CRIRES: Commissioning of the MACAO Adaptive Optics Module and General Status Report

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The installation and commissioning of CRIRES, the Cryogenic Infrared Echelle Spectrograph, marks the completion of the original plan for the first generation of VLT instrumentation. Here we report on the commissioning of the curvature sensing adaptive optics part (MACAO) of CRIRES in April 2006. This activity also brings the quasi-series production of the MACAO systems to an end. All four UTs are now equipped with one MACAO system each to feed interferometry while UT1 and UT4 have one additional dedicated system each integrated into instruments. A summary of the overall status of CRIRES is given as well.

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 µm at the Nasmyth focus A of the 8-m VLT Unit Telescope 1 (Antu). A curvature sensing adaptive optics system feed is used to minimise slit losses and to provide diffraction-limited spatial resolution along the slit. The nominal slit width of CRIRES is 0.2 arcsec.

A mosaic of four Aladdin III InSb-arrays packaged on custom-fabricated ceramics boards has been developed. This provides for an effective 4096 × 512 pixel focal plane array, to maximise the free spectral range covered in each exposure. Insertion of gas cells to measure high-precision radial velocities is foreseen. Spectro-polarimetry (circular and linear polarisation) will be added in the course of the project. To that end a cryogenic Wollaston prism in combination with retarders for magnetic Doppler imaging is foreseen. CRIRES is part of the initial first-generation instrumentation complement and is an in-house project done by ESO (for an in-depth description of CRIRES see e.g. Moorwood 2003 or Käufl et al. 2004). The CRIRES MACAO system carries series number 6 of the highly successful ESO curvature sensor AO systems which were originally developed for the interferometry feed of the VLT UTs, but were later also used for the VLT instruments SINFONI and CRIRES (see Arsenault et al. 2004, Bonnet et al. 2004 or Paufique et al. 2004; alternatively one can consult the ESO AO webpage *http://www.eso.org/projects/aot/* which contains detailed information).

In mid-2005 the assembly and integration activities of CRIRES had progressed such that the in-depth verification of the performance could be started. As the requirements on stability and reproducibility are relatively demanding this test phase resulted in requests for a variety of modifications which did not allow keeping the original schedule.

However, in February 2006 CRIRES ultimately passed the last fundamental milestone on its way to the VLT: the successful completion of an 'end-to-end' test of the system. Using a simulated cool star (black-body source and a gas cell with CO mimicking a COmosphere[1]) and a turbulence generator to generate 'seeing', the overall stability of the system, that is the Adaptive Optics System and the cryogenic spectrograph, was checked by recording spectra over many hours. The result of this test was that vibrations and other instabilities are generally at a level of the equivalent of 1/20th of a pixel (75 m/s Doppler shift equivalent) or less and thus in line with the specifications reflecting the astrophysical requirements.

How to move CRIRES from Garching to the VLT

Like any other VLT instrument, CRIRES had to pass the scrutiny of a review before shipment, termed PAE (Preliminary Acceptance Europe) in 'ESO-speak'. CRIRES consists of two relatively independent subunits: the adaptive optics part with the derotator, also carrying the calibration facilities and the cryostat with the cryogenic optical bench. Hence it was decided to split the PAE process in two, and to have the 'warm optics' part reviewed ahead of the rest of the instrument. This approach is also very much in line with the reintegration process at the VLT. The integration, alignment and testing of the AO part require special tools and a special test camera which in turn require a sequential integration at the telescope. The CRIRES warm-optics acceptance review took place at ESO on 24 February 2006, and thereafter packing and shipment of the units could start, subject to few additional checks. Packing of the 'warm optics' finally started on 28 February 2006 and the crates left ESO Headquarters on 8 March 2006. All boxes of this first batch arrived in good order on Paranal on 17 March and were met by a joint team of the ESO Instrumentation and Telescope Systems Divisions. Reintegration and installation of the components progressed rapidly with hardly any problem.

In the meantime, the CRIRES cold part underwent further improvements and testing in Garching. By the time of writing of this article the PAE for the complete instrument had been granted and the spectrograph arrived in good order on Paranal on 5 May. The commissioning of the complete instrument will be reported in the next issue of *The Messenger*.

Testing the adaptive optics at the telescope

The commissioning of the warm-optics part ran in parallel with the final preparation for the second part of the PAE. Thanks to the joint efforts of the team and of Paranal staff, the integration and realignment of the warm part in Paranal were successful: the MACAO system is now functional at full performance level.

Figure 1a shows the adaptive-optics part of CRIRES after reintegration. For test purposes an infrared test camera with a spatial sampling of 17 mas/pix (milli-arcseconds per pixel) was additionally installed to characterise the AO performance (to be compared with the diffraction limit: e.g. 1.2 λ/D = 45 mas at 1.45 µm). In fact, once CRIRES is installed with its infrared slit viewer, the sampling –

[1] COmosphere is a term coined by Tom Ayres to account for the very special chromospheres of cool stars dominated by the CO-molecule.

