CRIRES: A High Resolution Infrared Spectrograph for ESO's VLT

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ABSTRACT

CRIRES is a cryogenic, pre-dispersed, infrared echelle spectrograph designed to provide a resolving power $\lambda/\Delta\lambda$ of 10^5 between 1 and $5\mu m$ at the Nasmyth focus B of the 8m VLT unit telescope #**1** (Antu). A curvature sensing adaptive optics system feed is used to minimize slit losses and to provide diffraction limited spatial resolution along the slit. A mosaic of 4 Aladdin III InSb-arrays packaged on custom-fabricated ceramics boards has been developed. This provides for an effective 4096x512 pixel focal plane array, to maximize the free spectral range covered in each exposure. Insertion of gas cells to measure high precision radial velocities is foreseen. For measurement of circular polarization a Fresnel rhomb in combination with a Wollaston prism for magnetic Doppler imaging is foreseen. The implementation of full spectropolarimetry is under study. This is one result of a scientific workshop held at ESO in late 2003 to refine the science-case of CRIRES. Installation at the VLT is scheduled during the first half of 2005. Here we briefly recall the major design features of CRIRES and describe its current development status including a report of laboratory testing.

Keywords: Infrared Spectroscopy, Echelle, Cryogenic Movements, Zeeman-Effect

1. INTRODUCTION

The CRIRES spectrograph is part of the first generation of VLT instrumentation.[1] It was included in the very first call for VLT instruments in 1989. Then several options for this instrument were discussed during the *Workshop on High Resolution Spectroscopy with the VLT* held at ESO in 1992.[2] By then, however infrared astronomy had just left behind the era of single pixel detectors. In fact in those days there was even a strong case to build a Fourier-transform spectrometer, rather than a grating spectrograph. The small detector formats of those days would have left a grating spectrograph with a rather limited spectral coverage. The trade-offs then were analyzed in some details at ESO.[3] By 1997, however, detector formats and the respective performance had developed sufficiently to secure the formal inclusion of CRIRES in the VLT instrumentation plan. Moreover, there was some competition for the limited resources with in ESO. Finally the project then had its real start in 1999 with preliminary design review (PDR) in April 2000 and final design review (FDR) in Oct 2001. Since then practically all parts have been procured and almost all of the metal has been cut. CRIRES is in fact now approaching the end of integration: the fully integrated instrument (without detectors) had its first cool-down in early June 2004 (see figure 1).

While there is also a great variety of atomic lines the real objective of infrared high resolution spectroscopy at wavelengths $> 1\mu m$ is, to observe molecular rotational-vibrational transitions* Due to the ratio of molecular force constants relative to atomic energy levels these spectral features are clustering in the infrared. In the region

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*This is strictly true off course only for ground based infrared astronomy. Due to the fundamentally different background situation, the situation is somewhat different for instrumentation on a space based platform.

1-$5\mu m$ there is a great variety of transitions of species abundant in astronomical objects. In that sense CRIRES has been optimized for the observation of individual molecular rotational-vibrational bands, mostly occuring in stellar atmospheres.

To have an optimum match between the scientific requirements and the Procrustes' bed of technical constraints there was a second scientific workshop organized in Nov. 2003 at ESO on *High Resolution Infrared Spectroscopy in Astronomy.*[4] This workshop confirmed, that CRIRES the way it is being built is a long awaited unique observing facility, where there will be a great demand in astronomy ranging from the inner Solar system to damped Lyman-α absorption systems. While CRIRES design and status have already been presented on previous occasions - e.g in the context of SPIE-meetings[5] - in this article we will concentrate on integration, calibration and plannings for operation.

2. INSTRUMENT DESIGN

2.1. "Warm Optics" and Adaptive Optics Design Features

The optical layout is shown and described in fig2. CRIRES is a stationary instrument using an optical derotator. All warm optics of CRIRES is reflective (mostly diamond machined Al 6061 mirrors with broad-band protected Ag coating). The de-rotator design, optics and mechanics, is a straight copy of the one in use for the ESO UVES spectrograph. A detailed description[6] of the $(\lambda/4)$-retarder design has already been given elsewhere. The most challenging part of the warm optics is the MACAO-adaptive[7] optics system[†]. A specialized system[8] is being used for CRIRES. As the deformable mirror sits on a kinematic gimbal mount fast enough to do tip-tilt correction, the complete system, which re-images the VLT focus 1:1, adds only 4 extra reflections. Important features for CRIRES are that the dichroic feeding the curvature sensing wavefront sensor is also the entrance window to the Dewar and that the infrared slit-viewer camera is part of the AO control, so that any pointing problems or flexures or any other differential effect can be avoided all together or at least documented.

