

## VISIR Upgrade Overview and Status

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### ABSTRACT

We present an overview of the VISIR upgrade project. VISIR is the mid-infrared imager and spectrograph at ESO's VLT. The project team is comprised of ESO staff and members of the original VISIR consortium: CEA Saclay and ASTRON. The project plan is based on input from the ESO user community with the goal of enhancing the scientific performance and efficiency of VISIR by a combination of measures: installation of improved hardware, optimization of instrument operations and software support. The cornerstone of the upgrade is the 1k by 1k Si:As Aquarius detector array (Raytheon) which has demonstrated very good performance (sensitivity, stability) in the laboratory IR detector test facility (modified TIMMI 2 instrument). A prism spectroscopic mode will cover the N-band in a single observation. New scientific capabilities for high resolution and high-contrast imaging will be offered by sub-aperture mask (SAM) and phase-mask coronagraphic (4QPM/AGPM) modes. In order to make optimal use of favourable atmospheric conditions a water vapour monitor has been deployed on Paranal, allowing for real-time decisions and the introduction of a user-defined constraint on water vapour. Improved pipelines based on the ESO Reflex concept will provide better support to astronomers. The upgraded VISIR will be a powerful instrument providing background limited performance for diffraction-limited observations at an 8-m telescope. It will offer synergy with facilities such as ALMA, JWST, VLTI and SOFIA, while a wealth of targets is available from survey work (e.g. VISTA, WISE). In addition it will bring confirmation of the technical readiness and scientific value of several aspects of potential mid-IR instrumentation at Extremely Large Telescopes. The intervention on VISIR and installation of hardware has been completed in July and commissioning will take place during July and August. VISIR is scheduled to be available to the users starting Oct 2012.

**Keywords:** VISIR, VLT, mid-IR, Aquarius, upgrade, PWV, pipeline, Reflex, TIMMI 2

### 1. INTRODUCTION

VISIR is the mid-IR imager and spectrograph at ESO's Very Large Telescope (VLT). It was built by a French-Dutch consortium (Service d'Astrophysique CEA and ASTRON - PI: P.O. Lagage, Co-PI: J.W. Pel) and has been operational since the end of 2004. It is located at the Cassegrain focus of unit telescope (UT) 3 (Melipal) at VLT on Cerro Paranal (2635m) in Northern Chile. The instrument provides diffraction-limited imaging at high sensitivity in the two mid-infrared (mid-IR) atmospheric windows: the N-band between 8 to 13  $\mu\text{m}$  and the Q-band between 16.5 and 24.5  $\mu\text{m}$ . In addition, it features a long-slit spectrometer with a range of spectral resolutions between 150 and 30,000.

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For technical details of the instrument and its use we refer to the VISIR homepage at ESO: <http://www.eso.org/sci/facilities/paranal/instruments/visir/> and to the description of the instrument by the consortium<sup>1</sup>. Updates on the upgrade status are also available on a dedicated web page (<http://www.eso.org/sci/facilities/paranal/instruments/visir/upgradeproject.html>). ESO issues a call for proposals twice a year; preparation of proposals asking for observing time with VISIR is supported by an exposure time calculator: <http://www.eso.org/observing/etc/>.

In a dedicated study before the upgrade it was concluded that VISIR was performing below expectations for several reasons but the most important one was the lack of sensitivity of the detector the performance of which is also compromised by a lack of stability. In addition the operational set-up for VISIR was not optimal because it was strictly used as a bright time instrument and no independent real-time information of favourable observing conditions for mid-IR astronomy was available. Finally, the support provided by the data reduction software was considered not fully adequate compared to other facilities which are regularly used in combination with VISIR. As a conclusion we found that VISIR was underused by a relatively small part of the astronomical user community but that the instrument was well worth upgrading for the following reasons:

- Unique instrument for ESO community
- Located at an 8m telescope
  - Diffraction-limited performance possible
  - Sensitivity by large collecting area
- Reliable, well-built instrument
- Limitations known and understood
- Synergies with other facilities and pathfinder for E-ELT

Hence, when it became clear that a new detector array would become available it was decided to launch a project to upgrade VISIR. The VISIR upgrade project plans to optimise the science performance and output of VISIR by re-enforcing its strengths and by improving weaknesses as well as facilitating its use by the community<sup>2</sup>. The upgrade of VISIR has been approved by ESO's Instrumentation division in May 2010 and has been conducted in close collaboration between the project team and La Silla-Paranal observatory. Hardware replacements and modifications are currently underway followed by a commissioning phase on Paranal in August 2012. The upgraded VISIR should become available to the community in October 2012.