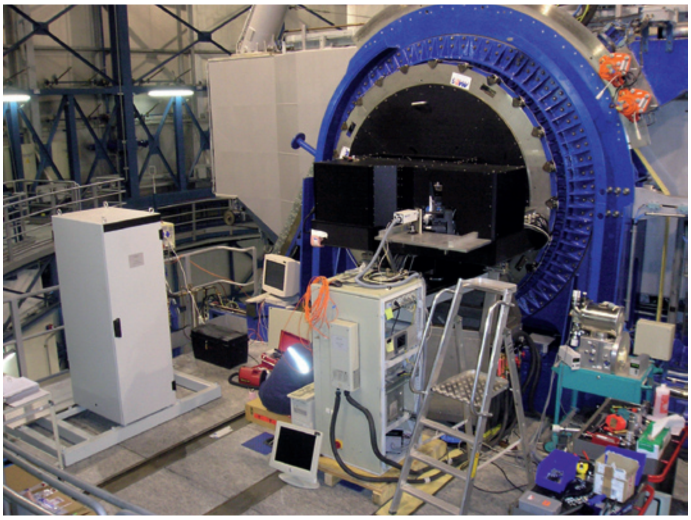

Figure 1a: A view of the CRIRES 'warm optics' nearly completely installed on the Nasmyth A platform of Antu (aka VLT UT1). The left electronics rack houses most of the entire AO related electronics, that is the real-time computer, the local control unit (LCU), the adaptive mirror control and the power supplies for all motors. Moreover the warm optics part comprises the calibration unit with continuum sources, spectral lamps and the gas-cell slide, which allows to port the 'Iodine-cell-method' for high-precision radial-velocity measurements into the infrared. The electronics rack in the centre is an auxiliary rack for the infrared test camera (which can be seen on the right side in preparation: the shiny cryostat cylinder on a blue table). At this point a normal CCD camera is still used for alignment. For the reflection in the centre, see Figure 1b.

Figure 1b: A team member, trying to sort out and reconnect the fibre bundle connecting the wave-front sensor lenslet array with the 60 avalanche photo diodes (APDs) contained in a special cabinet. The APDs are solid-state photon-counting detectors. As curvature wavefront sensing systems basically need only one fast photometric channel per sub-pupil, APDs were given preference over CCD-detectors, due to their extremely low noise level (typically 0.4 counts per loop cycle). APDs, however, are very sensitive and fragile devices, and the prevention of accidental (and catastrophic) overexposures is a key issue.

45 mas/pix – is no longer well suited to explore the AO-image quality (this camera scale was chosen to be able to explore a larger field for offset-guiding). Figure 1b shows part of the integration.

Figure 2 (next page) shows details inside the MACAO box. The commissioning culminated within a few minutes of twilight on 3 April to check the derotator algorithm. Official first light for the adaptive optics part with the infrared test camera was on 6 April when the AO control loop was closed at 23h24 UT on the 5th-magnitude B-star η Muscae. The following commissioning tasks could be finished so smoothly that the team gave back one night of commissioning time. The AO system characteristics are summarised in Table 1 and Figure 3 (next page) shows – as an example – an image of Io, the innermost Galilean moon of Jupiter with one of its active volcanoes showing up as a 'hot spot'[2]. The system has proven its stability by observing in all typical seeing conditions from 0.5 up to 1.5 arcsec. For bright stars with $m_R < 11$, Strehl ratios in *K*-band above 55 % are obtained for median seeing conditions (0.8″, τ_0 between 3 and 4 ms at 0.5 μm), at the level of performance of the other MACAO units.

Outlook

The commissioning of the complete system is ongoing and everything is prepared for first light on 4 June. A second commissioning run and potentially some science verification are planned for 4–13 August 2006. In mid-June there will be a first call for proposals for science verification programmes and at this point CRIRES will most likely be included in the next call for proposals (P79). More science verification is planned for P78 (1 October 2006 to 31 March 2007) and potentially also an early start of operations of CRIRES for normal programmes selected by ESO's OPC through the normal selection process.

[2] The first author remembers that during the time of his thesis project 20 years ago, 1 arcsec image quality on a 2–4-m-class telescope was considered 'excellent' and 2 arcsec was certainly average quality. Against this background, the images shown here constitute an amazing achievement of technology.

