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Full System Test and early Preliminary Acceptance Europe results for CRIRES+

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ABSTRACT

CRIRES$^+$ is the new high-resolution NIR echelle spectrograph intended to be operated at the platform B of VLT Unit telescope UT3. It will cover from Y to M bands (0.95-5.3um) with a spectral resolution of R = 50000 or R=100000. The main scientific goals are the search of super-Earths in the habitable zone of low-mass stars, the characterisation of transiting planets atmosphere and the study of the origin and evolution of stellar magnetic fields. Based on the heritage of the old adaptive optics (AO) assisted VLT instrument CRIRES, the new spectrograph will present improved optical layout, a new detector system and a new calibration unit providing optimal performances in terms of simultaneous wavelength coverage and radial velocity accuracy (a few m/s). The total observing efficiency will be enhanced by a factor of 10 with respect to CRIRES. An innovative spectro-polarimetry mode will be also offered and a new metrology system will ensure very high system stability and repeatability. Fiinally, the CRIRES$^+$ project will also provide the community with a new data reduction software (DRS) package. CRIRES$^+$ is currently at the initial phase of its Preliminary Acceptance in Europe (PAE) and it will be commissioned early in 2019 at VLT. This work outlines the main results obtained during the initial phase of the full system test at ESO HQ Garching.

Keywords: CRIRES+, VLT, high resolution spectroscopy, echelle spectrograph, infrared instrumentation

1. INTRODUCTION

The CRIRES Upgrade project (CRIRES$^+$)[1] intends to transform CRIRES[2] into a cross-dispersed echelle spectrograph improving performance and observing efficiency. The instrument will dedicated to the search of super-Earths in the habitable zone of low-mass stars, the characterisation of transiting planets atmosphere and the study of the origin and evolution of stellar magnetic fields.

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The upgrade process has been obtained through some main fundamental steps:
1) The improvement of the optical layout by a new cross-dispersed echelle unit[3,4] . This allows the simultaneous wavelength coverage to be increased by a factor of 10 with respect to the old configuration.
2) The replacement of the Aladdin detector system with a new mosaic of three HAWAII 2RG detectors and NGC controllers. The new detector array enlarges the focal plane array in cross-dispersion direction by a factor of 2.7 which allows to accommodate the cross-dispersed spectral format.
3) New high precision wavelength calibration methods[5] . A new etalon system and gas cells will be used to calibrate the instrument and obtain precise (a few m/s) radial velocities.
4) The introduction of a spectro-polarimetry unit[6,7] . The spectro-polarimetry module consists of a rotating stage equipped with two circularly polarizing beam splitters and two linearly polarizing beam splitters. The 2 pairs are optimized for YJ and HK bands with the entire operation wavelength range between 0.95 μm and 2.5 μm.
5) A new metrology system will ensure very high system stability and repeatability. This will comprise a fibre feed with an arc lamp spectrum that illuminates the echelle grating, automated tools for the detection and identification of reference lines, the computation of correctional adjustment, and feedback to the grating mechanism and to a piezo actuator for fine tuning.
6) A realigned adaptive optics system (MACAO)[8] , fully refurbished in terms of electronics and software.
7) A new data reduction software package (DRS).