2.2. Design Features for the Cryogenic Part

The cryogenic optics is with few exceptions all reflective and machined from Al 6061, with IR-enhanced Ag-coating for the pre-slit optics and Au coating for the main spectrograph and grating. More optical details are given in the caption to figure 2. Based on samples of fully resolved Solar infrared absorption spectra[9] the perturbation by the parasitic telluric absorption lines was studied. It was concluded that for an acceptable cancellation of these lines in result spectra (i.e. science spectrum divided by calibration star) a stability equivalent to $75\frac{m}{s}$ (i.e. $\frac{1}{20}$ of a pixel) would be required[‡] . In the same sense the reproducibility of the grating/prism set-ups should be of the same precision. The important features of CRIRES to achieve this goal are:

- **Infrared Slit Viewer:** CRIRES is equipped with an infrared slit viewer featuring a 1024^2 InSb Aladdin II array. There is a filter wheel with standard astronomical J, H and K filters, so that for the entire operating range of CRIRES differential refraction becomes truly negligible, while embedded objects can be well centered with the slit. In order to be able to observe stars in the brightness range of $-3 \leq m_J \leq 18$ there exist also various neutral density filters. The centering stability of the slit-viewer is of order of $5*10^{-3}$arcsec (see above).
- **Precision Grating Mount:** CRIRES has two movements which ultimately define the reproducibility of the spectra: the prism mount and the grating mount. Both units are driven by cryogenic stepper motors in combination with high precision lead screws. Rotation angle control is in closed loop by cryogenic encoders[§].

[†] MACAO, Multi-Applications Curvature Adaptive Optics: this is a quasi off-the-shelf system at ESO developed in 2 flavours: one for instrumentation being used in the VLT instruments SINFONI and CRIRES and one for feeding the interferometric focus with the VLT 8m unit telescopes. There is a great many presentations on this system in this conference series.

[‡] Off course, such problems could also be tackled in data-post-processing, but the idea here is, to avoid having to go through these troubles, as the goal of $75\frac{m}{s}$ seems to be achievable with limited efforts.

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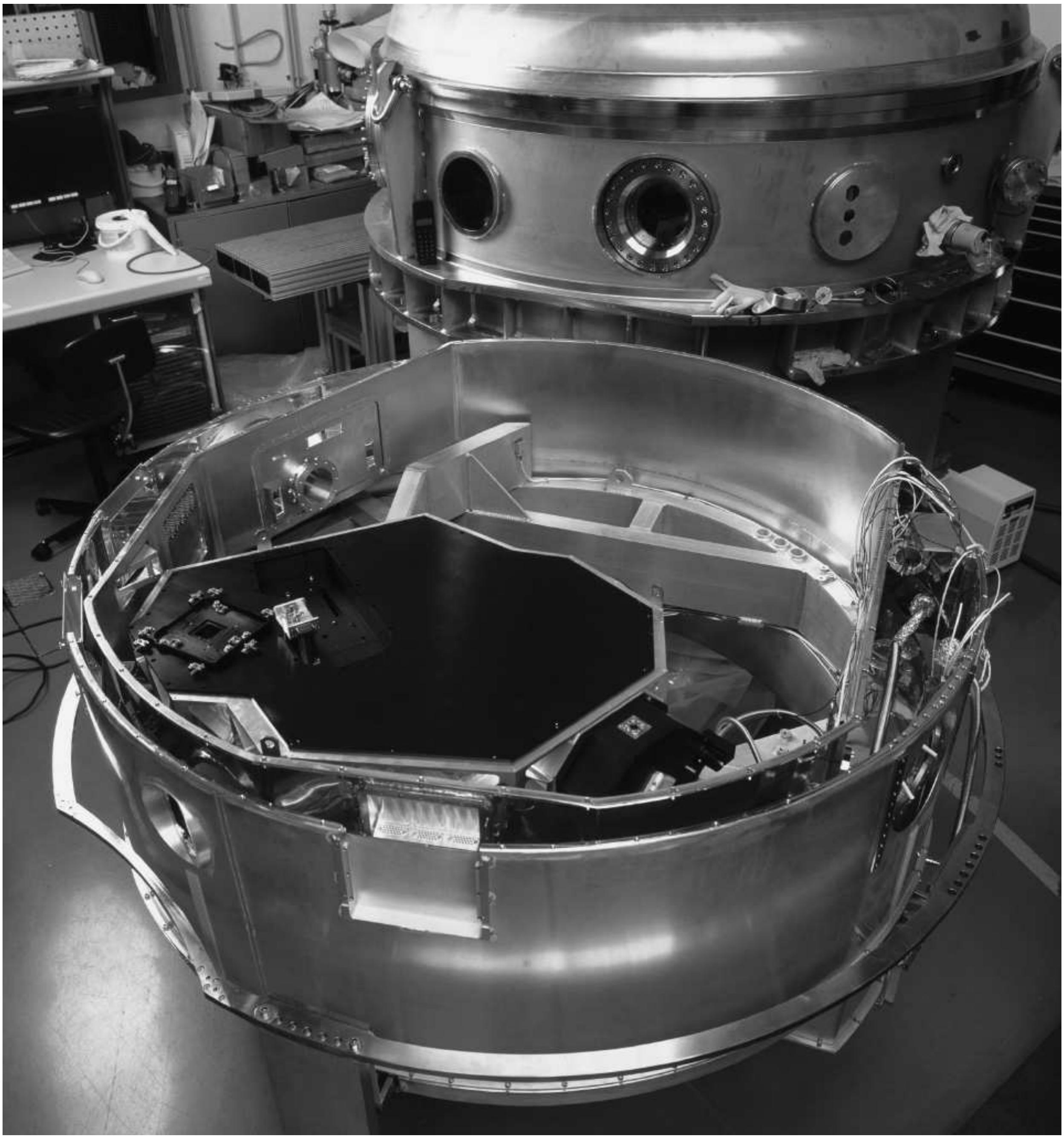

