# CRIRES+: a cross-dispersed high-resolution infrared spectrograph for the ESO VLT

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## ABSTRACT

High-resolution infrared spectroscopy plays an important role in astrophysics from the search for exoplanets to cosmology. Yet, many existing infrared spectrographs are limited by a rather small simultaneous wavelength coverage. The AO assisted CRIRES instrument, installed at the ESO VLT on Paranal, is one of the few IR (0.92-5.2 μm) high-resolution spectrographs in operation since 2006. However it has a limitation that hampers its efficient use: the wavelength range covered in a single exposure is limited to ~15 nanometers. The CRIRES Upgrade project (CRIRES+) will transform CRIRES into a cross-dispersed spectrograph and will also add new capabilities. By introducing cross-dispersion elements the simultaneously covered wavelength range will be increased by at least a factor of 10 with respect to the present configuration, while the operational wavelength range will be preserved. For advanced wavelength calibration, new custom made absorption gas cells and etalons will be added. A spectro-polarimetric unit will allow one for the first time to record circularly polarized spectra at the highest spectral resolution. This will be all supported by a new data reduction software which will allow the community to take full advantage of the new capabilities of CRIRES+.

**Keywords:** Upgrade of existing instrument, high spectral resolution spectrograph, infrared spectrograph

## 1. INTRODUCTION

High-resolution infrared (IR) spectroscopy plays an important role in astrophysics from the search for exoplanets to cosmology. The scientific community has recognized the need for large wavelength range, high-resolution IR spectrographs, and several are currently either in their design or already in their integration phase (i.e. iSHELL [9] and C-SHELL at the NASA Infrared Telescope Facility).

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The CRIRES instrument is an AO assisted IR (0.95 - 5.2 µm) high-resolution spectrograph installed at the Nasmyth A focus at the VLT-UT1 and in operation since 2006. CRIRES is quite a unique instrument accessing a parameter space which up to now was largely uncharted (Käufl et al. 2004 [1]). In its current setup, it consists of a single-order spectrograph providing long-slit (40") spectroscopy with a resolving power up to R=100,000. However, this is limited to a narrow single-shot spectral range (about 1/70 at 1 µm and 1/50 at 5 µm) resulting in low observation efficiency.