The goals of the upgrade is summarized in the following list:

- Improved performance of existing modes: achieve background limited performance for imaging and low-resolution spectroscopy
- Optimise use of observing time (more efficient N-band spectroscopy, knowledge of atmospheric conditions, in particular precipitable water vapour (PWV))
- Provide new science capabilities: new modes for high contrast and high resolution imaging
- Expand support of data analysis software in line with enhanced capabilities and ESO policies
- Conduct upgrade in close collaboration with Paranal and partners from the original consortium

## 2. AQUARIUS DETECTOR ARRAY

ESO funded the development of a new Si:As Impurity Band Conduction (IBC) array, code-named AQUARIUS, at Raytheon Vision Systems, Santa Barbara, USA. Five science devices, an engineering grade and multiplexers have been delivered to ESO, as part of this contract. AQUARIUS has 1024 x 1024 pixels, each  $30\text{ }\mu\text{m}^2$  in size and is therefore approximately five to six times larger in area than the previous generation of high background mid-IR detectors.

The architecture of the detector is such that it is split into two areas each of 512 rows and 1024 columns, at the top and bottom of the device, as shown in Figure 1 (left). Each area has 32 outputs, such that, each output is configured to read out 32 x 512 pixels, all 64 outputs from the two areas being read in parallel. This readout scheme also allows for 16 outputs rather than 64 to simplify system design for low background applications. With this multiplexer configuration it is possible to read the detector out at 150 Hz frame rates, each output operational at 3 MHz pixel rates. A windowed readout is possible, where a user selectable number of rows can be read, from the center outwards, with the remaining rows reset automatically. For example, a 1024 x 150 sized window, centred in the middle of the device, can be readout at 1 kHz frame rates. There is no advantage to windowing in the column direction since all outputs run in parallel.

All the typical detector read out modes are available and user-programmable with the simple control of five external clock control lines. These readout modes include, Global Reset where all pixels are reset at the same time; Rolling mode, where a row is read then immediately reset, then the next row is read and reset and so on, for a programmable row time which can overlap the read of the next row; Non-Destructive Read without reset and Row Reset Level Read (RRLR) where a row can be reset then read. Correlated Double Sampling, Fowler Sampling and Up-The-Ramp Sampling can all be implemented using any combination of these different read out modes. The multiplexer also has test rows, top and bottom and each output row of 32 pixels also has an on-chip generated reference level which can be read out and used for low frequency noise suppression. A more detailed description of the Aquarius array and its performance is given by Ives et al. (8453-38) at this SPIE conference.

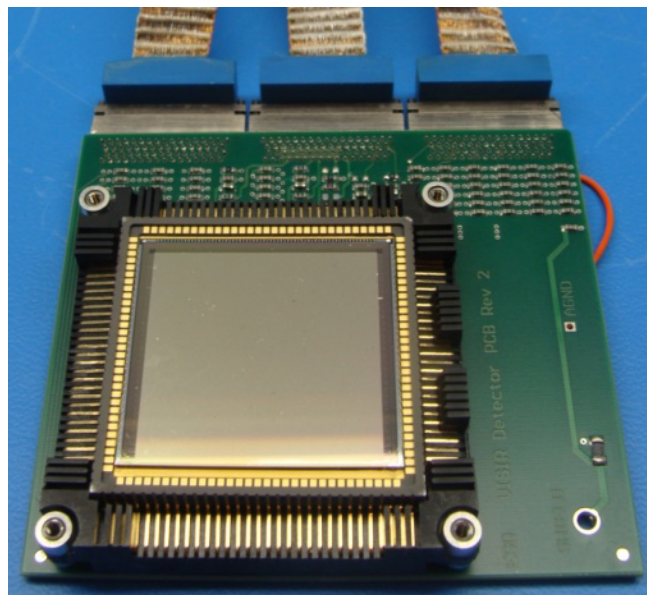
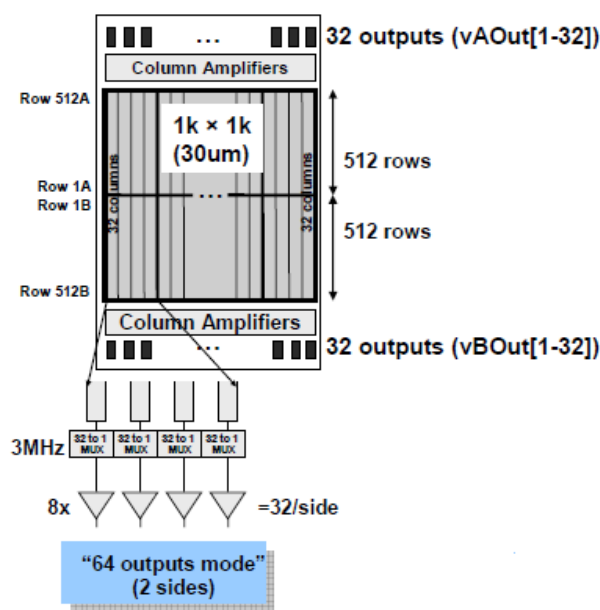


Figure 1. Left: Aquarius multiplexing readout scheme. Right: The Aquarius MUX mounted in its socket.

The Aquarius array has been fully tested and validated in the ESO IR detector test facility in Garching. This facility consists of the hardware of the original TIMMI 2 instrument which had been successfully operated on La Silla for many years. For its new purpose it has been fully refurbished and extensively upgraded in order to enable safe and efficient testing of detector devices.