Figure 1. The CRIRES cold structure in front of the CRIRES vacuum vessel. The cylindrical outer shield has a diameter of $\approx 1.4m$. The outer shield is floating, the inner shield actively cooled and also providing for a light shield. Around the outer shield one can see a ring which is the support structure holding the cryogenic assembly inside of the vacuum vessel. This ring is connected via fibre-glass sheets to the ambient temperature fixation inside of the vacuum vessel. The black structure in the foreground is the housing of the pre-slit optics and the predisperser (c.f. figure 2 for a schematics of the optical path). This unit - which encompasses also the infrared slit-viewer - is in itself a light-tight unit. In the back the welded Aluminum (Al 7075) frame of the cold optical bench is visible. In this location the main collimator of CRIRES (a three-mirror anastigmat) will be mounted. In the far end of the lab, the vacuum vessel of CRIRES can be seen. In June 2004 the whole unit has been cooled down for the first time, with the exception of the detector assemblies fully integrated.

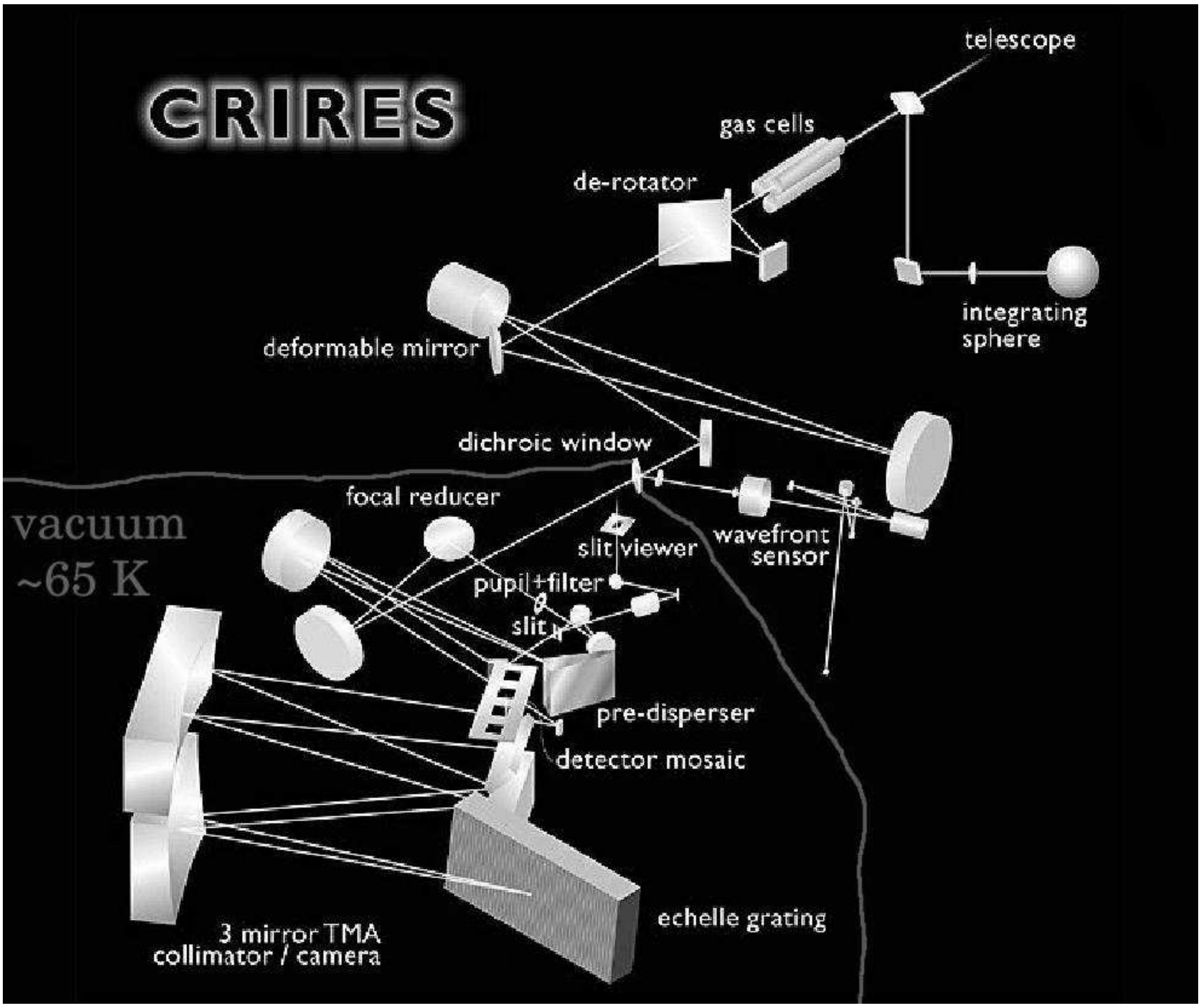

Figure 2. The CRIRES optical design: The VLT Nasmyth focus (f# 15) is close to the first mirror of the de-rotator assembly. There is a calibration unit (Neon and Krypton arc-lamps, Halogen lamp and an Infrared glower in combination with an integration sphere) for flat fielding and spectral calibration. In addition, a selection of gas-cells can be moved into the beam for calibration and for search for very small radial velocity changes similar to the