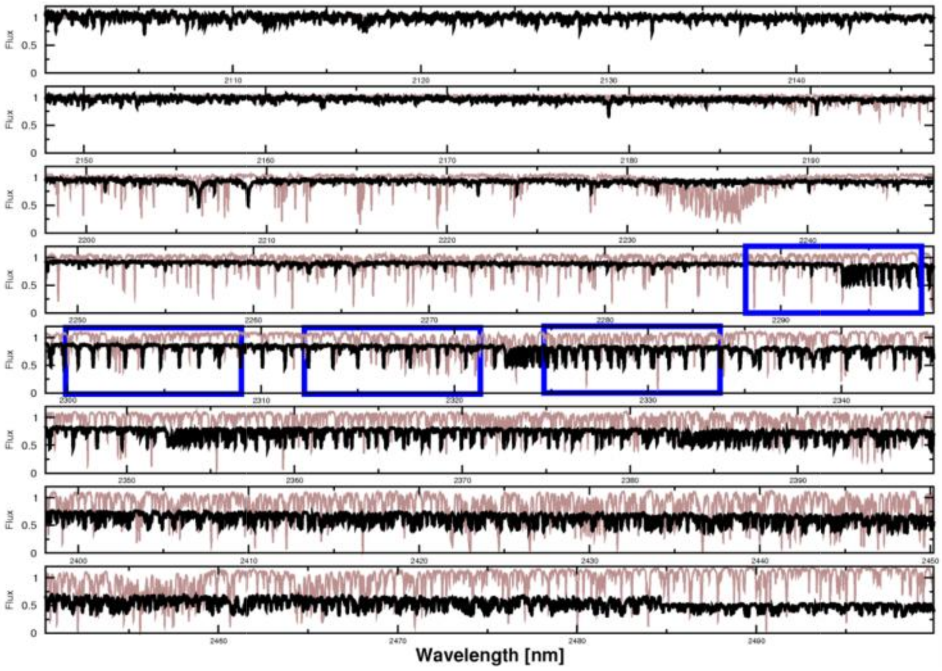


Figure 1: The wavelength coverage of the current CRIRES (the blue boxes correspond to the four Aladdin detectors currently installed) in K-band compared to the expected coverage of a single exposure from CRIRES+. The black line shows the spectrum of an M4 dwarf star (~ 0.15 $M_{\odot}$) and the brown line is a laboratory spectrum of the first gas cell prototype being developed at the University of Göttingen [3].

The main goal of the CRIRES+ upgrade project [2] is to enhance the observation efficiency of the instrument. In order to achieve this goal CRIRES+ will turn CRIRES into a fully cross-dispersed echelle spectrograph. This will increase the simultaneously covered wavelength range by an order of magnitude (see Figure 1) while the general accessible wavelength range will be preserved. The cross-dispersion upgrade will be supported by an upgrade of the scientific focal plane detector array to increase the number of accessible diffraction orders. In addition to the cross-dispersion upgrade, the CRIRES+ project will provide new wavelength calibration methods in order to reach a precision in the wavelength solution of 5 m/s in the high spectral resolution mode. Furthermore will CRIRES+ be equipped with new spectro-polarimetric unit capable of recording circularly polarized spectra.

This paper provides a general overview of the project, it's scientific goals and it's organization. The detailed designs of various sub-systems CRIRES+ are addressed in a series of papers [3, 4, 5, 6] in these proceedings.

## 2. SCIENTIFIC GOALS OF CRIRES+

During a Phase A study for CRIRES+ a set of scientific goals was defined to develop needs of the upgrade. The main three science drivers were defined to be: 1) *The search for Super-Earths and potentially habitable worlds around low-mass star*, 2) *The atmospheric characterization of Warm Jupiters, hot Super-Earths and potentially habitable worlds around low-mass stars* and last but not least 3) the investigation of *the origin and evolution of stellar magnetic fields*. These three scientific fields and their fundamental requirements on the instrument are described below. Furthermore, the consortium agreed with ESO at a very early stage of the project that CRIRES+ shall not jeopardize any of the science capabilities of current long slit CRIRES.

### 2.1.) A Search for Super-Earths in the Habitable Zone of Low-mass Stars

A large fraction of all exoplanets have been discovered primarily through radial velocity (RV) measurements. However, only 5% of the planets detected so far orbit stars with stellar masses less than about 0.5 $M_{\odot}$. Thus, we are lacking key knowledge about the process of planet formation around the most numerous stars in our galaxy – M dwarfs. Low mass stars are especially interesting because these objects are cool and the liquid water regions are quite close to the star. The reflex motion of an M star (0.15 $M_{\odot}$) with a 1 $M_{Earth}$ planet in its habitable zone is about 1 m/s. M dwarfs and brown dwarfs have low effective temperatures, radiating most of their energy in the IR (1.0 - 2.5 µm). A high-resolution IR spectrograph is therefore ideal for searching for low mass planets around these objects. Figure 2 shows the expected Doppler amplitudes for different planet masses at different semi-major axis.