The following parameters characterize the performance of the Aquarius based on this lab testing:

- Operating temperature 6-9 K; 8.5 K chosen for VISIR
- Integration capacity:  $0.6 \cdot 10^6 / 5 \cdot 10^6 \text{ e}^-$
- Input referred noise: 150/1400  $\text{e}^-$  rms
- Non-linearity (1/4 to 3/4 well):  $< 2\%$
- Dark current: 1.3  $\text{e}^-/\text{pixel}/\text{second}$  at 7 K
- Cross talk: 6-7% neighboring pixels

Of course the actual performance with respect to astronomical observations can only be evaluated by on-sky testing which is scheduled for August 2012. It is also important to note that VISIR will be the first instrument using ESO's newly developed next generation controller (NGC) for its Aquarius array. This combination has successfully been tested in the integration laboratory on Paranal and is ready for on-sky tests. By reading out all 64 Aquarius channels a data rate 16x higher than for the old VISIR will result. Operating VISIR in burst mode (at maximum speed) would overload the VLT infrastructure. Hence pre-cautions have been put in place which are fully supported by NGC: windowing of the detector and creating super-DITs by averaging over several individual DITs.

### 3. VISIR INTERVENTION AND INSTALLATION OF NEW HARDWARE

Following the last official close-out night of "old VISIR" on 7<sup>th</sup> May 2012, the complete instrument was dismantled from VLT UT-3 and brought to the integration hall of La-Silla Paranal Observatory, followed by a first cool down sequence to proof its performance in this temporary environment and to evaluate the status of "old VISIR". In the following weeks of May and June the optical instrument was disassembled and prepared for the integration of new hardware. Imager and spectrometer detectors were equipped with the Aquarius array integrated in dedicated detector mounts. Both detectors could be adjusted to optimum focus. Preliminary overall detector system performance testing in the range of 5.5K – 10K revealed optimized detector operation around 8.5K.

A second major upgrade task was the implementation of a prism optics in the VISIR spectrometer. One of four gratings on the carousel wheel was replaced by a ZnSe prism with dedicated cryogenic mount. The optical train was verified and adjusted by means of visible light and some correction optics, compensating the difference from visible to typical mid-infrared wavelengths.

During two cool down cycles in the integration hall laboratory the new VISIR components and the upgraded system performance were extensively verified. It is planned to re-install VISIR at VLT UT-3 in the second half of July 2012 for commissioning and first observations, followed by another short hardware intervention period with some final optical adjustments and optimizations in September.



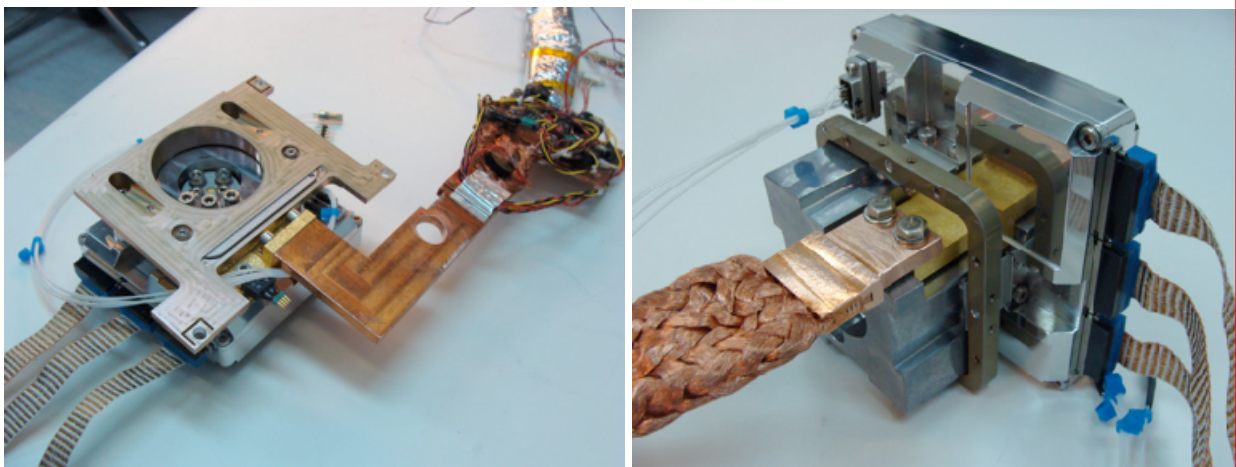


Figure 2. Left: The VISIR imager detector mount. Right: VISIR spectrometer detector mount.