Iodine-cell technique applied in optical spectrographs. Instead of the gas-cells retarders in a motorized mount can be placed to use CRIRES for spectro-polarimetry (see text). The de-rotator is followed by the curvature sensing adaptive optics system with the deformable mirror on a kinematic gimbal mount. The entrance window to the cryostat is a dichroic, separating the visible light with high efficiency for the AO wavefront control. The entire optical bench (c.f. fig1 and text) is cooled by 3 Closed Cycle Coolers to $\approx$ 65K. The pre-slit optics of CRIRES consists of an all-reflective re-imager with a cold-pupil stop, reducing the f-ratio to f# 7.5. Close to the cold pupil a Wollaston prism (MgF_2) can be inserted, eventually with a linear polarizer compensating instrumental polarisation. The slit-viewer has a CaF_2/Sapphire doublet as an objective giving a pixel scale of 0.1 arcsec/pixel and an unvignetted field-of-view of $25x50arcsec^2$. The main slit is continously adjustable up to several arcsec with a closed loop encoder controling the slit separation. The pre-disperser has a collimated beam diameter of 100mm and uses a ZnSe prism in retro-reflection. The collimator mirror can be slightly tilted with a piezo (see text). Order selection in the pre-dispersed spectrum is provided by a second intermediate slit located close to the small folding mirror. The main collimator, a three-mirror anastigmat, produces a 200mm collimated beam which illuminates a R2 Echelle grating (31.6 gr/mm). For convenience of the arrangement of the detector mosaic another folding mirror is being used.

