CRIRES Takes Shape

THE CRYOGENIC INFRARED ECHELLE SPECTROGRAPH BEING DEVELOPED BY ESO WILL PROVIDE A TOTALLY NEW CAPABILITY FOR HIGH RESOLUTION ($R \sim 10^5$) INFRARED SPECTROSCOPY BETWEEN 1 AND 5 μm AND OPEN UP ENTIRELY NEW FIELDS OF RESEARCH WITH THE VLT STARTING IN 2005.

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THE CRYOGENIC INFRARED ECHELLE Spectrograph (CRIRES) has had a relatively long gestation. It was included in the Call for First Generation VLT Instruments in 1989 as one of several options which were then discussed at the Workshop on High Resolution Spectroscopy with the VLT held at ESO in 1992 (High Resolution Spectroscopy with the VLT, ESO Conference and Workshop Proceedings No. 40, ed. M.-H. Ulrich). At that time there was still a lively ongoing debate about the relative merits of Fourier and dispersive spectrographs for high resolution infrared spectroscopy. Pierre Connes had pioneered the use of the former for very high resolution planetary spectroscopy already in the 1960s, when infrared arrays had only 1 pixel and dispersive instruments could not compete with the multiplex advantage of Fourier spectrometers. By 1992, however, low noise infrared array detectors were already available to infrared astronomers although still with rather small formats for echelle spectroscopy. Nevertheless there was clearly a consensus at the Workshop to include such a cryogenic echelle spectrograph in the instrument complement of the VLT. For various reasons (like finishing the VLT and its 1st complement of instruments), the real start of CRIRES was delayed for several years but since its real start in 1999 the progress has been rather rapid with PDR in April 2000, FDR in Oct. 2001 and start of the integration phase in Garching in 2002.

The characteristics of CRIRES are summarized in Table 1. Of particular interest are the fact that the detector mosaic actually being used now has over 4000 pixels in the dispersion direction (compared with around 64 proposed in 1992) and the use of adaptive optics to both minimize slit losses and improve the spatial resolution along the slit.

Table 1. CRIRES Main Characteristics

- Resolving power of ~10^5 from 1 to 5 μm
- Adaptive optics feed to maximize SNR and spatial resolution
- Echelle grating and prism pre-disperser
- Polarimetry with Fresnel rhomb retarder and Wollaston Prism
- Pixel size ~ 0.1″
- 0.2″ × 50″ slit
- 4096 × 1024 InSb array mosaic
- Slit viewing camera with 1024 × 1024 InSb array (0.05″ pixels)
- Calibration unit including absorption cells for accurate radial velocity measurements (< 50 m/s)
- Limiting magnitudes ~17 (*J*) to 11(*M*) in 1 hr

Science Objectives

The 1–5 μm region is rich in both atomic and molecular spectral features which offer unique probes of the chemical and physical conditions in a wide range of astrophysical environments. Table 2 summarizes some of the areas expected to be of high interest for observations with CRIRES. Most of these objectives require not only the wavelength coverage but also the high spectral resolution corresponding to a few km/s (e.g. for studying the kinematics of the cold ISM and for stellar abundance determinations) and with radial velocity precision better than 50 m/s (e.g. for radial velocity searches for exoplanets around cool low mass stars). Stellar magnetic field measurements are also of particular interest due to the existence of some particularly favourable infrared lines whose magnetic Zeeman splitting will be easier to measure than the visible lines currently used.

Testimony to the growing interest in high resolution infrared spectroscopy is the 4 day Workshop devoted to High Resolution Infrared Spectroscopy which took place in Garching from 18–21 Nov. 2003. There were about 130 attendees and a packed programme covering all of these topics as described in the summary which also appears in this issue (see page 52).

Table 2: Science Areas

- Planetary Atmospheres
- Exoplanets
  - Radial velocity reflex motion searches (cool and dust embedded stars)
  - Direct detection of planetary atmosphere spectral features
- Stars (atomic and molecular transitions, SiO, CO, CN, OH)
  - Abundances, COmospheres, winds, pulsations
  - Magnetic fields (Zeeman Doppler imaging)
  - Discs and their velocity fields
  - YSO inflows/outflows
- Interstellar Medium (ISM) - Milky Way and nearby galaxies
  - Chemistry and kinematics - $CO, CH_4, H_2O, OH, H_3^+$
  - Line of sight to YSOs
- Extragalactic
  - Nuclear kinematics
  - Intergalactic absorption studies