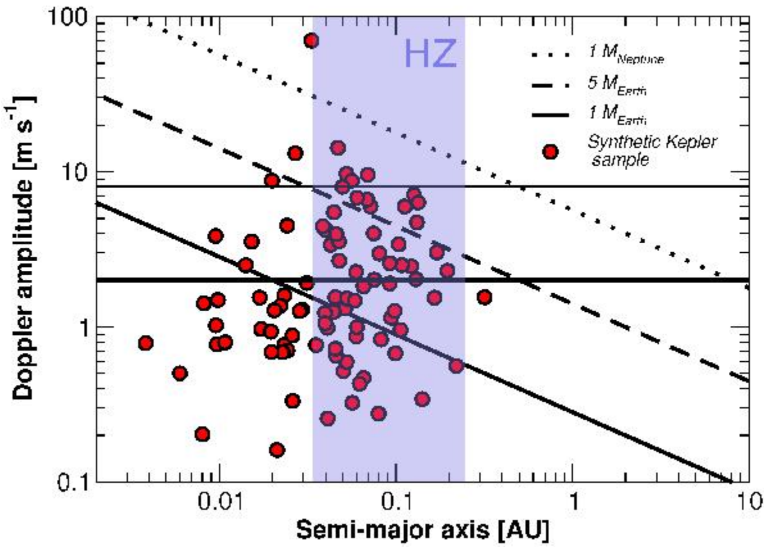


Figure 2: The expected Doppler amplitudes for different planet masses, depicted as diagonal lines, for a 0.1 Msun star are shown. The top horizontal line is the current radial velocity precision of CRIRES; the lower is a conservative predicted value for CRIRES+. These horizontal lines also display the estimate of the detection thresholds after obtaining 25 epochs. The red dots correspond to the expected planets based on Kepler results (Dressing & Charbonneau, 2013 [10]). The blue shaded zone is the approximate extent of the habitable zone for low mass stars.

### *2.2.)* Atmospheric characterization of transiting planets

In-transit spectroscopy of exoplanets currently provides us with the only means of studying exoplanetary atmospheres. Transiting planets are almost always close-in planets that are hot and radiate most of their light in the IR. Furthermore the IR is a spectral region where lines of molecular gases like CO, $NH_3$, $CH_4$, etc. are expected from the exoplanetary atmosphere. This important wavelength region is covered by CRIRES+, which will additionally allow tracking multiple absorption lines simultaneously.

**2.3.) The Origin and evolution of stellar magnetic fields**

Magnetic fields play a fundamental role in the life of all stars. They govern the emergence of stars from proto-stellar clouds, control the infall of gas on the surfaces of young stars and aid the formation of planetary systems. Measurements of magnetic fields have mostly been confined to A- and B-type stars, so our knowledge of magnetic fields in sun-like stars and the low end of the main sequence is still poor. CRIRES+ will make it possible to measure with greater accuracy magnetic fields in M-dwarfs and brown dwarfs for several reasons: 1) The Zeeman splitting of a spectral line is proportional to $\lambda^2$, so there is a huge leverage in going to the IR. 2) For cool objects most of the flux is in the IR so there is also a gain due to the increased signal-to-noise ratio. 3) In order to disentangle Zeeman broadening from other broadening effects one must compare the broadening of Zeeman sensitive lines to magnetically insensitive lines. The large wavelength coverage of CRIRES+ will include many more lines of different magnetic sensitivities needed for an accurate determination of the field strength. 4) The future capability of CRIRES+ to take circular polarized spectra will support these measurements.

## 3. UPGRADING CRIRES

The CRIRES upgrade project improves the instrument by either refurbishing, adding or replacing subsystems. Overall the upgrade project can be fragment into the following seven parts:

1. Transform CRIRES into an echelle spectrograph
2. New state-of-the-art detectors
3. New high precision wavelength calibration methods
4. Spectro-polarimetry with CRIRES+
5. Refurbishing the adaptive optics of CRIRES
6. Improve the instrumental metrology concept
7. New data reduction software

The different parts of the upgrade will be more detailed in the following. Together, they will significantly enhance the capabilities of this already powerful instrument

### 3.1. Transform CRIRES into an echelle spectrograph

In the course of the design studies it soon became apparent that in order to have a stable and reliable instrument it would become necessary to remove the entire cold pre-optics of CRIRES and to replace them with the new Cross-Dispersion Unit (CDU). Figure 4 gives an impression of the optical design of CRIRES+. A detailed discussion of the optical design can be found in Oliva et al. 2014 [6] and a discussion of the opto-mechanical design of the cold part in Lizon et al. 2014 [4] (both these proceedings).