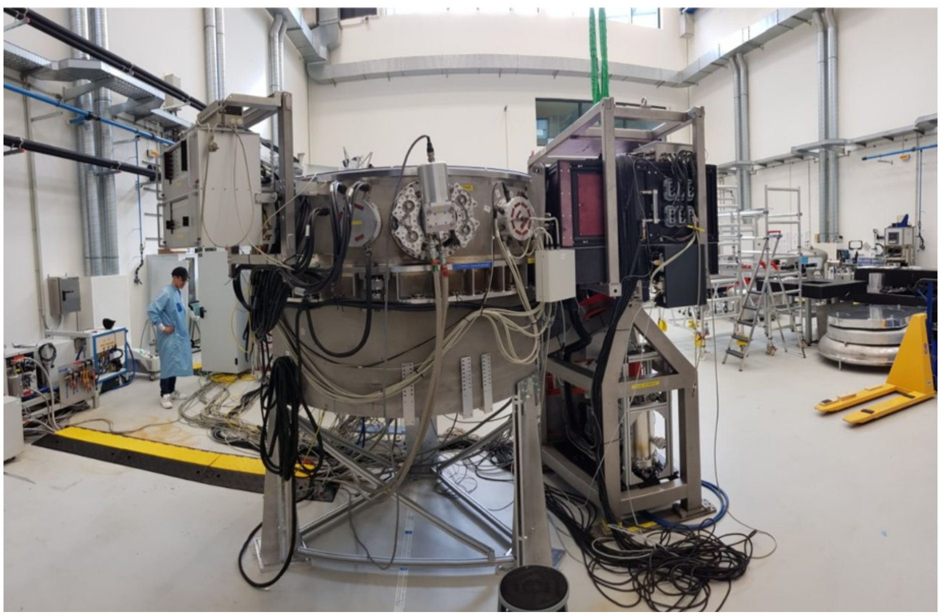

Figure 1. CRIRES$^+$ integrated in the laboratory at ESO Garching, Germany. On the right the warm optical bench is enclosed in a black cover. The cryogenic dewar is on the left side of the picture.

CRIRES$^+$ is based essentially on two main parts: the warm system and the cold system. The warm system comprises the calibration unit, the spectro-polarimetry unit, the de-rotator and the adaptive optics system MACAO. The warm optical bench (see Figure 1) is enclosed in a cover that protects the instrument from dome stray light during daylight calibrations. A constant flushing of dry nitrogen has been also introduced to reduce the contamination of the science spectra by water vapor spectral lines.
The cold system is based essentially on three sub-parts: The new slit unit with the Slit Viewer (SV) Detector, the new cross-disperser unit (CDU) and the final echelle unit with the Science Detectors. The slit unit is collocated just after the dichroic window which allows infrared light ($0.95\mu\text{m} < \lambda < 5.3\mu\text{m}$) to enter the cold dewar. The optical light is reflected and used for the adaptive optics system. Two slits engraved in a single slit plate are selectable: they corresponds to 0.4 and 0.2 arcsec and preserve the original CRIRES (oCRIRES

hereafter) spectral resolution of 50000 or 100000, respectively. The light reflected by the slit plate is used by the SV detector for target acquisition and support for the adaptive optics system.

The new CDU hosts a collimator mirror, order sorting filters to eliminate contamination by second- and

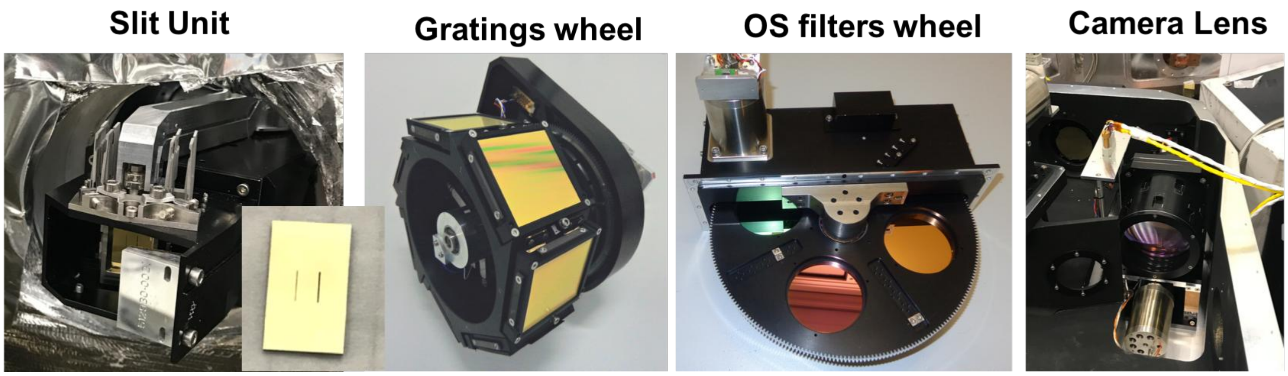

Figure 2. New optomechanic elements of CRIRES$^+$ cold part: slit unit with the slit plate, cross-disperser wheel with the gratings, order sorting filter wheel, camera lens.

