The Return of the Mid-infrared to the VLT: News from the VISIR Upgrade

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The VLT mid-infrared imager and spectrometer VISIR returns to science operations following an extended upgrade period. Among the most important modifications are: the imaging and spectroscopic detectors have been replaced with larger AQUARIUS (1024 by 1024 pixel) detector arrays; the *N*-band low-resolution grating has been exchanged; and support is now provided for precipitable water vapour monitoring, in order to select the best observing conditions. The AQUARIUS detectors stem from a development for very low background applications which result in excess noise under ground-based conditions. A series of interventions was needed to find a scheme that effectively exploits these detectors for ground-based use, involving the implementation of faster chopping. VISIR has been returned to service at the VLT with enhanced capabilities.

Introduction

The VLT Imager and Spectrometer for mid InfraRed (VISIR) is a combined imager and echelle spectrograph, providing access to the atmospheric *N*-band (7.7–13.3 μm) and *Q*-band (16–24μm) with a great variety of observing modes[1]. VISIR was originally built for ESO by the Service d'Astrophysique of the Commissariat à l'énergie atomique (CEA), Saclay, France, together with ASTRON, Netherlands Institute for Radio Astronomy in Dwingeloo. The instrument arrived at the Very Large Telescope (VLT) in 2004 (Lagage et al., 2004). VISIR was commissioned with small format detectors with less than excellent cosmetic quality and a low-resolution spectroscopy mode, which was not well matched to the science requirements.

Taking advantage of a detector development for the James Webb Space Telescope (JWST), new detectors (AQUARIUS) could be procured and were retrofitted in an upgrade intervention starting in mid-May 2012. The upgrade also included the integration of a water vapour radiometer, the Low Humidity And Temperature PROfiling microwave radiometer (LHATPRO) manufactured by Radiometer Physics GmbH (RPG), a new low spectral resolution prism mode and various means to enhance high-contrast and high spatial resolution imaging. Since late 2011, following a careful cross-calibration campaign, the radiometer is in full operation (Kerber et al., 2012). A first attempt to re-commission an optically and mechanically perfect VISIR in August 2012 was not successful, due to noise problems with the detector, which had not been diagnosed in laboratory testing. In August 2013 the path back to the telescope was finally established, which required enhancements to the Unit Telescopes (UTs) to allow for chopping at the original design frequency.

The status of the "new" VISIR after the second commissioning run in January 2015 is reported.

Scope of the upgrade

The main elements of the upgrade entailed:

- Change of both imager and spectrograph detectors from a 256 × 256 pixel device with 50 μm pixel pitch to the new AQUARIUS device (see Ives et al. [2014] for details). The AQUARIUS detectors have an area of 1024 × 1024 pixels and 30 μm pitch, so that the entire focal plane of ~ 25 mm by 25 mm, for which the VISIR optics had been designed, can be used. Since the new detectors dissipate typically an order of magnitude more power than the old ones below 10 K, an enhancement of the cooling harness was also required.
- Change of all detector cabling in the cryostat to connect the 2 × 64 detector outputs for signal frequencies up to ~ 10 MHz and addition of cold pre-amplifiers, just outside the spectrometer structure, to reduce cable lengths, minimising detector artefacts and spurious signals.
- Integration of the detectors into the new ESO standard acquisition system, the new detector controller (NGC).
- Exchange of the *N*-band low-resolution grating in the VISIR low–medium-resolution spectral arm with a new prism manufactured from zinc selenide (ZnSe; Figure 1).
- Enhancement of the high-contrast imaging capabilities of VISIR by adding coronagraphy and aperture masking (sparse aperture masking [SAM]) capabilities; the lead on this part was taken by CEA, Saclay.
- Improvement of the image quality. VISIR depends on receiving images without aberration from the VLT (without adaptive optics) and the diffraction limit of the VLT at 10 μm is ~ 0.3 arcseconds. Observing with a frame rate as high as ~ 100 Hz showed that image distortions appear and disappear; the high rate of these changes rules out an atmospheric origin and suggested image quality problems within the VLT itself.
- Providing the means to measure atmospheric water vapour (precipitable water vapour [PWV]) along the line of sight. For certain operational modes, e.g., imaging in the *Q*-band (~ 20 μm), PWV is as important for good performance in the infrared as the seeing is for high-definition imaging; PWV has been introduced as a constraint parameter for service mode. PWV can be very low on Paranal, resulting in excellent atmospheric transmission (Kerber et al., 2014a).