The cold optics of CRIRES+ will consist mainly of two sections: the Cross-Dispersion Unit (CDU, see red dashed circle in Figure 4) and the spectrograph unit. The latter comprises the actual echelle grating and a three mirror anastigmat structure to image the spectrum onto the scientific focal plane detector array. The spectrograph unit will remain unaffected by the upgrade. The CDU on the other hand replaces the previous pre-optics.

To get an impression of the optical design, we follow the optical path from the telescope interface (see Figure 4). The light first passes the de-rotator. The de-rotator is followed by a calibration unit (not depicted in Figure 4, [3]) which also houses the new polarimetry unit [5]. The light enters the cold dewar through a dichroic window. The optical light is reflected and used for the adaptive optics system (which shall also be refurbished in the course of the upgrade), the infrared light ($0.95\ \mu m < \lambda < 5.2\ \mu m$) will be transmitted to the cold optics of CRIRES+. The current dichroic will be replaced during the upgrade since it was found to not fulfill the high requirements imposed by the CRIRES+ science cases at the short wavelength end. The light will then pass through either of two slits that are 0.2 and 0.4 arcsec wide. This will preserve the spectral resolution of CRIRES (50,000 or 100,000, respectively). To cover the additional orders the spatial extent of the two main slits was reduced from 40 to 10 arcseconds, providing a balanced compromise (based on an analysis of the current and future scientific requirements and science cases) between cross-dispersion

