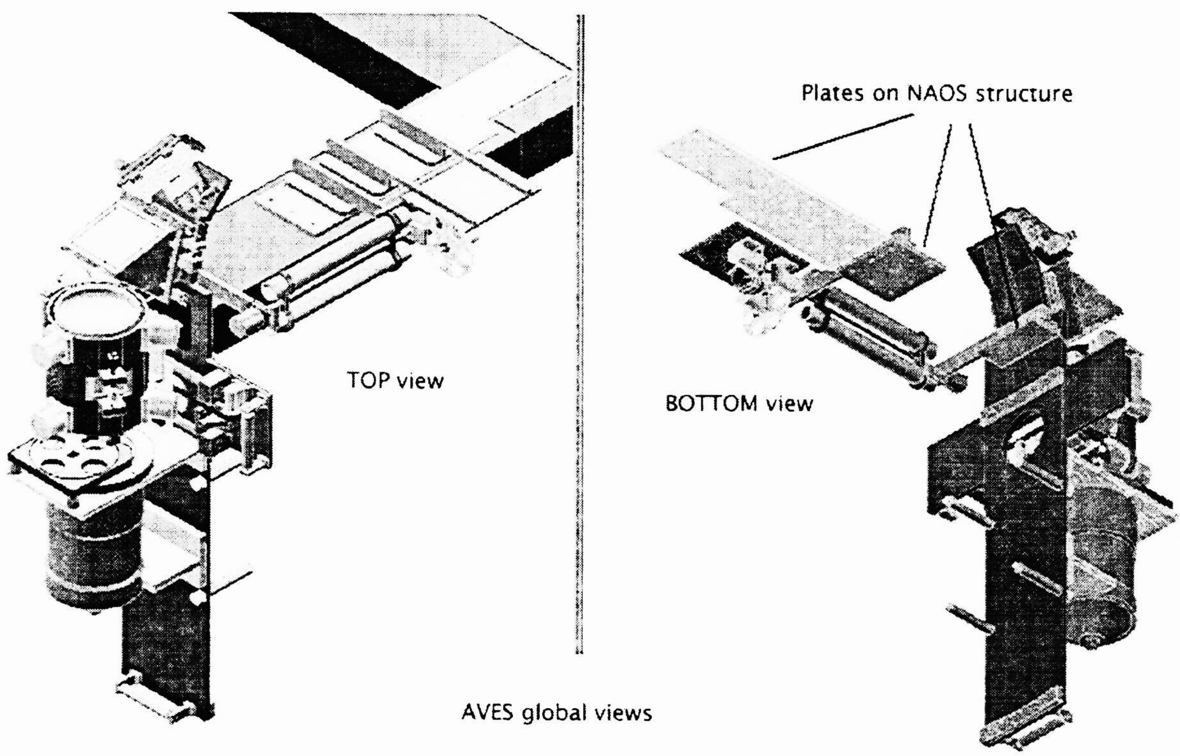

Figure 3. The mechanical structure of the AVES-IMCO instrument

5. MECHANICAL DESIGN

The mechanical structure of the full instrument is shown in Fig. 3. There are two main blocks, one internal and one external to the NAOS structure. The AVES spectrograph, the external exchange mechanism between the imaging and spectrograph modes, and the cryostat are accomodated on a baseplate fixed to the external structure of NAOS by means of a ladder as showed in Fig. 4 (note that the NAOS structure will rotate during observations).

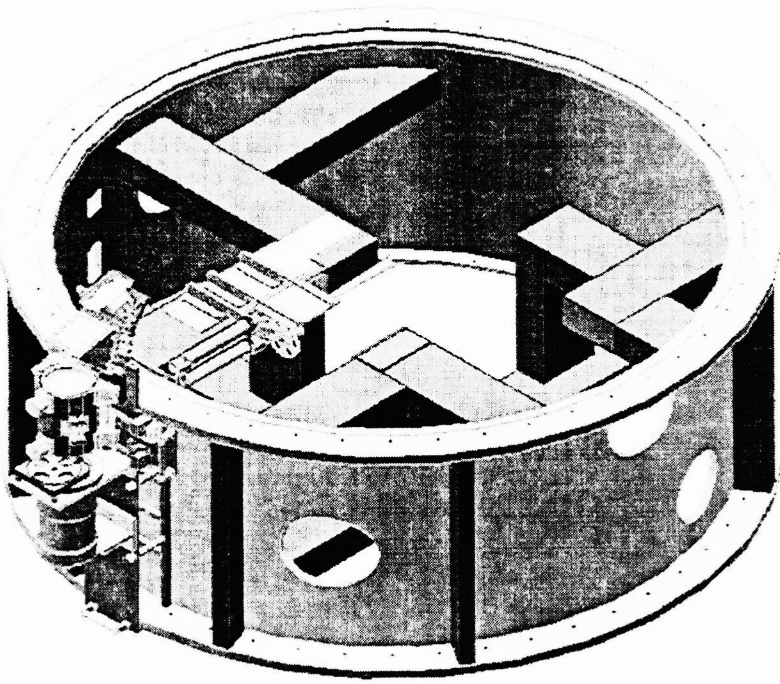

Figure 4. The AVES-IMCO instrument attached to NAOS

Starting from the centre of the baseplate where the external exchange mechanism is located, one can see, on one side, the housing of the collimator-camera optics, the prism and the grating, and on the other side the cryostat with the CCD detector. A motorized wheel which accomodates glasses of various thickness is used in front of the detector for passive compensation of the focal distance.