- Substantial modifications to operating software to ensure standard data flow from Phase 2 proposal specification through to the science archive.

Spectro-polarimetry in combination with the new prism mode, although originally planned and reviewed, was, in the end, not implemented. Optomechanical problems mounting the Wollaston prism in the spectrograph fore-optics introduced a high risk to the schedule for the intervention and its success.

The upgrade was led by ESO-Garching in close collaboration with the Paranal Observatory and CEA provided the concept and optics for the new high-definition imaging modes. ASTRON also supported with expertise and some spare parts.

First intervention, 2012

To minimise downtime, an intervention of four months was planned, starting in May 2012. After a final check on-sky of the old configuration (close-out calibration), VISIR was moved to the instrument integration hall laboratory where the old detectors were checked and then the instrument was disassembled into its basic sub-units. The low and medium spectral resolution unit (carousel, Figure 2) was removed. After a complete disassambly of this very complex and delicate unit, a pocket was milled into the aluminum base part to create the space for the prism mount. After re-assembly and re-alignment of the spectrograph optics with the optical proxy, the prism was pre-aligned with a HeNe laser. The spectrograph detector mount and the imager detector mount were both modified to take the new AQUARIUS arrays. Some improvements to the baffling and the stray-light rejection of the imager for the larger optical field, accessible with the larger detector, were also made. Finally the aperture wheel was modified for the coronagraphic optics, and special filters and pupil masks were added to the imager filter wheel for coronagraphy and high-contrast imaging.

Alignment and testing of the re-assembled units was initially performed using optical light at room temperature with the bare detector multiplexer, thus avoiding the need to close and cool down the instrument. The tests were very successful, so that the “new” VISIR was integrated, evacuated and cooled down for the first time early in July 2012. The first infrared-light test in the laboratory indicated almost perfect optical quality, while the prism spectrum was also found to be well centred. Further tests showed perfect cosmetic quality and no signs of noise problems, so that by the end of July 2012 VISIR was ready, as planned, for re-commissioning on Unit Telescope 3 (UT3).

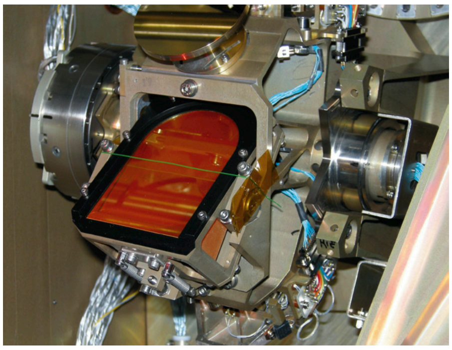

Figure 1. Close-up view of the new ZnSe prism. The prism was designed to disperse the 10 μm window over ~ 900 pixels with a pupil size of approximately 50 mm. The green wire was used during alignment to mark the centre of the pupil.

Re-commissioning, first attempt

The first night of re-commissioning began with the basic optical tests: the VISIR optical quality and the cosmetics of the detectors appeared to be quite impressive. However on the second night it became apparent that VISIR was substantially less sensitive in comparison to the situation before the upgrade. Moreover, it appeared that the conversion gain of the detector in the spectrograph was approximately three times higher than in the imager. After three more nights of testing the detectors, optics, software, etc., VISIR was dismounted from the telescope and brought back to the integration laboratory, in order to investigate this (quite confusing) situation further.

After lengthy investigations, which excluded optical problems with VISIR, it was ascertained that the detector material, developed for the low-background location of JWST operating at the Lagrange point, L2, was optimised for extremely low dark currents. This introduced an excess low-frequency noise (ELFN) in the high-flux applications relevant to ground-based astronomy. This phenomenon was described 30 years ago by Stapelbroek et al. (1984). The ELFN is a form of correlated noise caused by fluctuations in the space charge induced by ionisation/recombination in the blocking layer. It manifests as a memory of photons in subsequent frames.
It appears that this effect was not properly accounted for in the design of the Si:As detector material hybridised on the AQUARIUS multiplexer for the ESO detectors (see Ives et al. [2014] and references therein). Careful analysis of the spectral energy distribution of the detector noise indicated that the ELFN can be filtered out, if the chopper frequency is increased from fractions of a Hertz to the original specification of the VLT secondary mirror (M2) of 4–5 Hz.

