CRIRES:a high-resolution infrared spectrograph for the VLT

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ABSTRACT

CRIRES is a cryogenic, pre-dispersed, infrared echelle spectrograph designed to provide a resolving power of 10^5 between 1 and 5μm at a Nasmyth focus of one of the 8m VLT telescopes. A curvature sensing adaptive optics sytem feed is used to minimize slit losses and a 4096x512 pixel mosaic of Aladdin arrays is being developed to maximixe the free spectral range covered in each order. Insertion of gas cells to measure high precision radial velocities is foreseen and the possibility of combining a Fresnel rhomb with a Wollaston prism for magnetic Doppler imaging is under study. Installation at the VLT is scheduled during the second half of 2004. Here we briefly recall the major design features of CRIRES and describe its current development status.

Keywords: Infrared astronomy, spectroscopy, high resolution, echelle spectrograph, Very Large Telescope

1. INTRODUCTION

CRIRES is a high resolution infrared spectrograph being developed at ESO to provide a resolving power of 10^5 between 1 and 5 μm at one of the Nasmyth focii of the ESO VLT. Its main characteristics are summarized in table 1. Within the suite of ESO VLT instruments (see http://www.eso.org/instruments/) it will be complementary to UVES, which provides comparable resolution in the UV and visible, and ISAAC which provides an order of magnitude lower resolving power over the same infrared wavelength range. Its scientific drivers include the study of solar system bodies and exoplanets; stellar abundances, atmopheric structure and magnetic fields and the dynamics and chemistry of the molecular ISM. After studying various trade-offs its design features adaptive optics to minimize slit losses; a prism pre-disperser, a conventional (e.g as opposed to immersed) echelle grating and a 4096x512 pixel detector mosaic designed to record simultaneously as much of a single order as possible. It is likely that a Fresnel rhomb and Wollaston prism will also be incorporated to allow magnetic field studies by magnetic Doppler imaging [1]. Special care and attention has been paid in the design to achieving the best possible wavelength stability and reproducibility to both maximixe its scientific capability and operational efficiency. The latter will also benefit from the overall science operations concept developed at the ESO VLT during the last few years.

The history of CRIRES dates back to around 1989 when it was included in the very first Call for First Generation VLT instrument proposals. At that time, however, the required array detectors were still in their infancy and their formats of around 64x64 pixels did not offer an overwhelmingly attractive spectral coverage. By late 1997 both the scientific interest and detector prospects had grown sufficiently to secure its formal inclusion in the VLT instrument plan. Because of conflicts with other projects, work started in earnest only in 1999 and has proceeded well since then with the Provisional Design Review being passed in April 2000 and the Final Design Review in October 2001. The basic concepts and optical design have been presented at an earlier SPIE meeting [2]. Here we report on the considerable progress made since then in realizing this new facility for the ESO community.

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Table 1. Main characteristics of CRIRES.

Wavelenght range	1-5 μm
Resolving power (2 pixels)	100.000
Slit width	0.2-1 arsec.
Slit length	50 $''$
Pixel size	0.1$''$
Adaptive optics feed	60 actuator curvature sensing system
Calibration system	Integrating sphere + cont.+line lamps + gas cells
Slit viewer	Aladdin array, filters, 0.05$''$/pix.
Pre-disperser	ZnSe prism
Echelle grating	40x20cm, 31.6 lines/mm, 63.5 deg. blaze
Polarimetry	Fresnel rhomb + Wollaston prism
Detector array	4096 x512 pixels using 4 Aladdin arrays