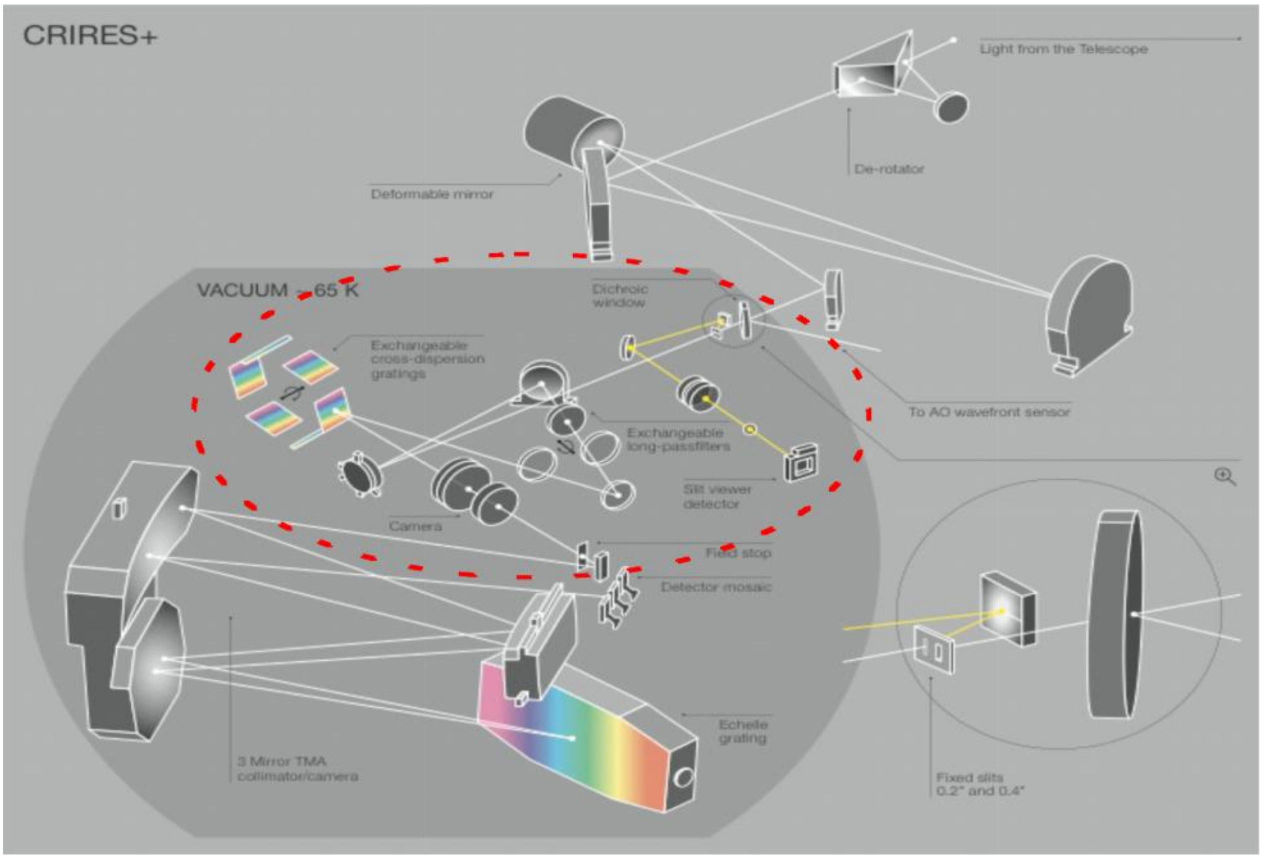


Figure 4: Optical Design of CRIRES+. The red dashed circle indicates the Cross-Dispersion Unit replacing the current pre-optics unit.

implementation and catering the current CRIRES long slit usage. The 10 arcsec slit will not limit observations of extended sources and allow nodding for precise background subtraction observing methods. The light reflected by the slit decker will used by the slit viewer camera to assist the adaptive optics system in centering the targets PSF on the slit. After passing through the main slit the beam is collimated to a 50 mm parallel beam.

The cross-dispersion of the spectrum will be performed by reflection gratings. Six gratings are foreseen and are mounted on a cryogenic wheel. Each of them is optimized for operation in a single wavelength band (Y, J, H, K, L and M). Another wheel will carry the order sorting filters to eliminate contamination by second- and third-order spectra of the gratings. The re-imaging of the slit is then performed by a fixed lens camera, designed for the full wavelength coverage and used for all observing modes. In this configuration, the observing modes will require only one exposure to cover the full Y-Band, two exposures, with different echelle angles, for the J, H and K bands and three exposures with different echelle angles will be needed to cover the L and M Bands. Overall the new design will maintain the current throughput of CRIRES with the goal of increasing it.

### 3.2. New state-of-the-art detectors

The third major part of the upgrade project is to increase the coverage of the focal plane by introducing a set of new detectors. The current CRIRES scientific detector system uses 4 Raytheon 1024 x 1024 pixel InSb Aladdin arrays as described in Dorn et al. 2006 [7]. Another Aladdin detector is used for the slit-viewer camera. Due to the planned cross dispersion a larger field is required to cover the ten orders per band with a slit length of 10”. Therefore a new and current state-of-the-art detector mosaic will be installed in CRIRES+. Figure 5 gives a comparison between the current CRIRES focal plane array area and the future array of CRIRES+. The future detector array, composed of 3 Hawaii 2RG detectors

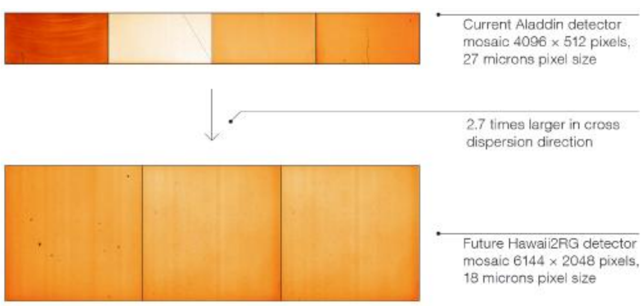


Figure 6: Current CRIRES science focal plane detector array compared to the new detectors with an increase in area of a factor of 2.7 in cross-dispersion direction.