Figure 2. Close look at the VISIR low- and medium-resolution assembly. The unit in the lower left is the carousel, a precision rotary stage used to scan the gratings. At the top right is an optical bench with a CMOS camera rigged as proxy for the infrared optical axis. Slightly above the carousel the mount of the special prism can be seen, which compensates the alignment for the change in refractive index between the HeNe laser and the desired central wavelength (10.5 μm) and the thermal shift between room temperature and the operating temperature of VISIR (~ 28 K).

In addition it was also found that the detector material in the spectrograph stemmed from a different batch to the one of the imager, and under nominal bias there was avalanche gain in the spectrograph, mimicking a higher conversion gain, which, in turn, manifested as an optical problem with the imager. The energy to create a charge in a photoconductor sensitive to 28 μm is of order of 1/25 eV, so a typical detector bias of

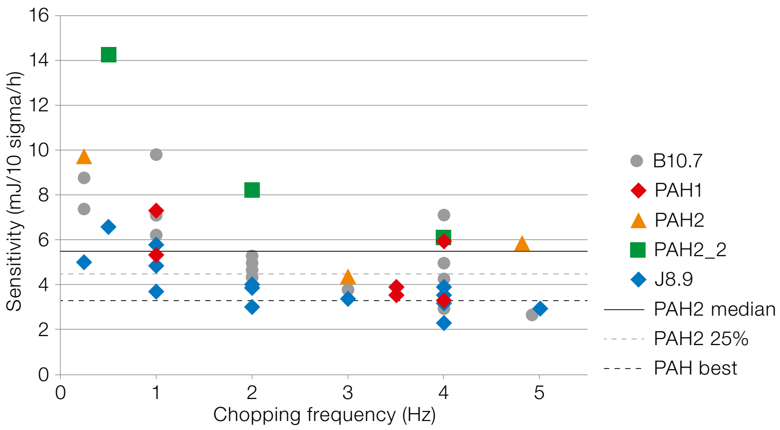

Figure 3. The on-sky sensitivity performance of VISIR is shown as a function of the M2 chopping frequency. The horizontal black lines give the performance of the "old" VISIR at the nominal chopping frequency (~ 0.25 Hz): the best-ever value, the 25th percentile and the median. The various symbols denote measurements taken during commissioning runs in November 2014 and January 2015, referring to the respective filter names of VISIR: the trend with chopping frequency is obvious. There is some scatter in these data that result from variable sky conditions, but once routine operations have started better statistics will soon become available.

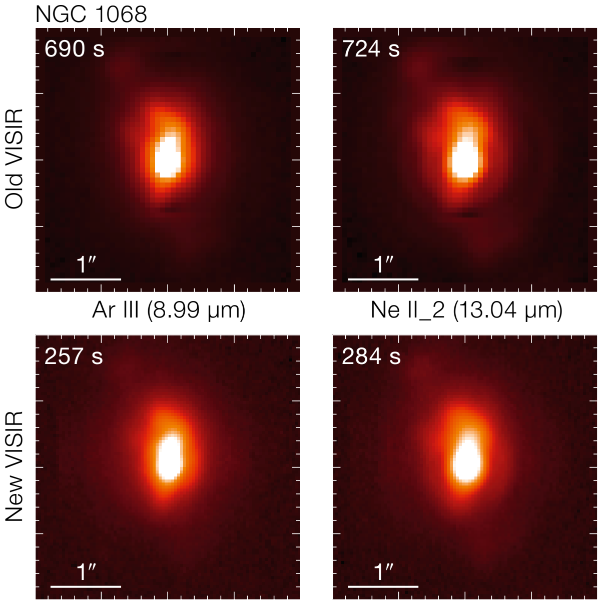

Figure 4. Comparison of images of the active galactic nucleus of NGC 1068 taken with the "old" and the "new" VISIR. After the upgrade, the same quality can be achieved in substantially less time, while having much finer spatial sampling, relevant for all image processing involving deconvolution.