2. INSTRUMENT DESIGN

2.1. Optical Layout

Fig. 1 shows the optical layout. Light enters from the direction of the telescope Nasmyth focus, either via the telescope or from a calibration unit consisting of an integrating sphere illuminated by continuum or line lamps for flat-fielding and wavelength calibration. Higher accuracy wavelength calibration is achieved using sky lines or narrow absorption lines in the gas cells which can be inserted in the beam as shown. The gas cell turret will also contain a Fresnel rhombus or quarter wave plate whose insertion can be combined with that of a Wollaston prism in the first pupil image plane for measuring circular polarization. Following the calibration unit is a 3 mirror de-rotator which is used to counteract the telescope field rotation when making long slit observations. Then comes the adaptive optics system used to concentrate the light at the 0.2 arcsec wide spectrograph slit. The AO system comprises a 60 element deformable mirror, mounted on a tip-tilt stage, on which is formed a pupil image by the two mirror relay optics; the dichroic window which transmits infrared light to the cryogenically cooled spectrograph while reflecting visible light to the wavefront sensor (WFS) which uses an avalanche photodiode (APD) detector and can be translated in x,y at $\simeq$ 0.5 Hz to maintain object centering as determined by the slit viewer. As far as possible, the design of the AO system and its individual components have been copied from the MACAO system being developed by ESO for VLTI and the SINFONI instrument [3]. The spectrograph is housed in a vacuum vessel and with its optics cooled to $\simeq$ 65 K and the detectors to $\simeq$ 25 K. Following the input window, a pupil image is formed at the position of a cold stop which limits parasitic background and where the Wollaston prism can be inserted. Light then either passes through the slit or is reflected to the slit viewing camera. Light passing through the slit enters the prism spectrometer where it is dispersed and then exits through an output slit sized to limit the wavelength range passing into the high resolution section to a single order. The high resolution spectrograph consists of a 40x20 cm, 31.6 lines/mm, 63.5 deg. blaze echelle grating plus a TMA (three mirror anastigmat) which acts first as the collimator and then the camera to image the spectrum on the 4096 x 512 pixel array detector. Fig. 2 shows a picture of the echelle grating replicated onto our Al grating blank and already delivered by Thermo RGL.

2.2. Cryomechanical Design Features

Fig. 3 is an artist's view of CRIRES mounted at one of the VLT Nasmyth focii. The main elements are the cryogenically cooled spectrograph in its vacuum vessel, the table mounted un-cooled pre-optics (calibration unit, field de-rotator, adaptive optics system) between it and the telescope Nasmyth adapter/rotator and the electronics racks. The instrument is mounted stationary on the platform primarily to ensure achievement of the