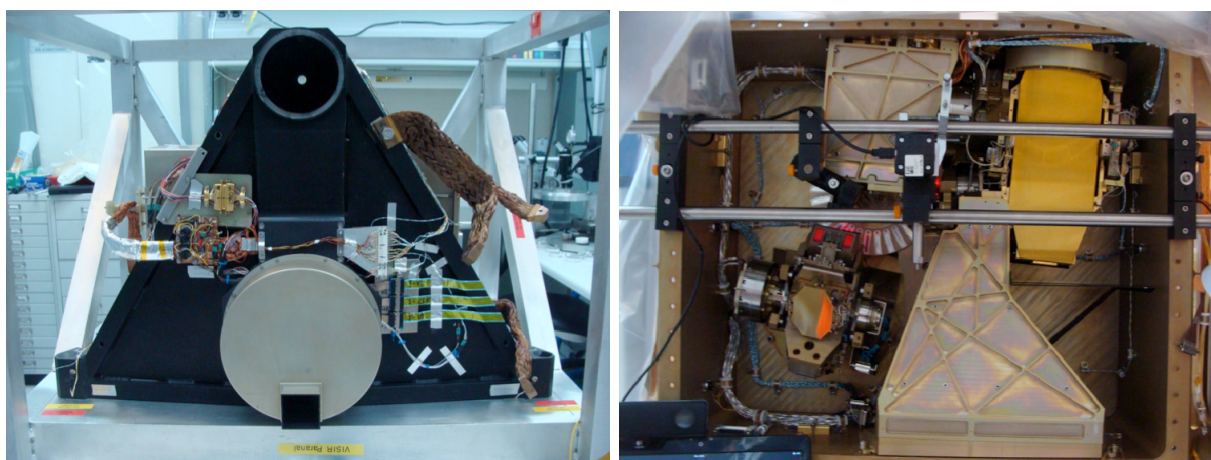


Figure 3. Left: The VISIR imager fully integrated after the intervention. Right: Optical alignment of VISIR spectrometer with CMOS camera and laser.

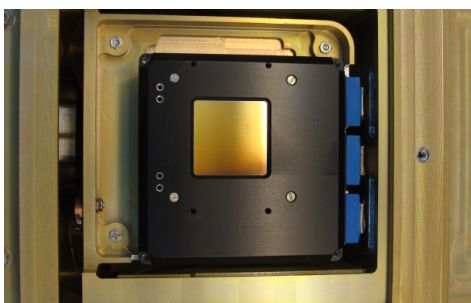


Figure 4: The Aquarius 1k x 1k detector array integrated with VISIR spectrometer (sensitive area is 30.72 mm x 30.72 mm).

### 3.1 N-band Spectroscopy

VISIR's spectrograph arm uses two collimators, one for high-resolution Echelle spectroscopy, the other for low and medium resolution work. We have replaced the low resolution gratings with one single ZnSe prism (Fig. 5), which will allow for long-slit spectroscopy in the N-band with a spectral resolution  $\lambda/\Delta\sim 500$  at  $\lambda\sim 8\mu\text{m}$  and  $\sim 800$  at  $\lambda\sim 13\mu\text{m}$  in one exposure, hence providing a gain of four in observing efficiency for the full N-band spectrum. This mode will have both uncompromised through-put – no order sorting filter – and very good image quality, as a prism will perform much better than a grating. The upgrade of the low-resolution mode will give a boost to spectrometric differential observing techniques. The prism has been tested in Garching down to temperatures of 27 K and cooling/warm-up rates of up to 20 K/h. At this point it has been installed and aligned with optical light and the mode will be tested on sky in August.

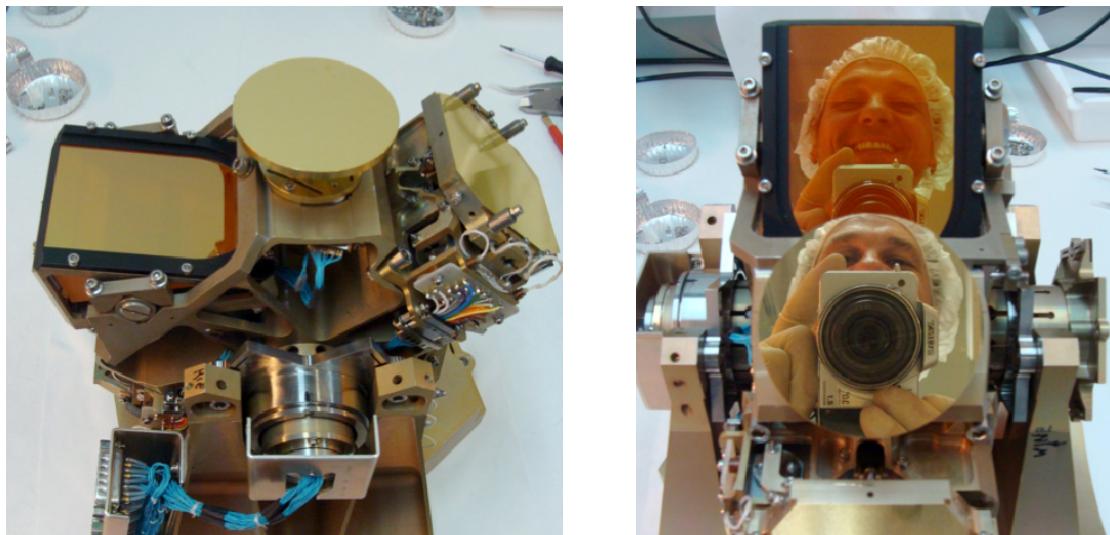


Figure 5. Left: Upgraded grating carousel wheel with prism mount. Right: documenting a job well done.