1.5 V is some 40 times higher. The charge diffusing through the photoconductor can be accelerated sufficiently to create, via impact ionisation, secondary charges and so on. In the VISIR spectrometer case, there were of order three charges generated per detected photon; as this is a very noisy process, avalanche gain needs to be avoided. Strong fringing was observed in echelle spectroscopy and it was evident that the antireflection coating of the AQUARIUS detectors was not optimised for 10.5 μm, as specified by ESO, but for ~ 6 μm — again a JWST value.

Since there was no option for a new detector design, the only way to improve performance was to investigate faster chopping with M2. The VLT's tracking precision, however, relies on vernier corrections using M2, normally referred to as fast guiding. The original implementation for VISIR was that each chopper state lasted substantially longer than the fast guiding time constant. Thus fast chopping was incompatible with the requirements for having a diffraction-limited telescope. With the ongoing replacement of obsolete elements, such as the technical CCDs in the VLT adaptors, the controllers and the network, this incompatibility could be re-addressed and using the art, or the tools, of control engineering the control loop could be tuned as well, providing the capability for simultaneous diffraction-limited imaging and high chopping frequency.

A test in August 2013 confirmed that VISIR can indeed achieve sensitivities close to the theoretical limit (background-noise-limited performance, BLIP; see Käufl et al., 1991), provided that fast image modulation is applied, be it by chopping or by drift scanning; the latter being now the preferred method in submillimetre and radio astronomy. Then, in a series of three short technical test runs, the necessary changes to the VLT operation were implemented and verified. The status of the upgrade is summarised in Kerber et al. (2014b).

Meanwhile, in the context of the laboratory testing of more AQUARIUS detectors for the MATISSE instrument, the second generation VLT interferometer mid-infrared instrument (Lopez et al., 2014), it was found that some of the leadless chip carriers into which the detectors are integrated are warped so badly that the mount designed for VISIR could damage them. This concern led to another intervention in the summer of 2014, in which both detector mounts were checked. The imager detector carrier was found to be flat without blemishes. However the mount was changed to a new design compatible with the warped carriers. The spectrograph detector had no significant damage either, but was replaced anyway with a device not showing avalanche gain and the mount was upgraded. Thereafter VISIR was ready to go back to the telescope and a first commissioning took place in November 2014.

The progress in 2014 and the long and unplanned interruption of observations led to a joint decision between the project team and Paranal science operations to have VISIR included in the call for proposals for Period 95, albeit with some restrictions, even though commissioning had not even started. In total 27 proposals were received for VISIR and 21 were awarded observing time.

Re-commissioning of VISIR

The focus of the commissioning was: to verify the fast chopping with field stabilisation using VISIR as a test camera; integrate the new detector controllers into the operations software to allow for robust synchronisation in fast chopping; modify and verify templates for the modes offered in Period 95; and establish the

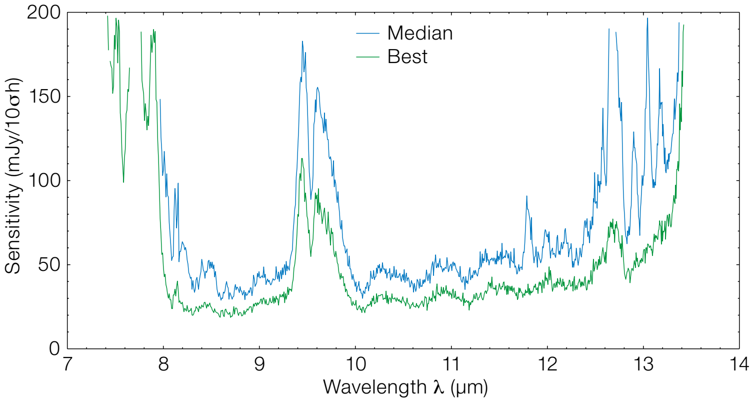

Figure 5. Sensitivity samples for the *N*-band low-resolution mode, as observed during the re-commissioning of VISIR in January 2015. This plot shows how many mJy a source needs to emit at a certain wavelength to be detected with a signal-to-noise ratio of ten in one hour. The plots retrace atmospheric radiance, i.e., the inverse of the transmission. Special attention is drawn to the region around 12.8 μm, the wavelength of the [Ne II] emission line: the difference between the two graphs is largely due to changes in water vapour above the telescope so that selection of low-PWV periods will pay off when observing the [Ne II] transition in H II regions.