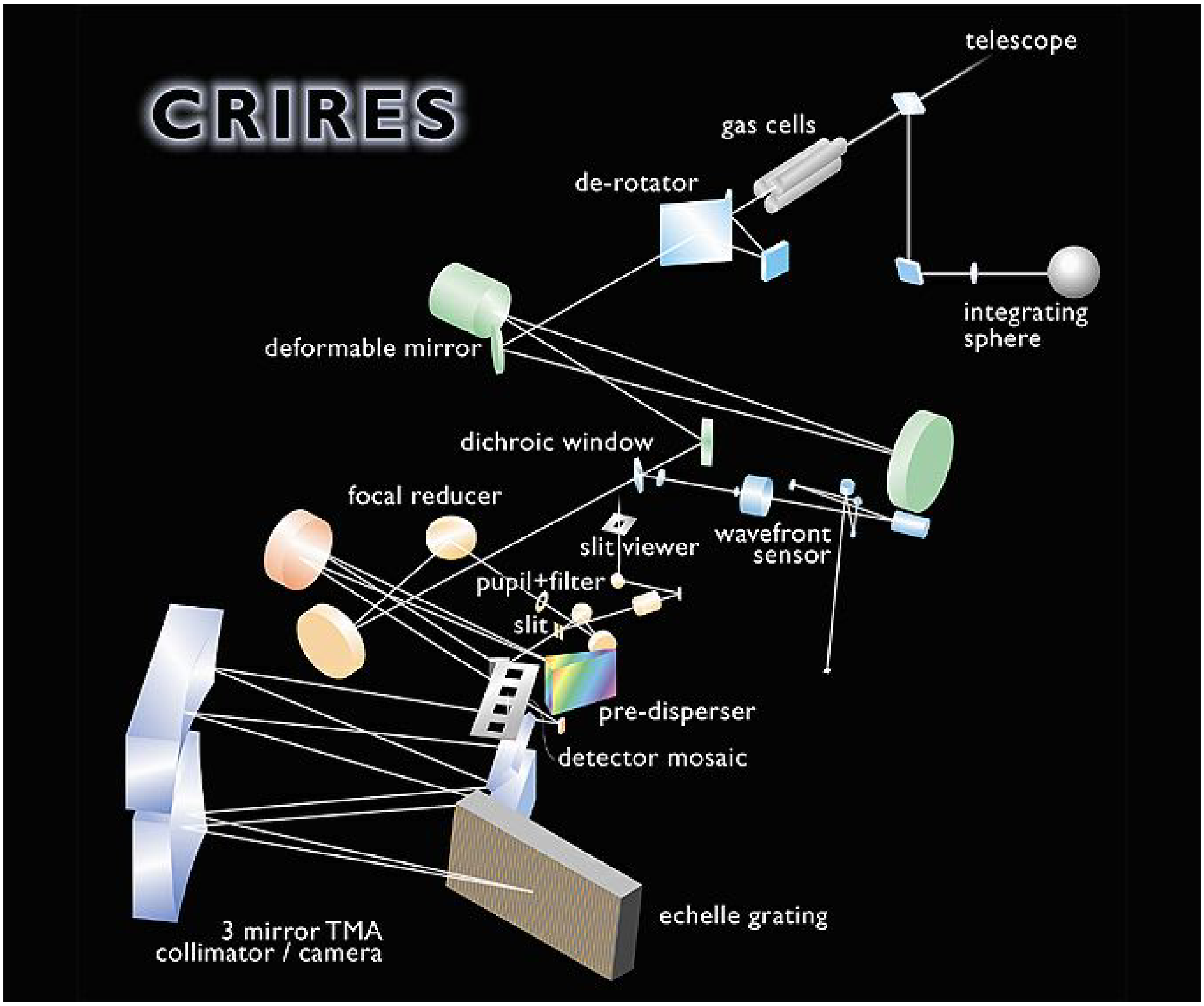

Figure 1. CRIRES optical layout.

high wavelength stability requirements by minimizing flexure and temperature variations. The vacuum vessel is made of austenitic stainless steel with a high internal reflectivity achieved by manual polishing followed by electro-polishing. Attached to it can be seen one of the cold heads of the two Leybold closed cycle coolers, the instrument mounted turbomolecular pump, connector flanges, pressure gauges, overpressure safety valve and the small temperature controlled cabinets housing the two sets of front end electronics for the detectors. Underneath is the support and alignment structure which also provides access to a port in the lower lid of the vacuum vessel through which the grating unit can be accessed and removed. To the left can also be seen the pre-vacuum pump.

Inside, the mirror optics and most of the mechanical structure is made of aluminium alloy. The TMA mirrors have a thin ($\simeq 30\mu$m) nickel coating on the reflective surface which is diamond turned then conventionally polished and finally ion beam polished before gold coating. Although nickel coating is usually applied on both sides we have found by modelling that, although reducing bending, this increases the total wavefront aberration compared with plating a single surface. The remaining mirrors are being nickel plated, diamond turned and hand post polished. The only non-reflecting optics in the system apart from the window is the ZnSe prism using