Inside NAOS, and attached to the NAOS structure, there is the internal exchange mechanism (two parallel tubes rotating about a common axis) and a plate which accomodates the ADC system and the mask-slit wheel. This part forms the internal block of the instrument, whereas the external exchange mechanism, the spectrograph and the detector form the external block. The plate with the ADC system and the mask-slit wheel is rigidly attached to the parallel instrument support plate by means of two arms. The light passes from the internal to the external block through a hole in the NAOS structure. Details of the mechanical structure are shown in Fig. 5.

There are three motorized functions inside the NAOS structure: the ADC system, the mask-slit wheel and the internal exchange mechanism. This is the prize one has to pay to combine both imaging and spectrographic functions in one instrument. In the original AVES design proposed in Ref. 2, there were no imaging functions, the slit could be brought to the outside of the NAOS structure and there were no motors inside NAOS. A much simpler but less ambitious instrument is still possible if only the spectrographic capability is retained.

The optical elements are adjustable by means of screws for alignement and focussing. A finite-element and thermal analysis is under way. The calibration system (type and positioning of the calibration lamps) is still to be defined in detail, but bringing the calibration lights inside NAOS through fibers should not be a problem. A filter wheel accomodating different filters must also be inserted for the optical path for the imaging mode.

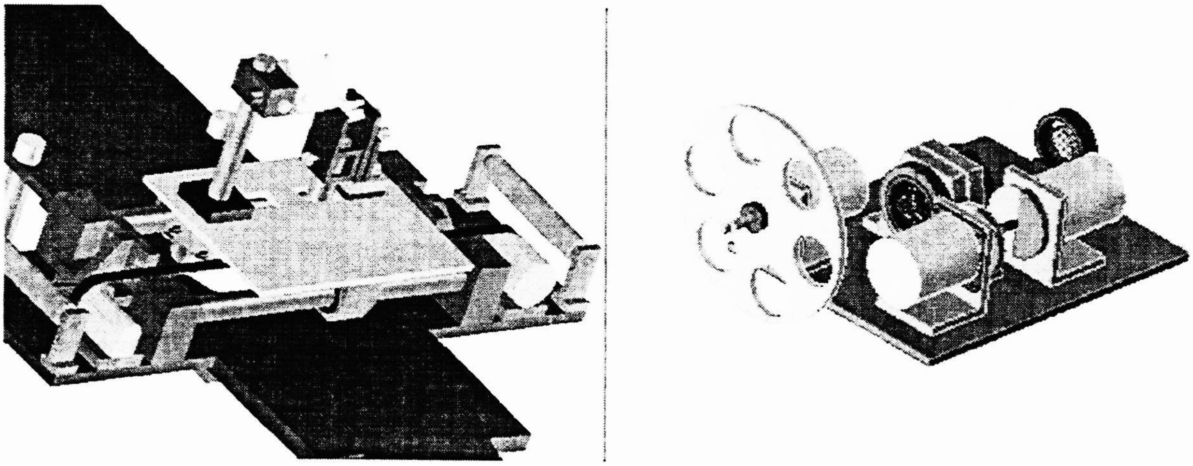

Figure 5. Details of the mechanical structure On the left hand side, the external exhange mechanism to switch between the imaging and spectrograph modes; on the right hand sight, the internal plate accomodating the motorized ADC system and the slit/mask wheel.

6. INSTRUMENT CONTROL ELECTRONICS AND SOFTWARE

The design of the instrument control electronics and control software will comply with ESO VLT standards. This may appear as a limitation for the trasportability of the instrument to other telescopes (the AVES spectrograph was originally conceived as a compact low-weight instrument easily transportable to other telescopes or AO foci[2]). However, the present design, which combines imaging and spectroscopic capabilities in one instrument, is very specific for the secondary port of NAOS, and the adoption of VLT standards is the only reasonable choice.

The control software of AVES is broken down into two main packages, the Instrument Control Sofware (ICS) and the Observation Software (OS), both based on the concepts of the VLT software environment. The user and High-level Software interact with the AVES OS at the level of the Instrument Workstation (IWS) running the Unix operating system. The control electronics of the single hardware devices (i.e. motors, lamps, etc.) is located instead on the Local Control Unit (LCU) consisting of a VMEbus system with a CPU board, running the VxWorks operating system. The VLT Common Software will provide the common services for both the IWS and the LCU

Since the instrument is still in a preliminary design phase, the instrument functions that are to be controlled by the instrument electronics and software can only be defined in a general way. They include the calibration system (lamps and selector mechanism), the ADC motors, the mask-slit wheel, the exchange mechanisms (both internal and external), and the filter/glass wheel. In addition, a number of sensors must be provided to check the instrument status.