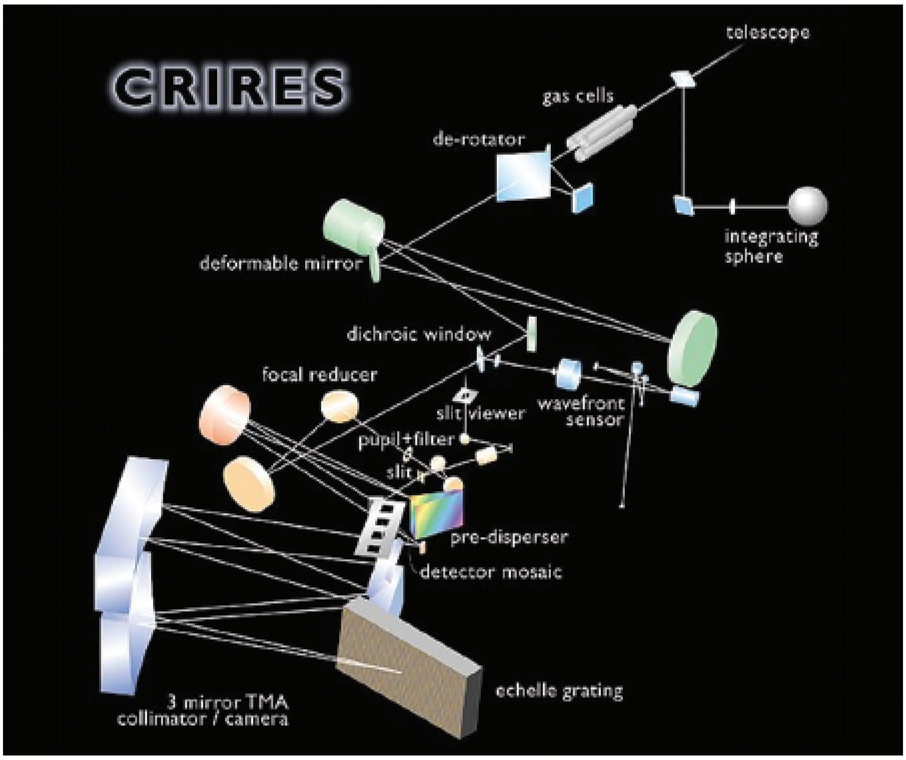

Figure 1: Optical layout of CRIRES. Light entering from the Nasmyth focus or the calibration unit passes through the de-rotator and adaptive optics system before entering the cryogenically cooled spectrograph via a dichroic window. Visible light reflected from this window is directed to the AO wavefront sensor. The cryogenically cooled optics comprises a pupil re-imaging system and Wollaston prism; the pre-disperser prism and the high resolution echelle spectrometer. The final spectrum is imaged on a 4096 × 1024 pixel mosaic of InSb detectors.

Instrument Design

Optical Layout

Figure 1 shows the optical layout of CRIRES. Light enters from the direction of the Nasmyth focus, either from the telescope or 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 gas cells which can be inserted in the beam as shown. The gas cell slide will also contain a specially designed ZnSe Fresnel rhomb whose insertion can be combined with that of a MgF_2 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. It features a 64 element deformable mirror mounted on a tip-tilt stage and on which is formed a pupil image by the two mirror relay optics. The dichroic window then transmits infrared light to the cryogenically cooled spectrograph while reflecting visible light to the wavefront sensor (WFS) which uses an optical CCD detector and can be translated in x,y at ~0.5 Hz to maintain object centring 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 developed by ESO for VLTI (Arsenault et al., *The Messenger*, 112, 7). The spectrograph is housed in a vacuum vessel and with its optics cooled to ~ 65 K and the detectors to ~ 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 40×20 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 as the camera to image the spectrum on the 4096 × 1024 pixel array detector.

Cryomechanical System

Figure 2 shows how CRIRES is expected to look when mounted at one of the VLT Nasmyth focii. The main elements are the cryogenically cooled spectrograph in its grey vacuum vessel; the table mounted pre-optics (calibration unit, field de-rotator, adaptive optics system coloured green) and the electronics racks (detector electronics in red and control electronics in yellow). The instrument is mounted stationary on the platform primarily to