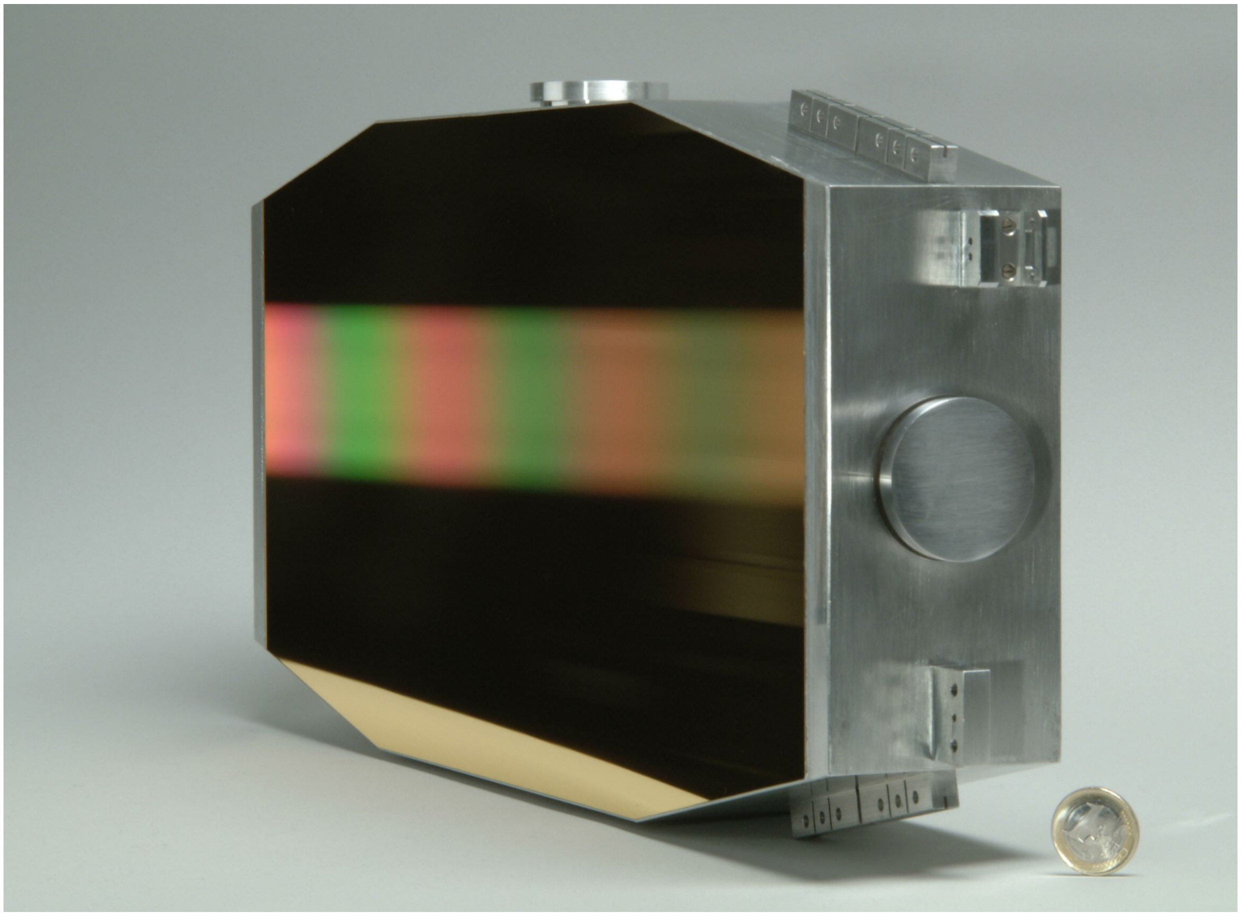

Figure 2. CRIRES echelle grating.

for order sorting.

Cryogenic mechanisms are required for scanning the prism ($\simeq$ 1 deg.) and echelle grating ($\pm$ 6 deg.), the two slits plus the slit viewer filter and Wollaston wheels. The scanning functions will be driven by cryogenic stepper motors (baseline Phytron) and high precision screws and equipped with high precision encoders. The current baseline is also to use stepper motor drives for the other functions although tests of piezo scanners are also underway as an alternative for the slits.

The total mass cooled to cryogenic temperatures is around 550Kg. Based on our experience with ISAAC we are confident that this can be cooled down to $\simeq$65K in 30hrs using the in-built liquid nitrogen flow pre-cooling system. The two closed cycle coolers are then used to maintain the instrument at this temperature and the detectors at around 25 K.