The entire mounts are fully assembled and have been thoroughly tested at ESO in our cryogenic test facility. It was found, that the grating can be set-up reproducible with a precision of 1 arcsec. This in turn means that the centre of gravity of a spectral line would in principle scatter by ±0.5 pixel for consecutive set-ups.

- **Piezo-Adjustable Collimator:** In spite of the high precision of the grating mount the goal for reproducibilty for the spectral set-ups is 0.05 pixel, i.e. with the grating scanner alone, one is lacking roughly an order of magnitude. For vernier adjustment of location of the spectrum on the detector an open loop Piezo-scanner has been integrated into the mount of the pre-disperser collimator. While the central region of a spectrum thus always can be adjusted precisely to the centre of the detector mount one has to watch, that the dispersion of the spectrograph also changes with the grating angle. However, the precision achieved for the grating mount (see above) makes this effect negligible.
- **Temperature Regulation:** Temperature changes can influence the spectrum in two ways: by warping of the optical bench and by temperature induced changes of the index of refraction of the pre-disperser prism. Comparison with other infrared instruments of ESO (e.g. ISAAC) it was found that without any stabilisation the requirement can just be achieved. In order to keep all drifts in CRIRES at a negligible level it was decided to temperature regulate the support points of the cold structure and to stabilize the temperature of the radiation shield.
- **Stability:** Beyond this, in case of trade-offs preference was always given to stability (and reliability). All parts, especially also the optics, is being assembled without any facilities for adjustment or alignment. This was feasible because of the high precision of parts and good experience with this approach in other projects.

The main slit assembly of CRIRES is continously adjustable, whereby the nominal slit width is 0.2 arcsec for 2-pixel Nyquist sampling.

2.3. Spectro-Polarimetry

As the ratio of Zeeman-splitting to intrinsic line width increases with λ, it is highly desirable to have a mode allowing to measure circular polarisation in lines. Moreover in many cases the contrast between active regions on a star and the photosphere is more favorable in the infrared.[6] Recently[10] it has become clear, that in fact all four Stokes parameters have to be measured in the Zeeman sensitive lines to allow for unambiguous reconstructions. At present the impact of this new requirement is being analyzed and it may be necessary to use an additional rotating $\lambda/2$ device at the level of the gas-cell selection unit (c.f. figure 2).

The cryogenic Wollaston prism is on a kinematic mount in the vicinity of the re-imager cold pupil stop. A similar (cemented) prism has been used without problems in a cryogenic environment for many years now in the ESO-SOFI instrument on LaSilla.

The calibration plan is being updated at the moment and a special set of external lamps has been designed, which can produce unpolarized, linearly polarized light (in two orthogonal directions) and 100% left- and right-hand circularly polarized light. In parallel the properties of instrumental polarisation is being analyzed using the Mueller matrix formalism. After all there are in total 27 (!) reflections before a photon finally arrives at the detector assembly. An effective strategy for calibrating instrumental polarisation and retardance is highly desirable.

2.4. Detectors

As there is a specific paper[11] in this conference series only a very short summary here. CRIRES in its focal plane will employ 4 Aladdin III arrays, which are integrated into an ESO-developed custom made three-side buttable ceramics package. While this design intrinsically aims at the smallest possible inter-detector gap (264 pixels) it also aims at a very good alignment and very high mechanical stability.