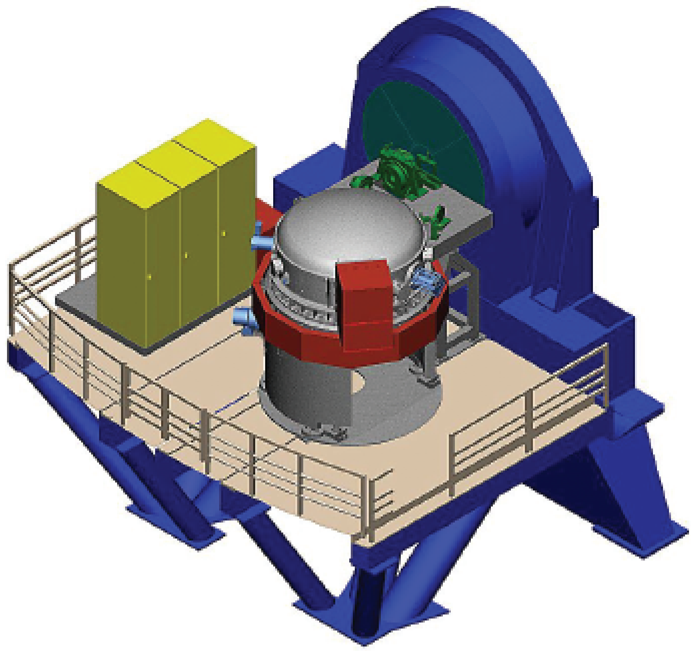

Figure 2: CRIRES installed at a Nasmyth focus. Shown in green are the de-rotator and part of the adaptive optics sytem installed on an optical table between the Nasmyth focus and the spectrograph. The spectrograph is cryogenically cooled and housed in the grey vacuum vessel. One of the closed cycle coolers plus the turbomolecular and backing pumps are coloured blue. The red boxes contain the front-end IRACE detector electronics and the yellow cabinets the control electronics for the complete instrument.

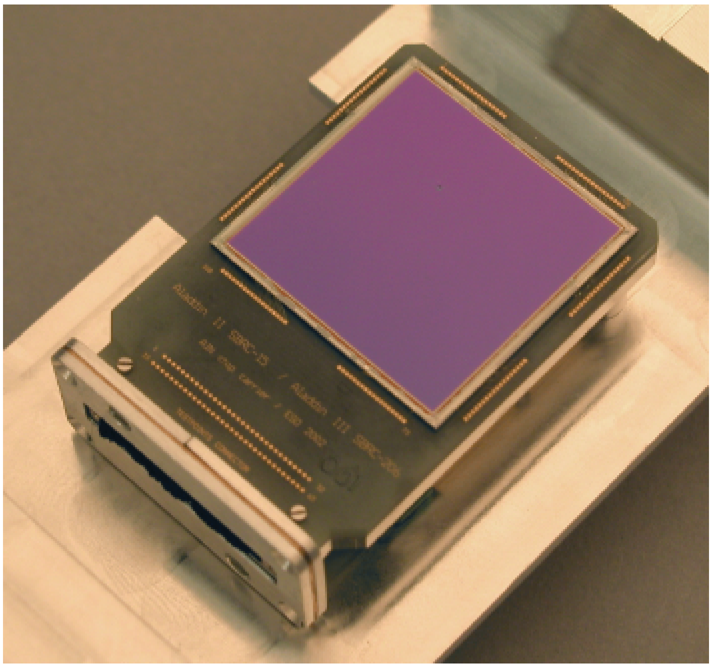

Figure 3: One of the Aladdin III 1024×1024 InSb arrays mounted on an ESO designed ceramic board.

ensure achievement of the 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 and inclusion of a warm shield. Attached to the vessel can be seen the cold head of one of the two Leybold closed cycle coolers, the instrument mounted turbomolecular pump, connector flanges, pressure gauges and the overpressure safety valve. 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 (~30 µm) nickel coating on the reflective surface which has been 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 used for order sorting.

Cryogenic mechanisms are required for scanning the prism (2 deg.) and echelle grating (12 deg.), the two slits plus the slit viewer filter and Wollaston wheels. The scanning functions will be driven by Phytron cryogenic stepper motors and high precision screws and equipped with high precision encoders.