The goal on thermal stability is to maintain the temperature stable within 0.1K and limit any variations of temperature gradients to $\leq$ 50 mK/m/hr. As CRIRES is stationary, has a high thermal inertia due to its large cryogenic mass and is rather uniformally cooled by the attachement of heat exchangers at several points on the cooling circuit, the short term stability may be better than this. To counter drifts due e.g to the external diurnal temperature variations, however, active temperature control is also foreseen using heaters mounted on a ring whose temperature will be controlled to $\simeq$ 0.1K and is connected to various points in the instrument by conducting braids. The pre-disperser collimator mirror is also equipped with piezos to allow fine active control of the spectrum position using atmospheric spectral lines for programmes requiring the highest spectral

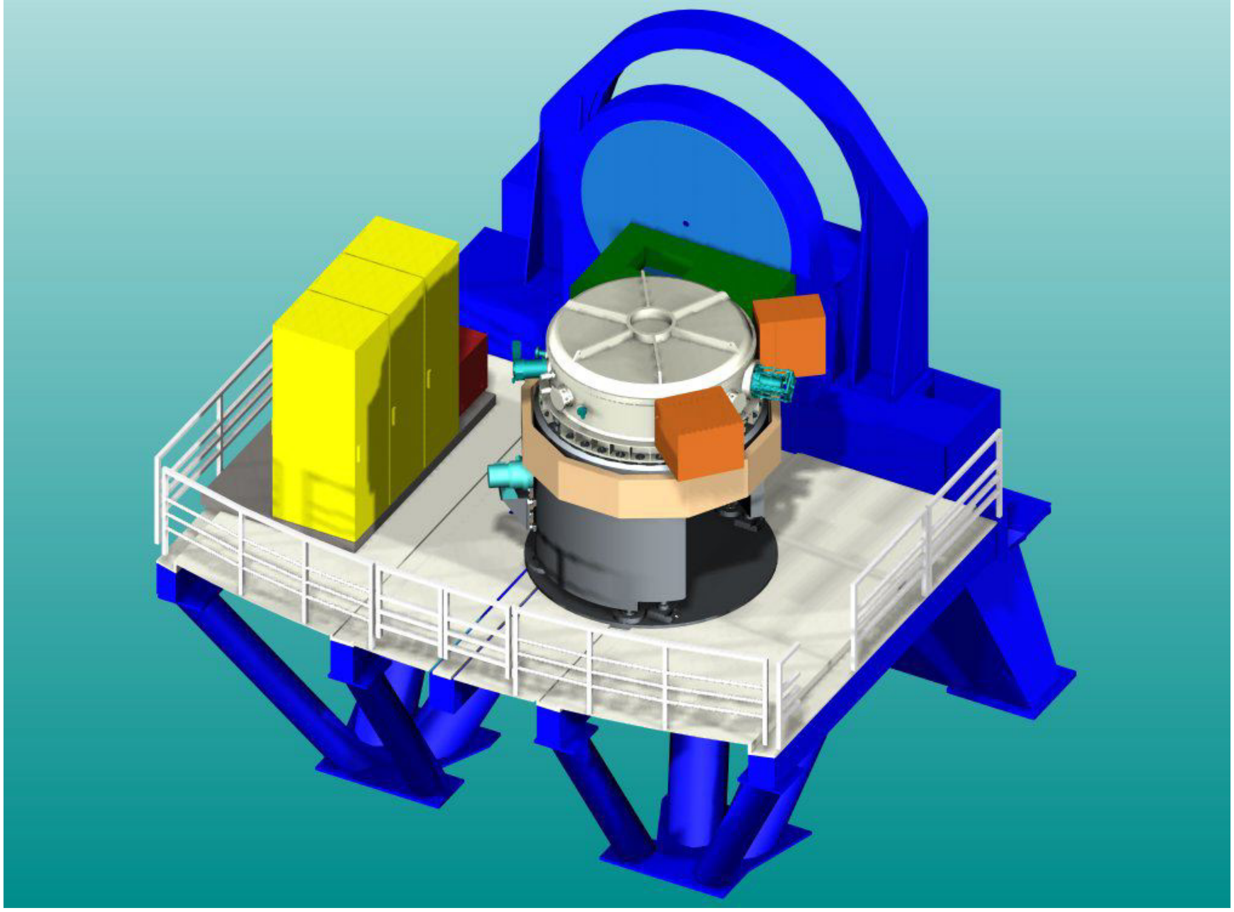

Figure 3. CRIRES mounted on the VLT Nasmyth platform.

stability.