## 4. NEW SCIENTIFIC MODES

### 4.1 The VISIR coronagraphic mode

This mode has been primarily designed to observe point sources (companion stars, brown dwarfs) at narrow angular separations from the primary (0.3-1 arcsec) and resolve the central regions of dusty disks (proto-planetary and debris-disk) at the same angular separations. Three devices have been installed in VISIR, two 4-quadrants phase masks (4QPM) developed in the framework of the MIRI image<sup>3</sup>, and one achromatic AGPM (Annular Groove Phase Mask, a vortex coronagraph<sup>4</sup>). The germanium-based 4QPMs are chromatic and are designed to work at a relatively well-defined wavelength (10.5 and the 11.3  $\mu\text{m}$ ,  $\delta\lambda=0.4$  and 0.6  $\mu\text{m}$  resp.) corresponding to spectral features of astrophysical interest (e.g. the 11.3 PAH emission band and adjacent continuum). The diamond-plate AGPM provided by the University of Liege (IAGL) is optimized to work on a broader range (12.25  $\mu\text{m}$  central wavelength,  $\delta\lambda=1.3\mu\text{m}$ ) and covers the [NeII] emission line at 12.8  $\mu\text{m}$ . The coronagraphic masks will be implemented at the VISIR focal plane after the entrance window. Dedicated Lyot stops have been designed and placed in front of the corresponding filters, in the pupil plane. Numerical simulations have shown that the best compromise in terms of rejection and sensitivity is reached using an

undersizing of 10% outer circular aperture w.r.t. the full pupil plane aperture, and a 10% oversized central obscuration to mask the VLT M2 emission and diffraction. The simulated performances are shown in Figure 6.

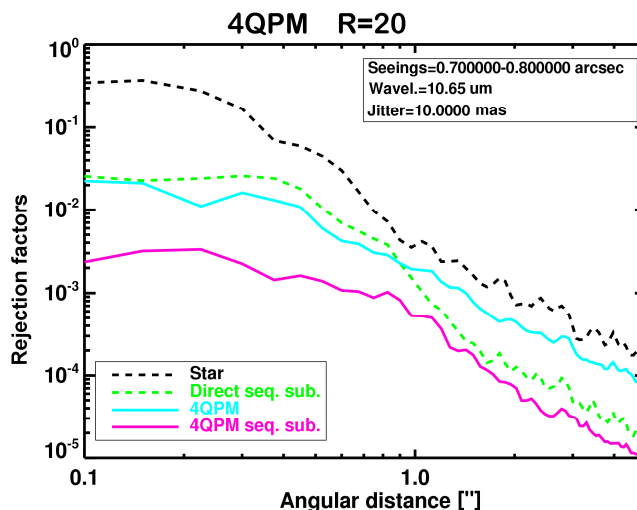


Figure 6: Rejection performances of VISIR in standard imaging mode and coronagraphic mode (assuming a seeing of 0.7"). The rejection factor is defined as the ability to detect a point source close to a bright source of flux unity. When observing in direct imaging (black dashed curve), a source 20 times fainter than the primary can be detected at a distance of 0.5". After PSF subtraction using a reference star (observed under slightly different conditions of seeing (0.8")), this factor grows to ~100 (green dashed line). When observing in coronagraphic mode, the rejection factors at the same distance are about 125 (light blue line) and 660 after PSF subtraction (magenta solid line).

## 4.2 The sub-aperture mode (SAM)

This mode allows to bridge the gap between the mono-pupil imaging mode and the interferometric instruments (e.g VLT/MIDI). A pupil plane mask combined with a filter is implemented in a free slot of the filter wheel. This non-redundant mask<sup>5</sup> contains 7 holes building a network of 21 baselines. The integrated transmission is about 25%. This mode is particularly well suited to overcome the moderate phase errors due to the infrared seeing. It is optimized to detect faint extensions or companions around bright objects in the 0.5-2  $\lambda/D$  distance range (0.1-0.4 arcsec, see e.g. Monnier<sup>6</sup>). Two wavelengths/filters have been implemented : (10.5 and the 11.3  $\mu\text{m}$ ,  $\text{dl}=0.4$  and 0.6  $\mu\text{m}$  resp.). The masks were cut in aluminium 508T6 thin plate and covered with an absorbing layer obtained after an anodization process.

## 5. DATA REDUCTION SOFTWARE

The VISIR upgrade poses several challenges to the existing data reduction software (pipeline). The new detector is 16 times larger which increases the memory usage, processing time and disk space requirements significantly. Also the use of burst mode increases the amount of data the pipeline needs to handle by several magnitudes. To cope with this data rate the pipeline makes use of multiple CPU cores and vector extensions available on most modern machines and uses highly optimized third party libraries like `fftw3`<sup>7</sup> for performance critical tasks.