The total mass cooled to cryogenic temperatures is around 550 kg. Based on our experience with ISAAC we are confident that this can be cooled down to ~65 K in 30 hours 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 0.1 K and limit any variations of temperature gradients to < 50 mK/m/hr. As CRIRES is stationary, has a high thermal inertia due to its large cryogenic mass and is rather uniformly cooled by the attachment 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 ~0.1 K 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

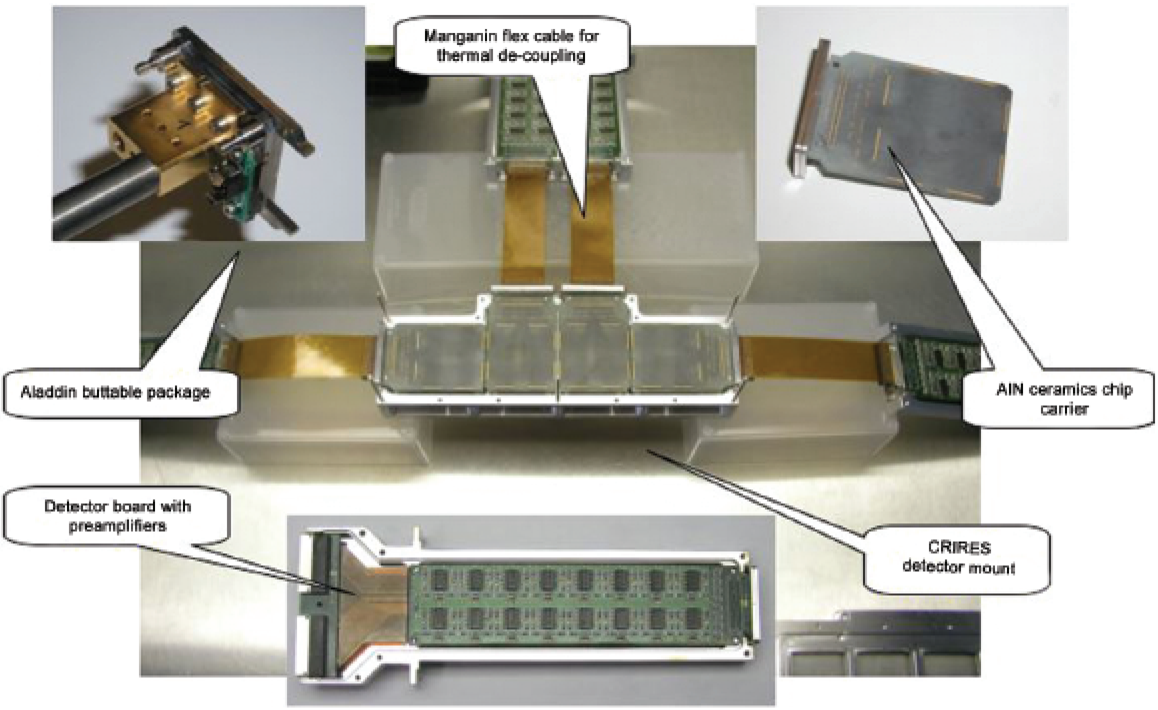

Figure 4: Detector mosaic. Each of the four array detectors is glued to a ceramic carrier of the type shown on the upper right and then mounted on the unit shown at the upper left which comprises a kinematic mount, a copper block for cooling and a temperature sensor. They are each connected to the acquisition electronics via 64 cryogenic preamplifiers and manganin flat band cables and mosaiced together as shown in the centre.

spectral lines for programmes requiring the highest spectral stability.

In order to meet the stringent thermal and straylight requirements the entire optical system is enclosed within a light shield plus an aluminium alloy radiation shield 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.

Detector Mosaic

CRIRES uses 5 Raytheon 1024 × 1024 pixel InSb Aladdin arrays, one for the slit viewer and 4 in the spectrograph focal plane which provides a useful optical field of 135 × 21mm. Three of the arrays are Aladdin IIIs procured specifically for CRIRES while the fourth is a rather old Aladdin II, from the first best effort batch made for ESO which yielded the ISAAC and CONICA arrays, and which had a number of cracks but exceptionally low dark current (< 0.001 e^-/s). These arrays have now been re-packaged to be 3 side buttable so that they can be packed in a 4×1 format with a spacing between arrays of only 264 pixels. To do this, each array was removed from its original LCC package by Raytheon and glued onto the specially designed ESO mount consisting of a multilayer, co-fired, AIN (aluminium nitride) ceramic carrier, as shown in Fig. 3, and then glued to an adjustable invar base plate. These are then mounted to form the mosaic as shown in Fig. 4. The upper left 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 and a temperature sensor. 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. As the slit is only 512 pixels long we do not require 4 useable quadrants per array and have thus saved money by buying ‘reject’ arrays with one or more defect quadrants. The re-packaging has recently been completed and the first array is now under test at ESO. Unfortunately, the old Aladdin II, which has a thinner substrate than the Aladdin IIIs, was broken during the re-packaging process and it remains to be seen if the required two quadrants are still operational.