In order to meet the stringent thermal and straylight requirements the entire optical system is enclosed within a light shield plus two AlMg radiation shields with mirror finish quality. Care is also being taken (e.g by using an intermediate connector) to avoid light leaks at the penetrations of cables. Essentially the only light path into the high resolution section of the instrument is through the narrow order isolation slit at the exit of the prism pre-disperser.

2.3. Detectors

CRIRES uses 5 Raytheon 1024x1024 pixel InSb Aladdin arrays, one for the slit viewer and 4 in the spectrograph focal plane which provides a useful optical field of 135x21 mm. All the arrays required are already available at ESO or Raytheon but the four science arrays are being re-packaged to be quasi 3 side buttable so that they can be packed in a 4x1 format with a spacing between arrays of only 264 pixels. To do this, each array will be removed from its original LCC package by Raytheon and glued on the specially designed mount consisting of a multilayer, co-fired, AlN (aluminium nitride) ceramic carrier glued to an adjustable invar base plate shown in Fig. 4 and developed at ESO. The right hand view shows the rear side of the mount on which are a copper block for the cooling braid connections, a 3-point kinematic mount, a temperature sensor and a heating resistor. Also to be seen is the connector to the two layer flexible manganin boards which interface each detector to a preamplifier board equipped with 64 cryogenic operational amplifiers [5]. As the slit is only 512 pixels long we do not require 4 useable quadrants per array and the actual arrays selected will be optimally oriented as