### 5.1 Imaging

The imaging data reduction consists of applying the Chop-Nod correction, rejecting exposures of bad quality and co-addition. The object position in the images varies on a sub pixel scale due to atmospherically perturbations and small

mechanical vibrations (see Fig. 7). In order to obtain the best quality of the end product the pipeline tries to detect the shifts in the object position between each image and accounts for it during the co-addition. This is especially important for the burst mode data where the exposure time of each image is so small it can resolve many perturbation and vibration effects. For this technique to work best the intensity of the objects must be large enough to be visible in each exposure. If it is too low some images must first be averaged to gain a high enough signal to noise ratio, losing some of the spatial information in the process.

For this position detection two methods are currently offered to the user:

- Use the brightest pixel of the image
- Cross-correlation of the image to a template.

Both methods obtain sub pixel precision by linearly taking into account the profile around the detected object position. The brightest pixel method is very well suited for single standard stars which have a well defined brightest pixel. For extended objects or exposures with multiple objects the cross-correlation is more robust.

The template to correlate against is either supplied by the user or generated from the available data. The generated template is created in two steps. First a range of exposures is averaged to archive a strong object detection and in the next step the same exposures are cross-correlated against this average in order to detect the preliminary shifts in the objects position. These images are then co-added, taking into account the shifts, and the result used as the template for the whole data set.

Several properties of the images, like standard deviation, median and normalized cross correlation, are gathered and used to reject images of too low quality. The remaining images are then co-added to give the final result. For an example result using old detector data processed by the current pipeline see Fig. 7 (right).

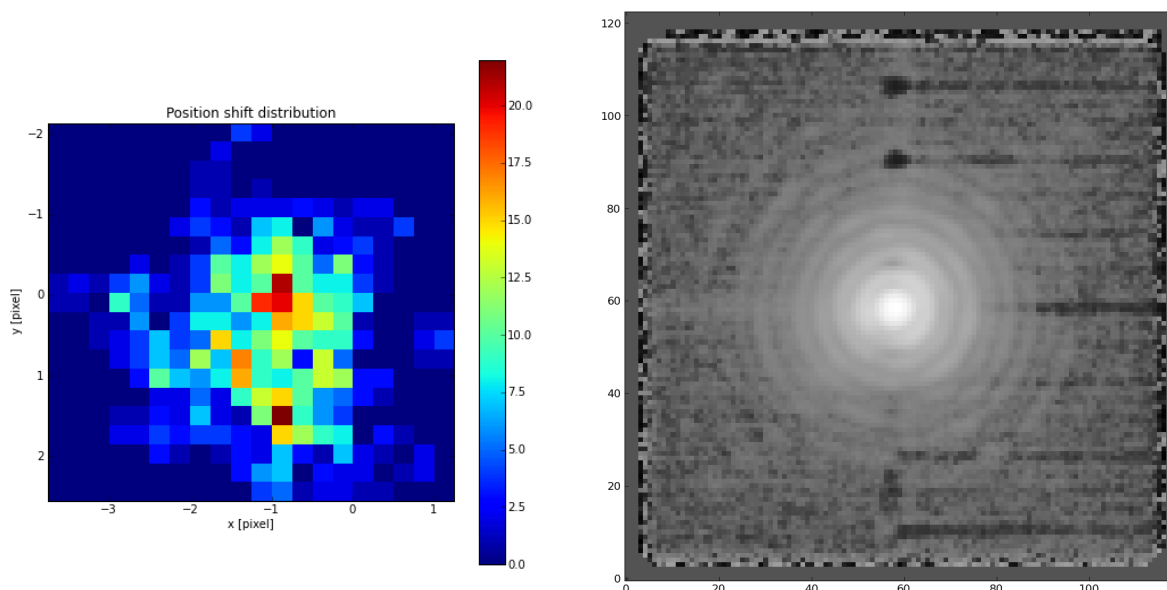


Figure 7. Left: Distribution of the object position shifts in burst data taken with the old detector. It is clearly visible that not correcting for the shifts would result in a significantly worse resolution of the end product. Right: Final pipeline result for a standard star taken with the old detector in burst mode in an arcsinh greyscale. The positional offset correction done for each image in the pipeline makes many airy rings visible.



## 5.2 Spectroscopy

The first stages of the processing of spectroscopy data is similar to the imaging data. Before one can extract a spectrum from the data, the raw data must first be co-added. Spectroscopy exposures are normally dominated by strong sky emission lines. These lines have much higher amplitudes than the actual signal so they must be aligned very well before they are subtracted during the chop-nod correction. Very small misalignments on the order of one percent cause strong residuals in the final image due to the large amplitudes and steep gradients of the sky lines. These properties on the other hand can be used to apply a simpler and more robust alignment method than in the imaging case.

As two chop exposures are very close in time to each other the sky lines in both are likely to be very similar in shape and amplitude (see Fig. 7). In order to correct for slight offsets in the wavelength direction one can subtract the skylines of one chop image with a slightly shifted version of itself. This self-shifted subtraction will look very similar to the real subtraction of the two chop images if the self-shift is equal to the real shift. So the squared difference between the self-shifted subtraction and the chop image subtraction is compared for multiple shift values. The shift where the difference is minimal corresponds to the value required to align the two images almost perfectly.