The arrays will be read-out using a standard ESO IRACE controller having 128 channels (4×32) for the science arrays and 1×32 channels for the slit viewing camera.

Optomechanics Manufacture and Integration

Most of the CRIRES hardware has now been manufactured and integration has already started in Garching. Fig. 5 shows the vacuum vessel and its support structure on the right and the light shield on the left in the now very crowded assembly hall in Garching where also SINFONI, OmegaCam and various other systems are being integrated. The vacuum vessel partially visible on the far left is the old IRSPEC one which has been converted since retirement into a a cryogenic test

Figure 5: CRIRES vacuum vessel on the right and light shield to the left in the Garching assembly hall.

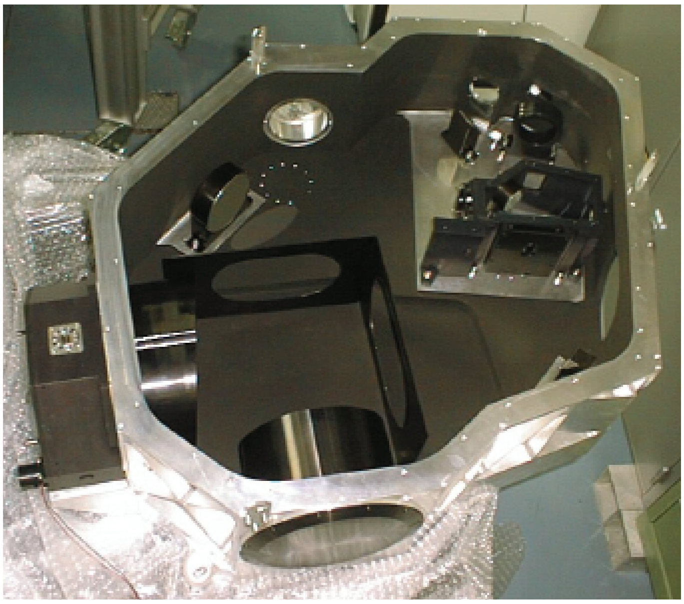

Figure 6: Partially assembled cryogenic pre-slit assembly.

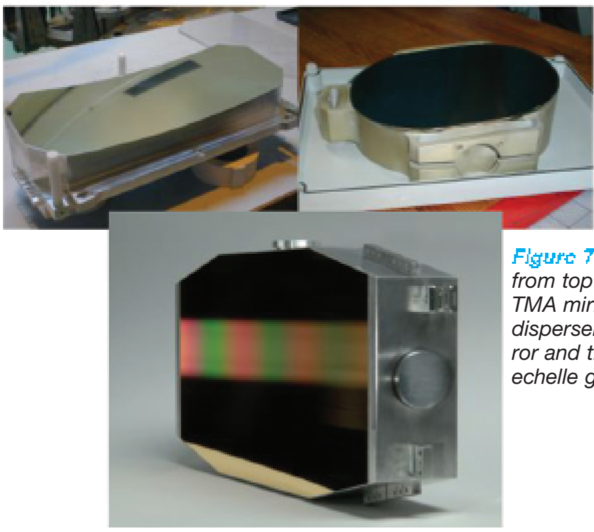

Figure 7: Clockwise from top left - one of the TMA mirrors, the pre-disperser collimator mirror and the 40×20cm echelle grating.