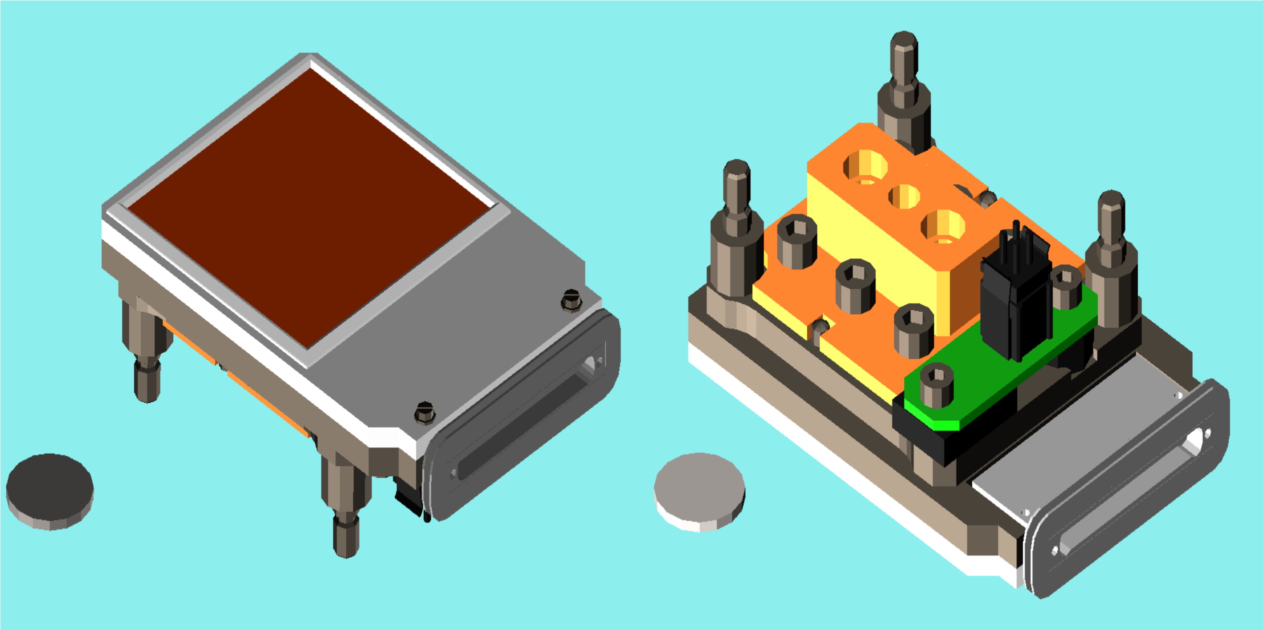

Figure 4. Ceramic carrier for the Aladdin arrays.

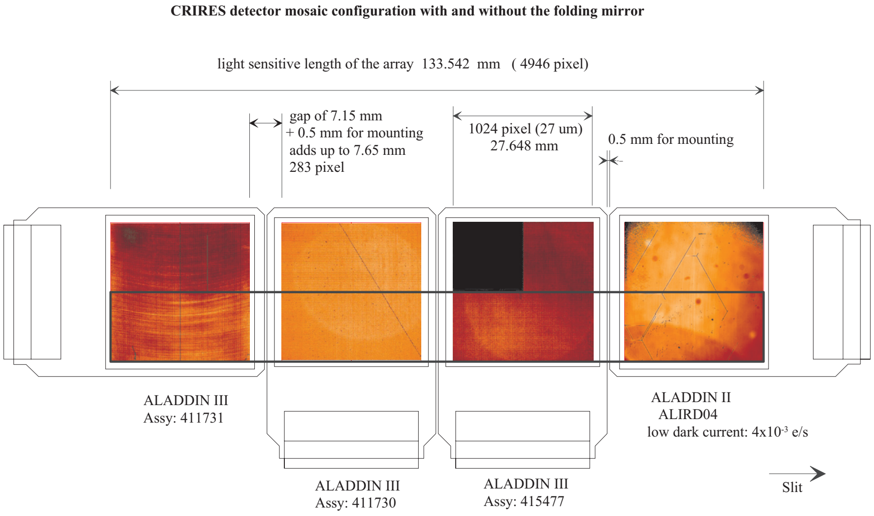

Figure 5. Layout of the 4 Aladdin detector mosaic.

shown in Fig. 5. The array on the right is one remaining from the first, ESO funded, foundry run several years ago and exhibits the lowest dark current measured so far in any array at ESO (14 electrons/hour with drift correction using dead pixels with open indium bumps) despite or maybe due to the presence of several pronounced cracks. This array has been included specifically to ensure the best possible noise performance at the shortest wavelengths.

The arrays will be read-out using standard ESO IRACE controllers [4] having 64 channels (4x16) for the science arrays and 32 channels for the slit viewing camera.