third-order spectra, a tip-tilt jitter mirror and a cryogenic wheel with six reflection gratings that perform the cross-dispersion of the spectrum (see Figure 2). Each grating is optimized for operation in a single wavelength band (Y, J, H, K, L and M)[9] . Through a camera lens (CFU) the beam is refocused on an intermediate field stop. After the field stop the beam enters in the echelle unit that is identical to CRIRES except for the new detectors array (TMA mirror and echelle grating are unchanged with respect to the old configuration).

Right now the full system of CRIRES$^+$ is integrated at ESO HQ in Garching, Germany (see Figure 1) and the initial phase of the fully operating system test just started. The current status of CRIRES+ including a detailed view on its various sub-systems is presented in the parallel SPIE work Follert et al 2018.

2. SYSTEM PERFORMANCE TEST

CRIRES$^+$ is currently approaching the initial phase of its Preliminary Acceptance in Europe (PAE) scheduled in September 2018. An intensive campaign of instrument characterisation is ongoing at ESO HQ in Garching to test functionality and reliability of the different sub units and integrated system. The main results obtained during this phase are outlined in the following sections.

2.1 The Cold Part

All the mechanical functions, all the optics and the detectors have been integrated and the alignment has been refined[10] . With already five cool-downs done, spectra could be obtained in all the bands. A thermal problem with the slit unit was fixed to allow it working with the decker function for the spectro-polarimetry mode. Lots of progress has been made in the area of electronics and control software. A new power stage for a proper excitation of the inductosy transducers is being designed and also a new power stage for the echelle grating stepper motor has been procured and integrated which can drive the motor with the proper current, increasing the echelle performance in term of positioning accuracy. The development of the CRIRES$^+$ Instrument Control Software (ICS) to Multiple-ICS architecture has proceeded and the implementation of the cryogenic function is completed.
Finally, the cold instrument has been lifted on a temporary mechanical structure to have the same height as the warm part with the adaptive optics system. This was necessary for the merging of the two parts and the preparation for the full system testing phase.

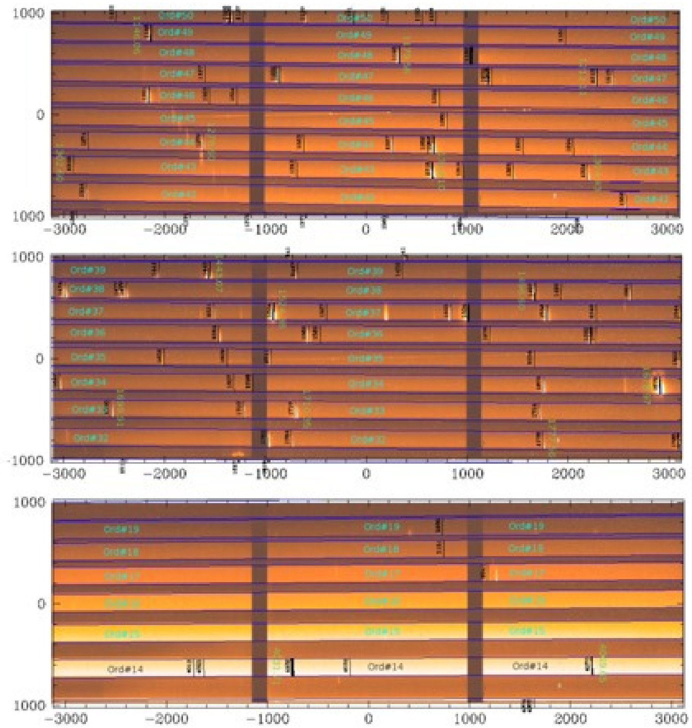

Figure 3. Sum of Krypton pen-ray and flat-field spectra (to show orders) in pixel units for J-Band (top), H-Band (center). Ambient light spectrum in L-Band (bottom). Logarithmic cut. Overlaid is the theoretical echellogram predicted by rays-tracing (black) and the wavelengths of selected lines (green).