The Observation Software (OS) runs entirely on the IWS, linked via network to the instrument LCUs. This software is intended to fully control a single observation, from its initial definition to the production and archiving of the scientific data. It will deal with both observing modes foreseen for AVES, i.e. the spectrographic mode and the imaging mode. It will control the scientific exposure, coordinating its execution by the FIERA Detector Control Software (DCS), and will interact with the ICS and the NAOS Super-OS to setup the instrument and control the observation. A Graphic User Interface (GUI) will be provided.

7. DETECTOR AND CONTROLLER

The spectrograph and imaging-coronograph modes of AVES will share the same CCD detector. The type of detector to be used is still to be defined, but a 2 K $\times$ 2K chip with 15 μm pixels with high quantum efficiency in the visible and in the red, high uniformity and low read-out noise is anticipated. Particular attention will be devoted to selecting a fringe-free device. This will be used in frame transfer mode (no shutter). Although a choice has not yet been performed, we aim at using a new "thick" device under development at several sites, which will be available in 3 years from now, the expected timescale for the completion of the instrument. For compatibility with ESO VLT standards, the FIERA controller should be used. We note however that this poses severe constraints on the weight of the instrument. The maximum weight allowed to be mounted on the NAOS structure is 70 kg, and this may easily be exceeded if the electronic boxes of FIERA are mounted on the structure. Alternative solutions under study include the possibility of locating FIERA at some distance from the NAOS structure, or to use a lighter CCD controller by providing all necessary hardware and software to interface the new controller with the standard ESO ICS.

8. EXPECTED PERFORMANCES

The expected performances of the AVES spectrograph were estimated in Ref. 2. The total efficiency was estimated to range from 0.12% to 0.19% depending on the adopted values for the AO transmission and the efficiency of the optical elements. Assuming an overall efficiency of 17% and a sky magnitude of R=20.9 per square arcsec, a S/N > 10/pixel(> 17 per resolution element) can be reached in 2 hours for R=22 (V=22.5). For R = 20 a S/N > 20/pixel can be reached in 1 hour. The gain with respect to GIRAFFE at the VLT (which has a similar resolution) should be more than one magnitude, mainly due to the reduction of the sky/ detector background[4]. The gain should be more than 2 magnitudes with respect to UVES, which however operates at a higher resolution, i.e. for typically brighter sources. A more accurate estimate of the performances of the instrument, based on more realistic assumptions of the AO performances and of the efficiency of the optical elements, is under way. Preliminary results indicate that the original expectations should be realistic and that the gain of at least one magnitude with respect to conventional spectrographs shall be reached.

9. STATUS OF THE PROJECT

The project is currently in phase A. The design study will be completed by the first half of year 2001. Construction of the instrument for the VLT is subject to ESO approval and to the availability of the secondary port of NAOS which has not yet been offered to the community. A proposal to ESO for use of the secondary port of NAOS will be submitted to ESO in March of this year. If approved by ESO, the instrument could be built in a very short time scale (less than 2 years) provided the necessary funds are obtained from national sources. With small modifications, the instrument could also be used at other telescopes and has already been proposed for use at the LBT. The construction of the instrument does not present any special technological challenge, the most critical area being likely the interface with NAOS and the thermomechanical stability of the instrument, to ensure a minimum degradation of the performances in long exposures. Use of the instrument with future AO laser guide systems would greatly increase the sky coverage thus enlarging the number of faint objects that could be investigated with this instrument. Although portability to other telescope is not straightforward in the present design, and would require major modifications, the basic concept could easily be replicated to other telescopes and/or to other AO foci. The small size and low cost of the instrument would warrant replication for other telescopes.

ACKNOWLEDGMENTS

We acknowledge the financial support to this project of Consorzio Nazionale per l'Astronomia e l'Astrofisica (CNAA). We thank Anne-Marie Lagrange and the LAOG team in Grenoble for suggesting the implementation of the imaging/coronograph mode.

REFERENCES

1. J. Ge, R. Angel, C. Shelton, "Optical Spectroscopy with a Near Single-mode Fiber Feed and Adaptive Optics", *Proceedings SPIE* **3355**, pp. 253–263, 1998.
2. L. Pasquini, B. Delabre, G. Avila, D. Bonaccini, "AVES: an Adaptive Optics Visual Echelle Spectrograph for the VLT", *Proceedings SPIE* **3355**, pp. 105–110, 1998.
3. G. Rousset, F. Lacombe, P. Puget, N. Hubin, E. Gendron, J.-M. Conan, P. Kern, P.-Y. Madec, D. Rabaud, D. Mouillet, A.-M. Lagrange, F. Rigout, "Design of the Nasmyth Adaptive Optics System (NAOS) of the VLT", *Proceedings SPIE* **3353**, pp. 508–516, 1998.
4. L. Pasquini, "FLAMES: a Multiobject Fiber Facility for the VLT", *Proceedings SPIE*, this volume, 2000.