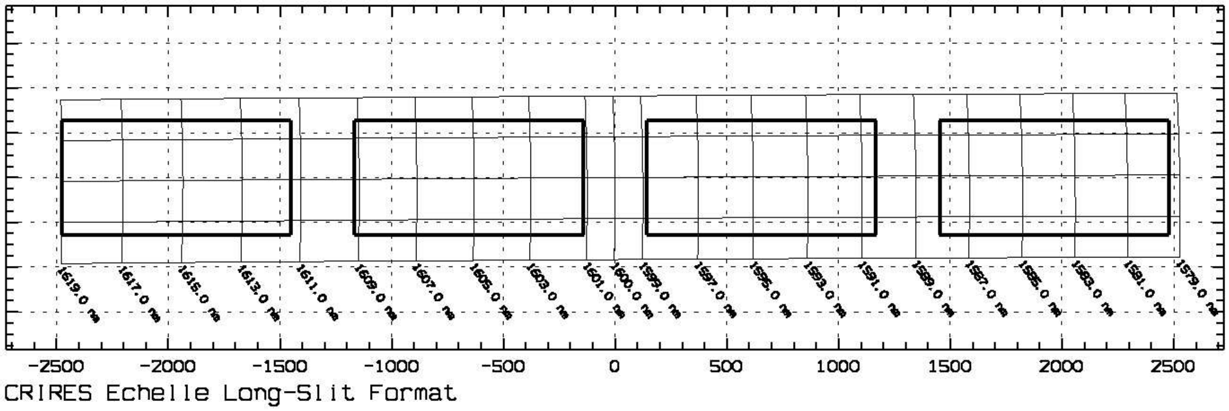

Figure 3. Example of the CRIRES spectral format: The figure shows the result of the optical design calculations plotted around $\lambda = 1600nm$. The coordinates are the nominal pixel addresses in the spectrograph focal plane. Monochromatic slit images are shown in λ-steps of 2 nm. In the horizontal (= dispersion) direction, spectral images separated by 10 arcsec along the slit are drawn. The dotted lines are aligned with the nominal detector coordinates. The borders of the 4 Aladdin III arrays, where the best 2 512^2 quadrants each are being used, is indicated as well.

The detectors are connected to the outside world with shielded cryogenic pre-amplifiers and carefully designed flat-band cabling so that a sufficiently low internal photon background in the instrument is assured. Details about the detectors have been described elsewhere.[12]

In cases where the inter-detector gap is not acceptable pairs of exposures will be done with the grating tilted by the equivalent of ≈630 pixel. Effectively this arrangement will then provide for ≈5500 pixel in dispersion direction, or at the nominal spectral resolution of $\lambda/\Delta\lambda$ of 10^5 to a quasi-instantaneous access to 2.7% of the spectrum while Nyquist sampling[¶].

3. CALIBRATION AND OPERATION

3.1. Operational Principles

At the nominal spectral resolution[‖] of CRIRES typically 50 grating settings will be sufficient to cover the entire infrared spectrum accessible from the ground in the range of $0.95 \leq \lambda \leq 5.2\mu m$. Only these discrete settings will be supported by the observatory. For each setting there are sufficient lines of the night sky available for an online wavelength calibration (see below). Set-ups will be done, by using the instrument physical model, to position the spectrum with the precision of typically 1/2 of a pixel. Thereafter a short spectral exposure is done and the offset of the sky lines relative to the tabulated nominal positions is being calculated. From this offset a correction voltage is being calculated and applied. If required, there may be another test-exposure to verify the results.

3.2. Instrument Model

In spite of the crowded scheme given in figure 2 CRIRES is from the model point of view rather simple: once the telescope/slit-viewer scale in the slit-plane have been calibrated, the pre-slit optics has no real influence anymore on spectral and spatial calibration. It it thus not part of the model. The pre-disperser can be easily represented by a re-imager with a magnification close to unity and, according to the optical design calculations

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[¶] For completeness it should be mentioned, that at the short wavelength end of the operations range approaching $\lambda \approx 1\mu m$ the orders will be shorter than the CRIRES focal plane.

[‖] At the price of vignetting the resolving power can be ramped up to values of up to typically 160000. Such an operation is not excluded but not part of the baseline considerations for instrument calibration and operation.

negligible distortion. The ZnSe-prism refractive index will be modeled with a Sellmeier formula. Using the arc-lamps in the calibration unit and ab-using the main-spectrograph as a 1-pixel photometer the prism assembly will be characterized, calibrated and the temperature coefficient $\frac{dn}{dT}$ of the ZnSe-prism will be determined. The main spectrograph can again be represented as a re-imager with a magnification close to unity but now substantial distortion. This distortion, however, is smooth and according to the optical design calculations can be parameterized with a set of polynomials. There is no reason to assume that the Echelle grating will not conform exactly to the grating formulae. In the focal plane the detector orientations and the detector positions need to be determined. In total there is a set of typically 50 parameters which need to be determined by fitting the model to the set of calibration measurements. The best approach and algorithms for this effort are presently being studied. Thereafter one should have a model describing with a precision of order of a fraction of a pixel where exactly in the slit plane a photon came from and which color it had when it ended up in a certain pixel in the focal plane. These modeling efforts will be based on established principles for Echelle spectrographs[13] applied also to other ESO instruments.