2.1.1 First echelle spectra

Different pen-ray lamp and Flat Field spectra in all the wavelength bands (Y,J,H,K,L,M) were acquired during the fifth cool-down of the CRIRES$^+$ spectrometer (see Figure 3) in order to identify the different spectra orders and to derive the angles by which the cross-disperser gratings and the Science Detector needed to be rotated to center the echellograms in the cross-disperser direction. Table 1 shows a comparison between predicted and observed parameters of the echellograms.

Table 1. Comparison between predicted and observed parameters of the echellograms. The correction angle in column 6 corresponds to the amount that was added to the angle of the cross-disperser grating in the rays-tracing model to match the observed spectra.

Band	Predicated λ-range (nm)	Orders	Observed λ-range (nm)	Orders	CDG angle correction
Y	974 - 1134	50-59	983 - 1142	51-58	-0.15°
J	1134 -1350	42-51	1138 - 1358	42-51	-0.06°
H	1480 - 1810	31-38	1446 - 1782	32-39	+0.05°
K	1950 - 2530	23-29	1795 - 2300	25-31	+0.55°
L	2850 - 4200	14-20	2850 - 4200	14-20	no change
M	3580 - 5500	10-16	3800 - 5870	10-15	-0.30°

2.1.2 Echelle Stability and Repeatability

Figure 4a shows the relative dispersion offset of echellograms in a series of metrology (SMS) and entrance slit exposures covering ∼8hrs. Results from oCRIRES data are also reported for comparison. Data were obtained illuminating the entrance slit and the metrology fibers with a Kr pen-ray on a cadence of ∼30s, no movement of any functions between the exposures, echelle grating was set at a fix encoder step position. The cross-disperser wheel set to the J-band grating (locked), it was not moved during the measurements. Then the echelle grating was moved to a different position and a further series of exposures was obtained. The echelle grating was moved back to the original position and the cycle was repeated. Each frame was dark subtracted and then the *pyraf imcentroid** task was used with a list of prominent isolated spectral features to measure the global translation of the echellogram (no attempt to measure distortion was made). Figure 4b shows the relative offset in dispersion