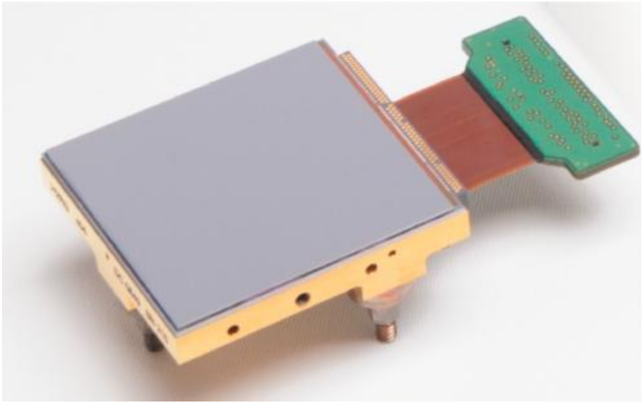

Figure 5: Picture of a ground based astronomy HgCdTe H2RG: Teledyne's H2RG ground based package allows 32- output operation to be used for CRIRES+.

(a single H2RG detector is shown in Figure 6), will span 6144 x 2048 pixels (37mm x 111mm) at a pixel size of 18µm. For comparison, the current mosaic spans only 4096 x 512 pixels with a pixel size of 27µm. The new detector mosaic will not only provide a larger area, but also lower noise, higher QE, better cosmetic quality, and much lower dark current. Also the gap between the detectors in the mosaic will be smaller. The detectors will be operated at 40K with cryogenic preamplifiers located next to the focal plane. All detector systems, including the slit viewer camera, will be upgraded to the current ESO standard detector controller NGC. This detector upgrade will not only significantly increase the coverage of the focal plane, but the increased spatial homogeneity of the pixel response will also result in improved data quality.

**3.3. New high precision wavelength calibration methods**

The CRIRES+ science cases also demand specialized, highly accurate wavelength calibration techniques. Therefore, another part of the upgrade is concerned with the introduction of novel calibration methods for CRIRES+. A more detailed description of the new wavelength calibration is described by Seemann et al. 2014 [3] in this conference.

One of the scientific goals of CRIRES+ is to find Super-Earths in the orbit of cool stars. The precision in the wavelength solution to reach this ambitious goal is of the order of 2-3 m/s. To achieve this goal CRIRES+ will adopt novel infrared absorption gas cells with multi- species gas fillings ($NH_3$, $^{13}CH_4$, $C_2H_2$). These gases will provide a set of homogeneously distributed absorption lines imprinted on the stellar spectra over the whole spectral range in which CRIRES+ will operate (see Figure 7). This, in combination with the advantages of a 10-fold increase in wavelength coverage (see Figure 1), will allow CRIRES+ to achieve the required precision on a regular basis. In addition it is intended to replace the existing thorium argon hollow cathode lamps with similar uranium neon lamps that produce a richer wavelength calibration spectrum.

Last but not least the consortium will also provide CRIRES+ with a new calibration system based on etalons. The etalons on the one hand cover spectral regions not supported by the gas cells with an unprecedented high precision wavelength calibration, but they will also serve as the calibration for the polarimetry unit. The latter is required since the polarimetry unit will be mounted to the same slider the gas cells will be mounted to, thus, it won't be possible to use both in unison.

**3.4. Spectro-polarimetry with CRIRES+**

The combination of a polarimeter with a cross-dispersed echelle spectrograph will make it possible to disentangle magnetic effects from other sources of line broadening. This will enable the study of the magnetic fields of premain sequence or late stars. The new polarimetry module planned for CRIRES+ uses two polarizing gratings (PGs) to split the incoming converging beam into left- and right circular polarized beams that continue along parallel optical axes. The choice of PGs as polarizing elements is motivated by their different behavior at short and long wavelengths, their small thickness, the possibility of producing large and homogeneous samples, and their modest price. The geometry of the periodic pattern that makes up the PGs is chosen such that infrared light (with wavelength longer than 1 micron) is deviated while optical light is transmitted essentially unaltered. Thus it will act as a polarizing beam splitter on circular polarization without disturbing the operation of the AO system. The polarization module consists of a rotating stage with two PGs. The rotation axis is parallel to the axis of the incoming beam. It allows the positions of the two output beams to be switched to allow calibration of the difference in throughput for the two beams. Laboratory tests were performed on a prototype system based on PGs and the measured polarization extinction, throughput, and scattering as a function of wavelength show that the proposed device fits the requirements for spectro-polarimetric measurements with CRIRES+ in the 1 to 2.7μm wavelength range. A more detailed description of the polarimetry unit can be found in Lockhart et al. 2014 [5] in these proceedings.