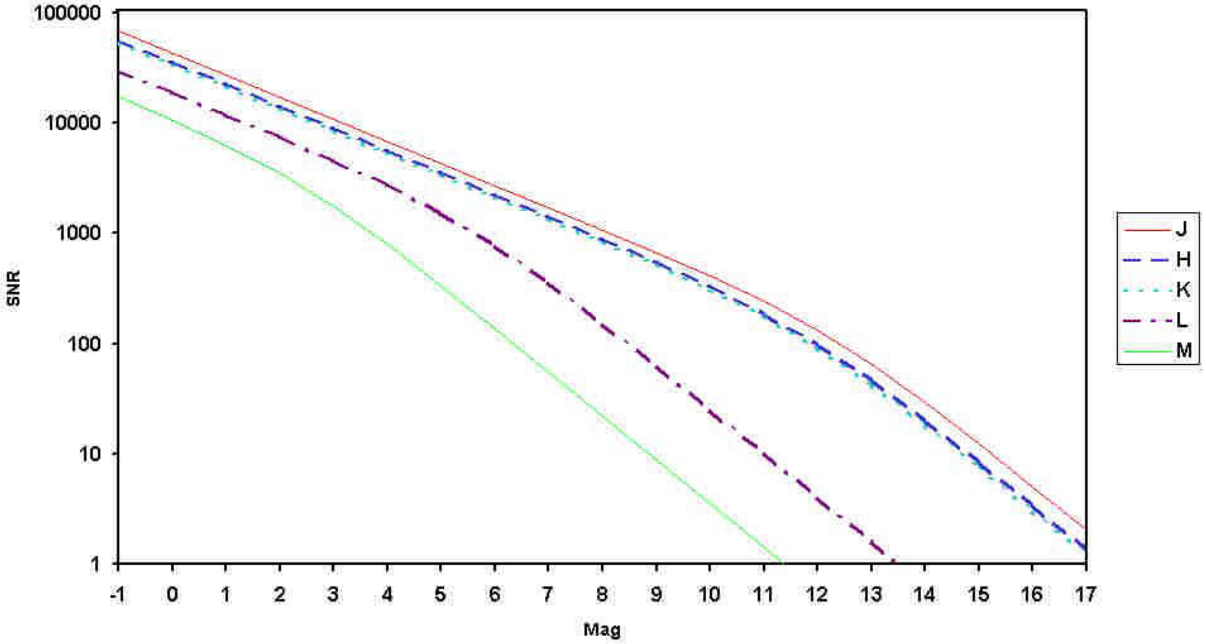

Figure 6. Signal to noise ratio in 1 hr as a function of magnitude.

3. DEVELOPMENT STATUS

As of July 2002. The optics has either been delivered (e.g echelle grating (Thermo RGL), AO deformable mirror(Cilas), dichroic (Cybernetics), filters (Barr)) or is in manufacture at Sagem (TMA), Axsys (other cryogenic mirrors), Seso (prism)... The table and mechanics for all the systems between the spectrograph and telescope focus (calibration unit, adaptive optics, field de-rotator) plus the vacuum vessel are in manufacture at Fijnmechanik in The Netherlands and SDMS in France respectively. A prototype of the echelle unit is working and being used now for tests to finally select the cryogenic motors (baseline Phytron) and encoder (linear or circular from Inductosyn). Design of the various other functions is well advanced and manufacturing contracts will start to be placed soon. Ordering of commercially available components e.g for the cryovacuum system is also underway. The 5 Aladdin detectors are essentially in hand and the development of the new ceramic carriers for the mosaic is well advanced. However, transfer of the arrays by Raythoen to the new carriers and tests that their dark currents meet requirements are still pending. The control system, detector software and some parts of the data pipeline are also progressing because they are essentially modified versions of what has been developed for earlier instruments such as ISAAC. Discussion are also underway with J. Hron and T. Lebzelter the University of Vienna concerning their possible support with the development of more CRIRES specific reduction and calibration tools. Overall we expect serious system integration to start before the end of the year and to meet our target for installation in 2004.

4. PERFORMANCE

Compared with most infrared astronomy programmes so far at the VLT, a larger fraction of the CRIRES science is likely to depend less on detection limit and more on the achievement of high signal to noise ratios on relatively bright objects (stars) and/or accurate radial velocities (e.g for detecting exoplanets). Fig. 6 shows the signal to noise ratio expected in about 1 hr as a function of object magnitude. At the longer wavelengths the performance is still limited by shot noise on the background whereas detector noise and/or dark current dominates at the shortest wavelengths. In order to be able to realize these high values in practice, however, possible sources of fringing (e.g interference filters) have had to be avoided and the requirement on the grating reproducibility has been set at $\simeq$ .05 pixel in order to avoid limitations by flat field artefacts. If the wavelength reproducibility cannot be achieved 'blind' it will be obtained by active spectrum control using sky lines as the reference. This means that the nominal velocity accuracy will also correspond to this or $\simeq$ 70 m/s. Even higher accuracy will be possible using the absorption gas cells although the actual gain will depend strongly on the actual line density of the selected gas in the wavelength region of interest.

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