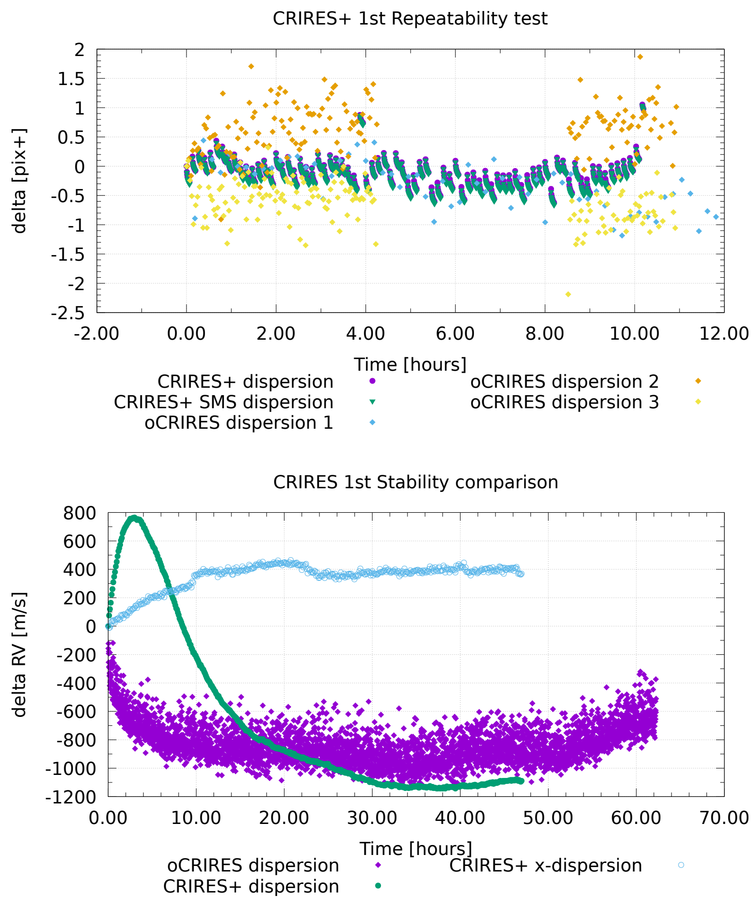

Figure 4. a) Top panel: Relative dispersion offset of echellograms in a series of metrology (SMS) and entrance slit exposures covering ∼8hrs. Results from oCRIRES data are also reported for comparison (brown and yellow points).
b) Bottom panel: Relative offset (in term of RV shift) in dispersion (green points) and cross-dispersion (blue points) direction of echellograms for a series of stability exposures covering ∼2 days.

and cross-dispersion direction (reported as RV shift in m/s) of echellograms for a series of stability exposures covering ∼2 days. For comparison oCRIRES values are reported in purple. Exposures are taken by metrology fibres illuminated with the Kr pen-ray on a cadence of 5mins and no movement of any other functions. The stability in the dispersion direction is not in spec for the first 24hrs, but it improves and it becomes within spec for the last 20hrs. However, a quick check of the temperature sensor log reveals that the values recorded by

*http://www.stsci.edu/institute/software_hardware/pyraf temperature sensors associated with the grating and its frame were varying by several tenths of a degree at the begin of the test before stabilising to better than 50mK. The stability in the cross-dispersion direction is within spec throughout, but it also improves towards the end of the measuring period.

2.1.3 Cryostat temperature control

The spectrograph is housed in a vacuum vessel, with its optics cooled to ∼65K and the detectors to ∼40K by 3 Closed Cycle Cooler cold heads. The first stage of the three heads is connected to the large main structure and to the radiation shield. The main components (TMA, grating unit and pre-disperser) are heat linked via the interface connection points and additional copper braids. The new CDU unit will also be thermally connected by two braids to the main structure. The instrument is stabilized in temperature using a series of heaters distributed on the main structure.

Three new Lakeshore units model 336 were installed on CRIRES$^+$:

Lakeshore 1: it drives 2 sensors, one monitoring the detector array (i.e. all 3 H2RGs) with feedback to heater and one used as spare.

Lakeshore 2: it drives one sensor with feedback to heater on the structure.

Lakeshore 3: channel A with feedback to heater on the structure, channel B to the echelle grating and channel C for the cross-disperser grating wheel.

The principle aim of the Lakeshore 3 is to control the temperature of the main cold structure within a control loop (no control of the CDU sub-structure). The improvement results in thermal stabilisation are shown in Figure 5. The main structure can reach a thermal stability better than 8mK.