References

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Bonnet H. et al. 2004, SPIE proc. 5490, 130
Käufl H. U. et al. 2004, SPIE proc. 5492, 1218
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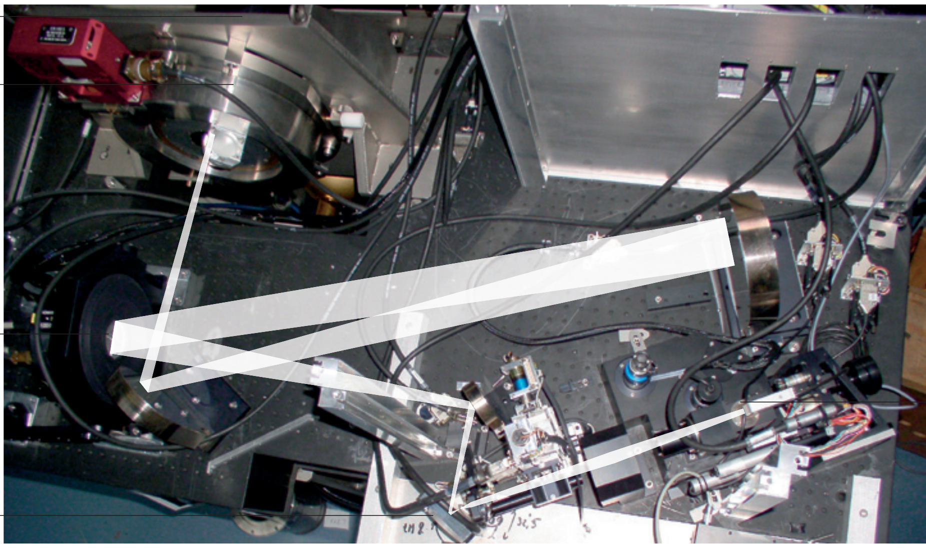

Figure 2: A close view of the optical path with the protective cover removed. The mirror labelled 'Dichroic' will be replaced at some point in late June by the CRIRES Cryostat Entrance Window. The dichroic shown here on a provisional mount will then become part of the CRIRES vacuum vessel. This mirror separates the light path at a transition wavelength of ~ 950 nm. This limits a bit the overlap with the corresponding optical spectrograph (UVES). 'DM + TTM' stands for deformable mirror in fast tip-tilt mount. It should be noted that the complete AO wavefront correction comes at the expense of only four extra reflections. The optical derotator is based on the one used in the VLT UV and Visible Echelle Spectrograph (UVES).

Table 1: Performance of the system; 'good seeing' was when the seeing was below 0.78″, while the 'bad seeing' was above 0.73″ (DIMM measurements). The Strehl values and ensquared energy indicated are for *K*-band, taking into account the aberrations introduced by the infrared test camera (82 %), and are therefore pessimistic. For a guidestar magnitude of R = 17.4 the value given for the Strehl ratio is only indicative: it is so low, that the concept of Strehl ratio starts loosing its meaning.

	R = 10	R = 13.5	R = 15	R = 17.4
Ensquared energy, good seeing	63 %	58 %	–	–
Ensquared energy, bad seeing	56 %	50 %	43 %	30 %
Best Strehl achieved	61 %	47 %	25 %	(6 %)

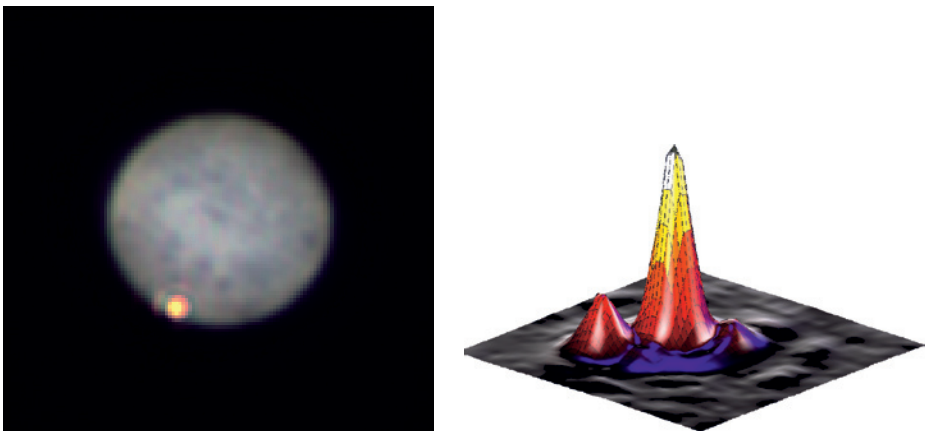

Figure 3: Left: A composite *JHK* false colour image of the Jovian Satellite Io. Io measures 3600 km and was at a distance of 4.45 AU. A volcanic eruption is visible, so bright that its airy pattern appears above the planet's background. The apparent diameter of the disc is 1.1 arcsec. On the right a 3D-image in *K*-band of the binary star HD 105196 ($m_V = 8.3/\Delta m_K = 1.3$) having a separation of 85 milliarcsec.