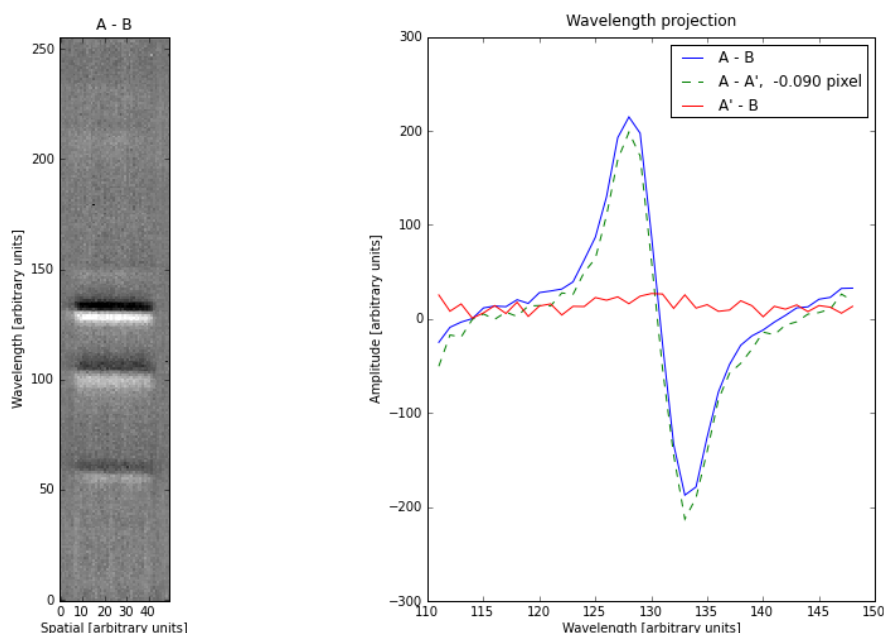


Figure 7. The left image shows the residuals which remain when the sky lines are not aligned perfectly before the subtraction. The right image shows the comparison of the self-shifted subtraction  $A - A'$  to the real subtraction  $A - B$ .

The spectrum is then obtained from the co-added image via optimal extraction<sup>8</sup>. In order to map the pixel space spectrum to a wavelength it is correlated with HITRAN data which is appropriately convolved as if it were taken by the VISIR spectrometer.

## 6. CLOSE-OUT CALIBRATION

Special closeout calibrations of VISIR were designed to be executed before the actual instrument upgrade. They are meant to serve two purposes:

- to provide additional calibration exposures needed for archival data before the configuration of the instrument is changed irreversibly, and
- to provide a set of standard observations as a well documented bench-mark for the comparison of the performance of VISIR before and after the upgrade.

The calibration data for VISIR are incomplete in terms of modes covered. Our aim was to obtain a set of data that will allow calibrating the most frequently used science modes also in case of a future homogeneous reprocessing of archival data but also to cover gaps in the existing calibration data.

The list of the close-out calibrations included day-time and night-time observations. The day-time data - darks and flat fields were taken during the day time operations and most of the instrument setups were covered. The night-time calibrations consisted of illumination correction data, imaging standard star observations for all 23 filters of VISIR taken in both small and intermediate field, as well as spectroscopic standard stars observations in different instrumental setups. Most of them were acquired on 08/05/12 in good (photometric) observing conditions.

## 7. SUPPORT OF SCIENCE OPERATIONS: PWV

A water vapour monitor that has been permanently deployed at ESO's Paranal observatory as a part of the VISIR upgrade project. The instrument selected is a Low Humidity and Temperature Profiling microwave radiometer (LHATPRO), manufactured by Radiometer Physics GmbH (RPG). The unit measures several channels across the strong water vapour emission line at 183 GHz, necessary for resolving the low levels of precipitable water vapour (PWV) that are prevalent on Paranal (median ~2.5 mm). The unit comprises the above humidity profiler (183-191 GHz), a temperature profiler (51-58 GHz), and an infrared radiometer (~10  $\mu$ m) for cloud detection. The instrument has been commissioned during a 2.5 week period in Oct/Nov 2011, by comparing its measurements of PWV and atmospheric profiles with the ones obtained by 22 radiosonde balloons. The RPG radiometer has been validated across the range 0.5 – 9 mm. Based on an absolute calibration using liquid nitrogen and comparison with the radiosondes, an accuracy of about 0.1 mm has been demonstrated for the PWV radiometer with an internal precision of 30  $\mu$ m. This ensures that reliable readings can be obtained in the driest of conditions encountered on Paranal which of course are the most valuable periods for IR astronomy. Details of the instrument and its operations are given in Kerber et al. (8446-135).