3.3. Spectral Extraction and Flat Fielding

Detailed spectral extraction with higher precision will then be done using the sky lines. There are 2 systems of skylines: the non-thermal lines originating from the OH radical produced from the chemical reaction of Ozone and Hydrogen in the upper atmosphere of our Earth[14] and the telluric absorption lines.[9] The absorptions lines are thermally radiating and longward of $\approx 1.8\mu m$ they give a very pronounced signal relative to the night-sky. This ensures ample overlap between the two line-systems and a high line density for calibration for all settings of CRIRES. These lines (line positions in literature typically at least 5 times more precise than the CRIRES resolution) can then be used with specialized software to extract spectra with really absolutely known wavelengths. At this point, it is foreseen to use the gas-cells with N_2O - which happens to be a NIST frequency standard - for a general cross check of the overall calibration procedure.

Zero-th order flat-fielding in slit and dispersion direction will be done with the internal calibration unit. Spectroscopic standard-star spectra will then be used for a true removal of instrumental and telluric features and spectro-photometric calibration. Classical infrared bright stars, however, are cool and so in consequence not really useful as spectrophotometric standards. Given the expected sensitivity for CRIRES (see below) we have scanned the Hipparcos Main Catalogue to select potential spectroscopic standards using the following selection criteria: $\delta \leq +30\,\mathrm{deg}$, stars B8 or earlier with $V \leq 4.0^{mag}$ and stars with spectral types B8-G0 with $V \leq 4.8^{mag}$. This left us with a list of 466 stars bright enough to be used up to $\lambda \approx 5\mu m$ (for wavelengths up to the L-band there are about 900 stars earlier then A1 which can be used). In some critical areas it will be necessary to measure stellar spectral templates and this is another good reason to restrict the number of grating settings supported by the observatory.

3.4. Breaking the $75\frac{m}{s}$ limit

At this point one is left with the biggest hard-to-calibrate uncertainty, that is the exact location of the stellar photocenter relative to the jaws of the entrance slit. An uncertainty equivalent to typically $75\frac{m}{s}$ appears to be a logical assumption in this context. Intrinsically the CRIRES stability may be of order of few m/s, but there is little hope to exploit this, due to the centering problem. So $75\frac{m}{s}$-equivalent measurement precision is, what the CRIRES team is committed to follow up as a goal. Unfortunately there are no plans to have something like an image slicer or image scrambler, which could help.

The only way to improve this is to try the IR-equivalent of the Iodine cell method by using a set of gas-cells in front of the spectrograph. For programs needing an absolute precision exceeding $75\frac{m}{s}$-equivalent (seismology, planet searches by reflex motion) it is considered a task of the proposing astronomers to find good spectral features both in the program star and in the gas-cell in a region where the telluric spectrum is forgiving. Then, as sensitivity is not really the limit, one should get of order of 20-50 lines from a star on the detector array (4000 pixels will help) and one should get centers of lines to a precision of typically 20m/s and averaging over 50 lines something like 3-5m/s .