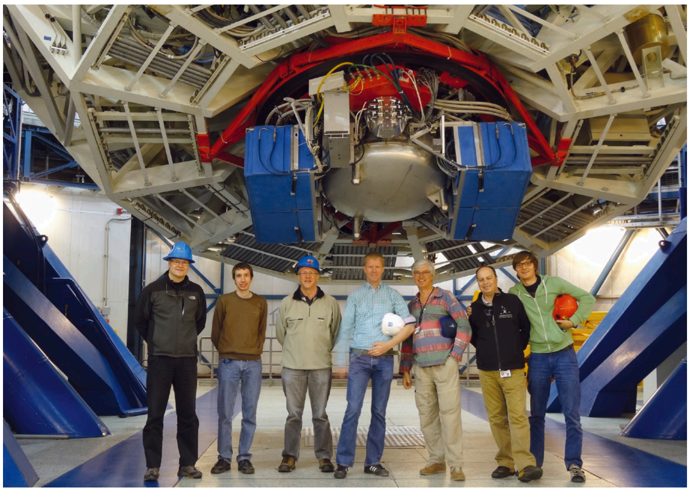

Figure 6. The re-commissioning team in front of the upgraded VISIR in January 2015. The signature of the upgrade is clearly visible between the blue boxes containing the electronics: to accommodate the connectors for the detector cabling required grafting in a new flange, almost a factor of two larger in diameter. To the left of this enlarged flange is an extra electronics box to adapt the AQUARIUS detectors to the standard voltage range of the ESO-NGC acquisition system.

data flow from the Phase 2 Proposal Preparation tool (P2PP) to the pipeline and science archive. The sensitivities of the image and low-dispersion spectrograph modes were then determined. For imaging, the sensitivities generally exceed those of the "old" VISIR (Figure 3), but for some filters the full field may be truncated to ~ 20 by 38 arcseconds for high-flux filters. Figure 4 shows, as an example, images in two emission-line filters for NGC 1068, before and after the upgrade. For *N*-band low-resolution spectroscopy, the sensitivity is generally up to a factor of two higher (correcting for the increased dispersion), while the throughput has been increased by a factor of four (c.f., Figure 5).

Performance and outlook

The main characteristics of VISIR after the upgrade can be summarised as follows:
- Imaging with sampling 0.045 arcseconds per pixel and field of view 38 by 38 arcseconds;
- Low-resolution prism spectroscopy over the complete *N*-band (7.7–13.3 μm) in one exposure at a spectral resolution ($\lambda/\Delta\lambda$) of 70 (8.0 μm) to 180 (13.3 μm) for a 1.0-arcsecond slit at a spatial scale of 0.076 arcseconds per pixel (slit length ~ 32 arcseconds).

Up-to-date information on the characteristics of the offered modes is available in the User Manual[2].

The *N*- and *Q*-band echelle spectroscopy will be commissioned in time for Period 95 with improved performance and 2.3 times the spectral coverage. It is then expected that for the call for proposals for Period 96 a variety of restrictions on the modes will be lifted.

VISIR, a true multimode instrument, is back in basic operation (see Figure 6). In the coming commissioning periods, several additional modes will be tested:
- coronagraphy;
- burst mode, and thus high speed photometry;
- imaging with sparse aperture masks;
- medium-resolution spectroscopy, especially in the *Q*-band and wavelengths beyond 20 μm.

Operations will support burst mode, offering the opportunity for frame selection and bringing background-limited performance within reach for most filters. Sub-aperture masking and coronagraphy will provide new scientific capabilities in terms of high-resolution, high-contrast imaging. We invite users to regularly check the VISIR upgrade web page[3] and follow the progress on VISIR towards full science operations.

One important aspect for the future will be exploring options to address the shortcomings of the AQUARIUS detectors, especially since other instrument activities at ESO would profit as well.

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Links

[1] VISIR instrument page: http://www.eso.org/instruments/visir/
[2] VISIR User Manual: http://www.eso.org/sci/facilities/paranal/instruments/visir/doc.html
[3] VISIR upgrade project news: http://www.eso.org/sci/facilities/paranal/instruments/visir/upgradeproject.html