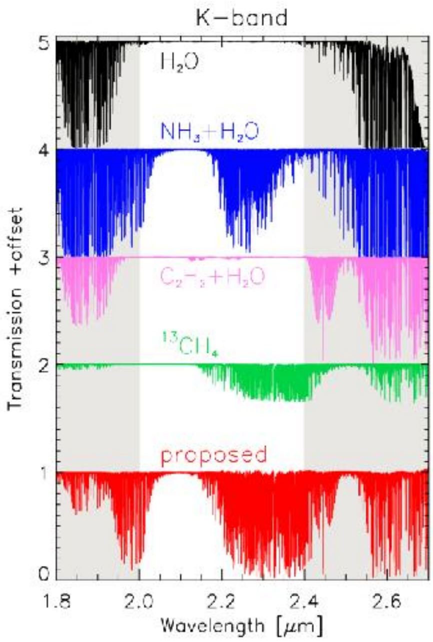

Figure 7: Absorption spectra for some of the selected gases for CRIRES+ and the resulting gas mixture absorption spectra (named proposed) measured in K-band.

### 3.5. Refurbishing the adaptive optics of CRIRES

The upgraded CRIRES+ foresees a lifetime of at least 10 years. CRIRES is operated in conjunction with a 60-element curvature adaptive optics system, MACAO, as described by Paufiqué et al. 2004 [8]. This system requires interventions to prevent its obsolescence. This is already planned for the MACAO VLTI systems installed in the coudé laboratories of the UTs. Accordingly, the CRIRES MACAO system will be refurbished in a similar manner to the VLTI systems by replacing and upgrading obsolete electronic boards. In addition it is planned to exchange the membrane mirror, recoat additional mirrors, realign the optics and re-commission the full AO-system.

### 3.6. Advance the instrumental metrology concept

In order to obtain the high quality data needed to explore exoplanet atmospheres, CRIRES+ will need to be able to perform highly stable exposures with high repeatability. The original CRIRES was limited by a spectral format reproducibility of about 1pixel due to imperfect positioning of the pre-disperser and echelle grating mechanisms. However, a system of metrology was developed that facilitated the fine-tuning of the positioning of these mechanisms such that a 0.1 pixel reproducibility was achieved. Since CRIRES+ retains the original echelle grating mechanism, an adapted version of the metrology system will be required. This will comprise a fibre feed with an arc lamp spectrum that illuminates the echelle grating, automated detection and identification of reference lines, computation of correctional adjustment, and feedback to the grating mechanism and to a piezo actuator for fine tuning.

### 3.7. New data reduction software

The CRIRES+ project will also provide the community with a new data reduction software (DRS) package. The CRIRES+ DRS will support all of the offered observing modes and plans to provide the user with both science and publication ready (tbc) data products. Since the development of the DRS is performed in close collaboration with the hardware upgrades, the entire instrumental knowledge of the consortium will be incorporated into the final software. In this way every future user can take advantage of the full capabilities of CRIRES+.