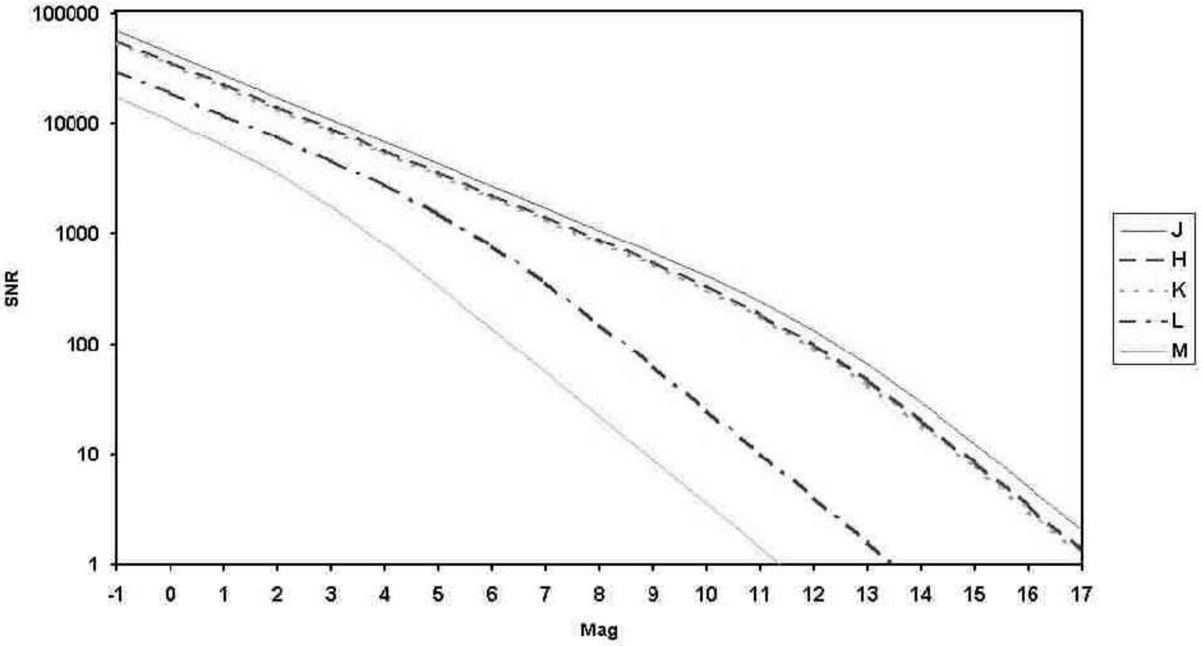

Figure 4. Plot of the expected CRIRES sensitivity: The graphs S/N versus magnitude have been calculated for 1 hour integration time conservatively, based on the acceptance measurements of components and the expected detector performances. The graphs for H and K nearly overlap.

4. DEVELOPMENT STATUS

At this point CRIRES is in the middle of the assembly and integration phase. The warm fore optics is assembled and fully integrated. All cryogenic optics has been delivered and tested in the ESO-cryogenic test facility. All critical functions have been qualified under operational conditions. All cabling in the cryostat is finished and a first cool-down was done early June 2004. In principle no major surprises are to be expected. The MACAO AO system had the control loop closed with a realistic turbulence simulated in the lab.[8] The detector read-out system (ESO standard IRACE system) is ready and the control electronics close to ready. Unfortunately the packaging of one of the four detectors was plagued by a concatenation of mishaps so that the complete assembly of the detector mosaic in a dedicated test facility is still pending. Software, building on the VLT-standard software is being finalized. In consequence, we expect first light in the laboratory later this summer or early fall. Commissioning at the VLT site will be in summer 2005.

5. PERFORMANCE

Sensitivity estimates for CRIRES are given in figure 4. It should be noted, that the K-band performance (and off course L and M) are more or less limited by the thermal background whereas in J and H the detector performance is setting the limits. This means, that J and H band could profit from technical development in the field of detectors, whereas for $\lambda \geq 2\mu m$ the performance is no longer strongly affected by the detector characteristics. On the other hand in this field the point-source sensitivity approaches that of the lower resolution spectrograph ISAAC. In this wavelength regime some projects, which do not necessarily need the spectral resolution of CRIRES may still profit from the high spectral resolution, as this allows for a better discrimination against telluric interferences.

6. CONCLUSIONS AND OUTLOOK

During the recent scientific workshop at ESO[4] it became apparent, that there is a strong interest in the community for the CRIRES instrument. In fact, on the spectroscopic modeling side the progress in the last decade has been breath-taking. In that sense CRIRES after commissioning will provide for a boost in the fields of "classic" infrared astronomy (late stars, star formation, Solar system ...) whereby the samples of objects can now be selected by meaningful criteria (other than the apparent brightness). New fields, e.g. the first direct detection of extrasolar planets or research in the extragalactic domain (e.g. quasar absorption line systems) are on the horizon. A sneak preview of the rich spectra to be expected can be found in the spatially resolved Fourier-transform-spectra of sun-spots[15] (quasi magnetized M-stars).

Based on the results of component and subsystem tests and on the overall status the CRIRES team is confident, that on the next major conference there will be a presentation of CRIRES commissioning and science verification data.

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the US - National Institute of Standards and Technology (NIST):
`http://physics.nist.gov/PhysRefData/wavenum/html/spect.html`
the online access to the archive of Solar Fourier Transform Spectrometer data from the Kitt-Peak Solar telescope through `ftp://ftp.noao.edu/fts` . The NSO/Kitt Peak FTS data being used in the CRIRES project were produced by NSF/NOAO.
the atlas of atomic lines maintained by Peter van Hoof, Physics Department Queen's University Belfast, Northern Ireland accessible through: `http://www.pa.uky.edu/~peter/atomic/`

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