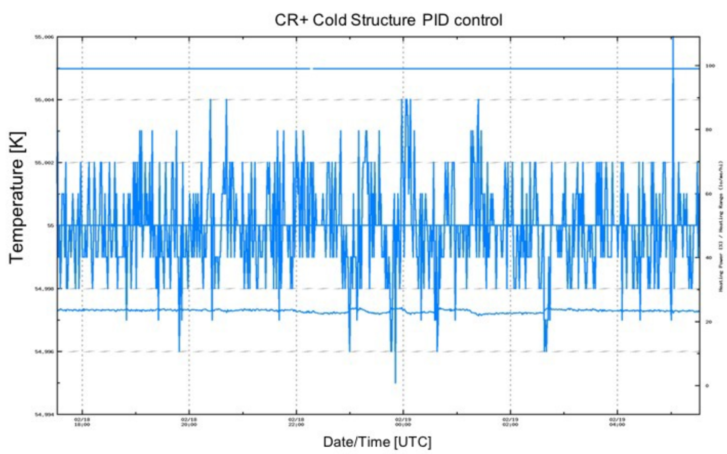

Figure 5. CRIRES$^+$ cold structure thermal stability. The main structure can reach a thermal stability better than 8mK.

2.1.4 Light Leak Investigations

Dedicated acquisition runs have pointed out the presence of a high level of background in the data frames (∼15.4±0.2e$^-$/sec on average) with visible patterns and structures (see Figure 6). A following detailed investigation revealed several light leaks at the level of the CDU unit and of the TMA structure. These leaks are now fixed and during cool-down six other background measurements will be repeated to verify the result.

2.2 The Warm Part

The integration of the warm part of the instrument including the AO system is completed. Final alignment and testing has been concluded. A significant work needed to be done on MACAO upgrade which was not planned for the CRIRES+ project (new APD counter board, new HVA boards, new I/O boards, Software upgrades). Currently, the MACAO calibrations are completed, and the remaining work is focused on higher level software activities and templates covering science (slit scanning especially), acquisition and technical health checks.

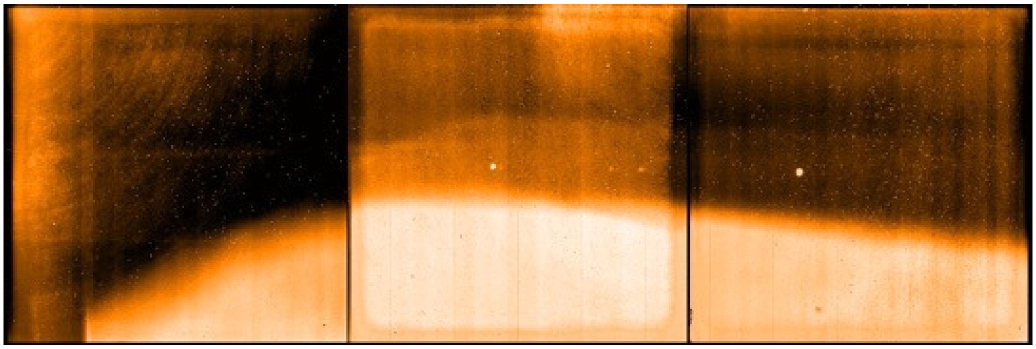

Figure 6. Instrument background measurement. The background level is not in specs and several structures are visible. A detailed investigation revealed several light leaks at the level of the CDU unit and of the TMA structure.

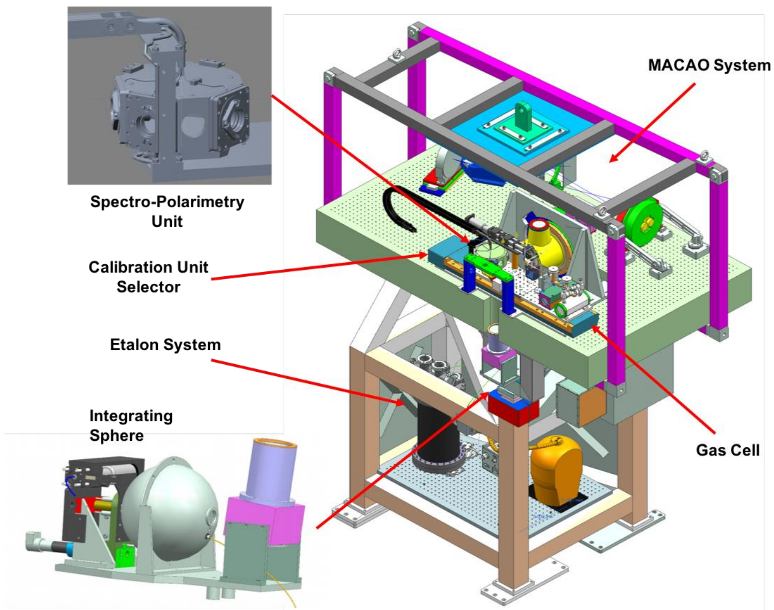

Figure 7. Warm part with all the sub-sytems.