Water vapour is one of the main sources of opacity in the Earth's atmosphere in the thermal infrared, the operating range of VISIR. The new PWV radiometer is a major upgrade over existing capabilities since it does not use on precious time on the UTs and also it provides much better time coverage and higher accuracy compared to the spectroscopic methods used previously<sup>9</sup>. Moreover, the PWV content of the atmosphere above Paranal is strongly variable, both on short timescales, and with pronounced seasonal variations. However, not all infrared observations are equally affected by the PWV conditions: whereas imaging and spectroscopy in the Q-band atmospheric window from 17-21 micrometers will strongly benefit from being done under conditions of relatively low water vapour, imaging in most wavelength regions of the N-band window (9-12  $\mu$ m) would be less sensitive to PWV contents. The introduction of the new PWV monitor on Paranal offers a clear opportunity to optimize the scientific return of infrared instruments like VISIR by matching the PWV needs of each observation carried-out in service-mode to the actual conditions measured in real-time by the PWV monitor. Furthermore, the addition of a real-time PWV monitoring capability to Paranal infrastructure will enable qualitatively new types of science projects that require conditions of particularly low PWV (e.g. high-resolution spectroscopy of water molecules in proto-planetary disks) to be successfully scheduled. Hence PWV will be introduced as a formal observing constraint, analogous to seeing or sky transparency in the optical, for VISIR observations from Oct

2012 onwards. More details on this new development are given in the presentation by M. van den Ancker et al. (8448-37).

## 8. OUTLOOK

The intervention and installation of the new and modified hardware on VISIR has been completed in July 2012. A first round of laboratory tests using the modified software has been successful. The team is preparing for the first on-sky commissioning run scheduled for late July/early August and we will update the community on our progress through the dedicated upgrade web page <http://www.eso.org/sci/facilities/paranal/instruments/visir/upgradeproject.html>. A call for science verification observations will be made based on the results of the first commissioning run. Also all relevant documentation will be updated for the next call for proposals and phase II submission. Observations with the new VISIR will start Oct 2012. With a view to the more distant future the performance of VISIR, its detector and new modes will be evaluated in detail providing important information for future instrumentation on the E-ELT.

We noticed that interest in the ESO user community for observations with VISIR has already increased in anticipation of the upgrade. We hope that the performance of the upgrade VISIR will meet the expectations of its users and we will work towards this goal during the next months.

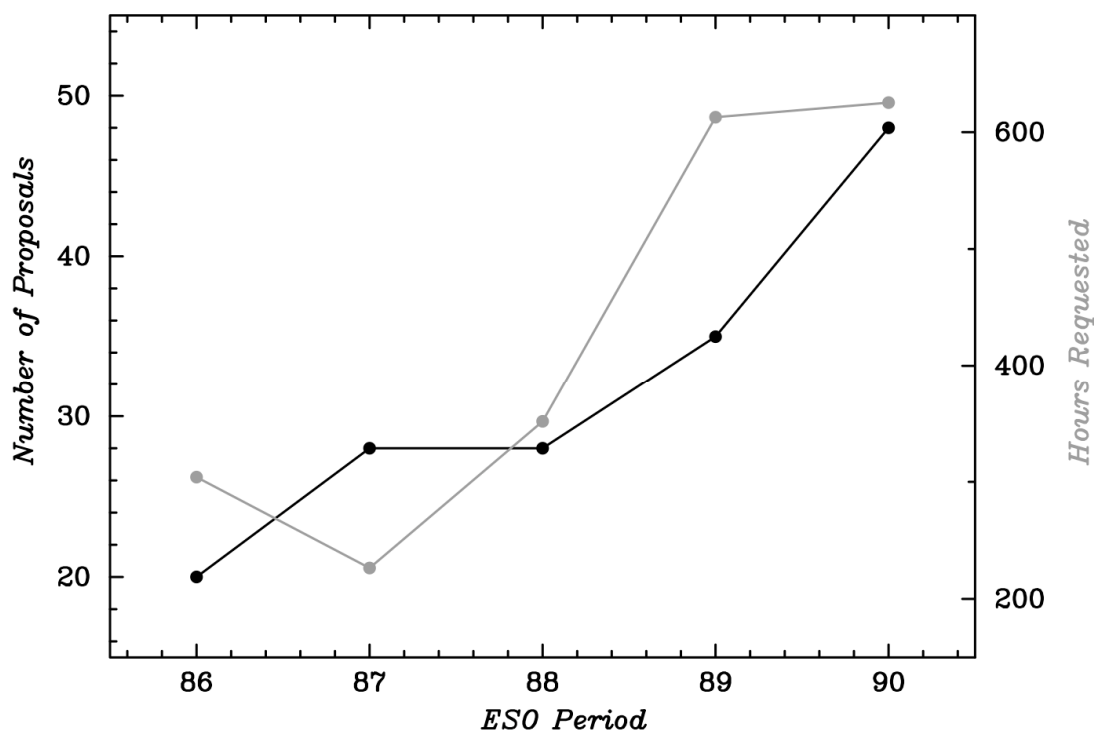


Figure 8. Evolution of the demand for VISIR observations: number of proposals received by ESO for a given period (black) and amount of time requested (grey). The interest in the community has increased in anticipation of the upgrade.

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