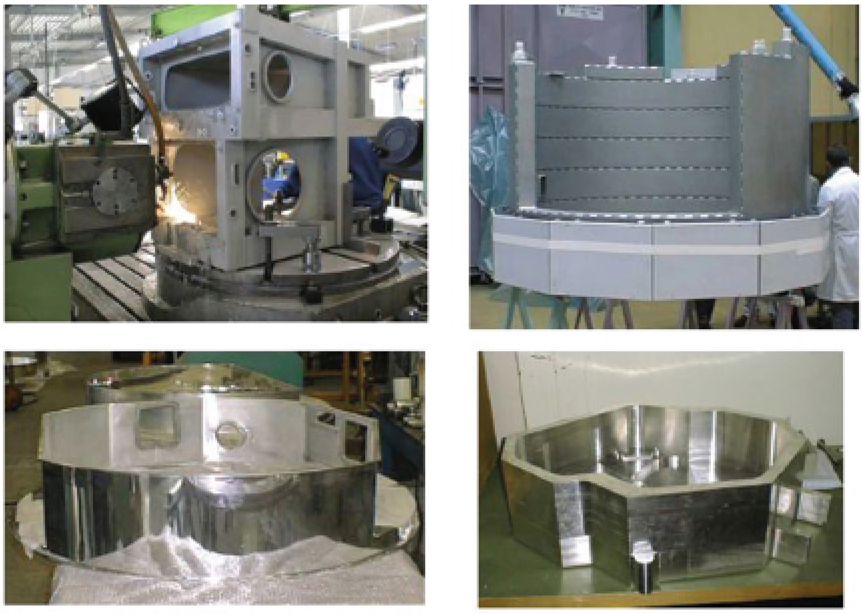

Figure 8: Clockwise from top left - the TMA support structure, instrument support structure, radiation shield and pre-slit optics housing during manufacturing.

facility used to qualify many of the ISAAC, SOFI and now CRIRES functions before integration. Figures 6 – 8 show various other optical and mechanical parts as described in the captions. In principle, everything could now go ahead full steam – were it not for those other instruments just mentioned plus a few other activities which are currently overloading our integration laboratory. To be fair however, some of items shown were also delivered late and we are still awaiting delivery from Sagem of the TMA mirrors which have just been accepted at their premises in France.

Electronics and Software

The electronics and software for controlling both the CRIRES spectrometer and the AO system are proceeding well. Motors are being driven and their control parameters fine tuned. The Observing Software and Real Time Displays are being finalized. The IRACE detector acquisition electronics and software are being used for the detector tests. On the Science Operations side, the instrument observing modes have also been defined, the corresponding observing templates are being coded and first thoughts are being given to the pipeline.

CRIRES on sky?

Unless anything goes seriously wrong with CRIRES or one of those other projects competing for the same manpower we expect to see 1st light on the VLT in the first quarter of 2005. Watch this space.

Addendum to "The History and Development of the ESO Active Optics System" (*The ESO Messenger* No.113)

R.N. Wilson

Following my article, I received a most interesting e-mail from my ex-colleague of ESO and good friend, Daniel Enard. He was concerned about the precise chronology of the development of the ESO Shack-Hartmann image analyser – see the second section of my article. Enard pointed out that *he* and I first visited Roland Shack together in February 1976, *before* the 3.6 m telescope was set up some months later. Already before then I knew of the Shack proposal as I had been receiving the "Optical Sciences Center Newsletter", in which it was first published in 1971 (see Ref. W99 in my article). This was why we visited Shack to learn more about it. Shack complained bitterly of lack of interest in the American community and was encouraged by our deep and practical interest.

In further discussions with Francis Franza, we have now concluded that he and I visited Shack again in 1977 (not in 1979 as I wrote in my article) and it was then that Shack gave me the lenslet raster. This was the difficult element: otherwise the construction of the S-H image analyser was quite straightforward. It was with this original raster, made on a lathe by Shack, that ANTARES I was built in 1978 (see W99, Fig. 2.24) for testing *off-line* ESO telescopes on La Silla. The S-H plates were measured on the PDS measuring machine at ESO Garching. We believe that this was the first Shack-Hartmann image analyser actually built and used for testing telescopes. In view of its importance today in so many active and adaptive optics applications, we see this now as an important step forward in the necessary technology.

Franza and I investigated a number of possibilities of producing S-H rasters mechanically with a German firm, but the firm went bankrupt before any results came out. The breakthrough in this procurement problem came when I gave a talk in Graz about Active Optics in 1981 and Franza saw a poster presentation of a *laser etching* technique presented by the RCA Laboratories in Zurich, later renamed the Paul Scherrer Institute (see W99). Two successful negative masters were afterwards made to an ESO contract and replicas were made for the final raster screens by Jobin-Yvon in Paris. This was the source of all successful screens used for the further experiments in ESO and for the NTT. The masters for the VLT were also made by the Paul Scherrer Institute, which also supplied the replicas.

Shack's original mechanical method of raster manufacture is now probably only of historical interest, but it nevertheless showed his genius. He produced rows of cylindrical lenses by stepping on the lathe and fine grinding and polishing with a concave cylindrical rod. Then he turned the raster through 90° and produced cross-cylindrical lenses. He had proved theoretically that the difference between these cross-cylindrical lenses and true axially symmetrical lenses was well below the diffraction limit for such extremely weak lenses with 1 mm square aperture and 80 mm focal length.

My thanks are due to Daniel Enard and Francis Franza for further clarifying this historical development, which was of fundamental importance for both the NTT and the VLT.