# 4. CRIRES+ PROJECT ORGANIZATION

## 4.1. The CRIRES+ Consortium

The CRIRES upgrade project – CRIRES+ - is a joint effort of a European consortium. The consortium is composed of the following institutes:

- *Thüringer Landessternwarte (TLS), Tautenburg (Germany)*
- *Uppsala University (UU), Department of Physics & Astronomy (Sweden)*
- *European Southern Observatory (ESO), Germany*
- *Georg-August-Universität Goettingen (IAG), Institut für Astrophysik (Germany)*
- *Istituto Nazionale di Astrofisica, Osservatorio Astrofisico di Arcetri (Italy)*

The consortium is led by Prof. Artie Hatzes (PI, TLS). The contributions and responsibilities of the four ESO external institutes within the consortium are regulated by a Memorandum of Understanding signed in early 2013. The collaboration with ESO is governed by a Collaboration Agreement signed in June 2014. The project management of CRIRES+ is a joined effort of the ESO Project Manager (R. J. Dorn) and the consortium Project Manager (R. Follert). They are also the main line of communication between ESO and the consortium.

Each of the member institutes provides their own expertise to the project. The work packages revolving around the upgrade of the CRIRES cold part are led by ESO with support from consortium engineers. This concerns mainly the opto-mechanical design, the control electronics and control software as well as the new science detector focal plane array. Many subsystems rely heavily on ESO standards being implemented and tested many times. In this way the project can benefit to a maximum extend from the knowledge and experience of ESO. Furthermore, this approach will ensure that the upgrade project can be completed within a much shorter timescale than projects of similar complexity. The optical design of CRIRES+ including the optimization of the cross-dispersion elements on the other hand is a contribution from our partners at the observatory in Arcetri (near Florence, Italy), which have an outstanding understanding of infrared spectrographs.

The calibration unit including the new gas absorption cells and the etalons are provided by the University of Göttingen (Germany). This institute has considerable experience with wavelength calibration systems for infrared spectrographs, for example they provided the current ammonium cell for CRIRES.

The University of Uppsala (Sweden) is in charge of the polarimetry unit and of the data reduction software. In addition, the funding by the Swedish Wallenberg Foundation is providing the required investments for the new detector array.

## 4.3. Project schedule and resource planning

The CRIRES upgrade project started with a Phase A study in late 2011 which was successfully concluded in early 2013. In June 2013 the project got officially approved by the ESO council. The project is currently in its preliminary design phase lasting until early 2015. The preliminary design review (PDR) for the CRIRES+ system will be accompanied by a optical final design review (FDR). This will allow us to start the procurement processes for the optical long lead items. The preliminary design phase will be followed by a final design phase to be concluded in late 2015 by the system FDR.

The main integration phase will then commence in 2016 including extensive system testing at ESO premises. Since the upgrade relies mainly on standard components for the complex cross-dispersion unit upgrade the acceptance Europe is envisaged for late 2016. The instrument will then be shipped back to the Very Large Telescope (VLT) Observatory at Cerro Paranal, Chile. After a detailed commissioning phase the upgraded instrument shall be approved in late 2017 and then made available to the community. Table 1 below gives an overview of the project milestones.

The consortium is funded through a grant of the BMBF (German ministry of education and science, for the German partners), while the Swedish group is funded by a grant of the Wallenberg foundation. The fact that most of the infrastructure of CRIRES as well as the spectrograph unit will be re-used for CRIRES+ allows it to provide an outstanding instrument at a minimum cost. In addition, the project can be completed in a comparably very short time frame due to the experience of the team which build the current CRIRES instrument as well as due to the decision to use ESO standard components in many places.

Table 1: Milestones of the CRIRES+ project.

| Milestone | Due Time |
|---|---|
| End of Phase A / **ESO** Council Approval | June 2013 |
| Preliminary Design Review | April 2015 |
| Final Design Review | December 2015 |
| Acceptance Europe | December 2016 |
| Acceptance VLT observatory | November 2017 |

## 5. CONCLUSION

CRIRES+ combines a unique combination of telescope collective area (installed at an 8 m class telescope), spectral resolution (R~100,000), accessible wavelength range (0.95 - 5.2 µm) and a high simultaneous wavelength coverage (only 2-4 settings to cover the entire J band without any gaps). Thus, the CRIRES+ upgrade will provide the community with an excellent instrument to do excellent science with.

## ACKNOWLEDGMENTS

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