2.2.1 Calibration Unit

The calibration unit and the associated subsystems like the gas cells and calibration lamps are integrated. Figure 8 shows a summary of all the calibration sources offered for CRIRES$^+$. The Fabry-Perot Etalon vacuum system has been tested and is comfortably in compliance with the subsystem requirements. Etalon laboratory measurements have shown excellent results providing RV stability of 1.3m/s and 3.3m/s over time scales of 30 hours and 60 hours respectively. The subsystem is completed and awaiting final PAE testing. For a more detailed description of this system and the relevant recent test we refer to Seemann et al. 2018.[11]

2.2.2 Spectro-Polarimetry Unit

The University of Uppsala re-installed the polarization unit including the YJ and HK-band polarization gratings (PGs) and the HK-band quarter wave plates (QWP) for the spectro-polarimetry unit. Test have been carried out which confirm the polarimeter works with MACAO in all band without the need of additional blocking filters. For a more detailed description of this system and the relevant recent test we refer to Piskunov et al. 2018.[12]

Type	Principal use	Location	Notes
(Atmospheric lines)	Wavelength calibration	Sky	L & M band where the lamps have few lines and continuum
Halogen lamp	Flat Fields	Integrating Sphere	Extended spectrum/black body, temperature: 3000-3100K
IR black body source	Flat Fields	Integrating Sphere	Extended spectrum/black body, temperature: 1100-1150K
Krypton pen-ray	Wavelength calibration, alignment	Integrating Sphere	Sparse spectral features
Ne pen-ray	Wavelength calibration	Integrating Sphere	Sparse spectral features
He-Ne Laser	Alignment, health checks on resolution	Feeds Int. Sphere	Dual wavelength 1.15258984μm and 3.392235μm. Coupled to an IR fiber that will transmit both lines that feeds the IS.
U/Ne HCL	Wavelength calibration	On carriage	Dense spectral features up to K-band. Illuminates the entrance slit uniformly.
Metrology fibre source (U/Ar HCL)	Metrology	Under warm optics table, near IS (location of and assembly of oCRIRES Th/Ar)	U/Ar HCL feeds a fibre that passes to the cryostat. Provides ≥2 isolated high S/N reference features in a narrow wavelength range.
New Gas-Cells	Wavelength calibration	On carriage	Custom mixture of Ammonia, Acetylene Methane-13. Uniform set of absorption lines in the range of CO band.
Fabry Perot Etalon	Wavelength calibration	Under warm optics table, Feeds IS	Frequent, regularly spaced, reference wavelength features with uniform dynamic range from Y- to K-band.

Figure 8. Summary of the calibration sources offered for CRIRES$^+$

3. CONCLUSIONS

CRIRES$^+$ will replace the VIMOS instrument on platform B of VLT Unit telescope UT3, full commissioning starting in January 2019. The installation of CRIRES$^+$ will occur in two phases: first, the warm part of the instrument will be installed, which includes the calibration unit and MACAO AO system; second, the cryogenic vessel or cold part, which houses the slit viewer system and the spectrograph, will be placed. The commissioning will also reflect this two phases procedure.

CRIRES$^+$ is currently approaching the initial phase of its Preliminary Acceptance in Europe (PAE) scheduled in September 2018. An intensive campaign of instrument characterisation is ongoing at ESO HQ in Garching to test functionality and reliability of the different sub units and integrated system.

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