Successful Commissioning of VISIR: the mid-infrared VLT Instrument

VISIR is the ESO-VLT instrument dedicated to observations through the two mid-infrared atmospheric windows (the so-called N and Q bands). VISIR was installed in April 2004 at the Cassegrain focus of Melipal, the third of the four 8.2 meter VLT unit telescopes; first light was obtained on May 1st. This cryogenic instrument combines imaging capabilities at the diffraction limit of the telescope (0.3 arcsec at 10 microns) over a field up to 51 arcsec, and long-slit (32 arcsec) grating spectroscopy capabilities with various spectral resolutions up to 25,000 at 10 microns and 12,500 at 20 microns. The instrument will be offered to the community for ESO period 75 (proposal due date: October 1st 2004).

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VISIR stands for VLT Imager and Spectrometer for the mid-InfraRed (mid-IR). This cryogenic instrument, optimised for diffraction-limited performance in both mid-IR atmospheric windows, the *N* and *Q* bands (Fig. 1), combines imaging capabilities with various magnifications, with slit grating spectroscopy with various spectral resolutions, up to R = 25,000 at 10 μm and 12,500 at 20 μm.

The contract to design and build VISIR was signed in November 1996 between ESO and a French-Dutch consortium of institutes led by Service d'Astrophysique of CEA/ DSM/DAPNIA; the Dutch partner is ASTRON, Dwingeloo. One year after the signature of the contract, VISIR passed the *Preliminary Design Review*, which concluded that VISIR was feasible (Rio et al. 1998). The project passed the *Final Design Review* in 1999 (Lagage et al. 2000). The instrument was then manufactured, integrated and suffered from unexpected events, such as fire and then flooding in the Saclay building housing the VISIR laboratory! After extensive tests in the laboratory (Lagage et al. 2003), VISIR was shipped to Paranal in March 2004; after that everything went very smoothly. The instrument was transported fully integrated, so that in April it could be mounted almost right away onto Melipal, the third of the four 8.2-m VLT Unit Telescopes (Fig. 2). First images were obtained on May 1st, a few hours after feeding VISIR with sky light. The second commissioning (from June 30 to July 7) was jeopardized by bad weather conditions (4 nights fully lost and 3 nights rather poor). During the two commissioning runs, several observing modes were sufficiently tested to consider to offer them to the community at the next call for observing proposals (deadline October 1, 2004). To finish commissioning, a third commissioning run took place from August 27 to September 5. All the VISIR modes have now been successfully tested. The results from this last run will be reported later.

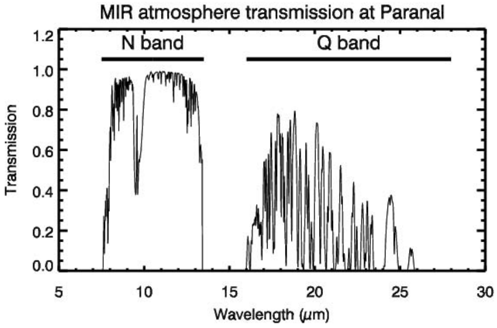

Figure 1: Mid-IR transmission of the atmosphere at Paranal, computed using the HITRAN model. The *N* window (8-13 microns) is a good window, especially in the 11 micron range; the only bad part is around 9.5 microns (ozone band). The *Q* window (17-25 microns) is a poorer window and the transmission depends crucially on the water vapour content of the atmosphere. For the transmission given in the figure, good atmospheric conditions of 1.5 mm of precipitable water vapour were assumed.

SCIENTIFIC CAPABILITIES AND OBSERVING MODES

The mid-IR region is the domain of excellence to study both warm dust and gas (molecular or atomic) in various objects in the Universe, from nearby objects such as comets to quasars. Warm dust at an equilibrium temperature ranging between 80 and 400 K is best detected in the mid-IR through its thermal emission; grains small enough to be transiently heated to high temperature, the so-called VSGs (Very Small Grains), can emit in the mid-IR, even if their “mean” temperature is very low. Broad solid-state dust features (for amorphous or crystalline silicate dust around 10 and 20 microns) are observable from the ground, as well as the so-called PolyAromatic Hydrocarbonates (PAHs) bands at 12.7, 11.3 and 8.6 microns. Concerning gas transitions, two of the three lowest energy (i.e. pure rotational) quadrupole transitions of molecular hydrogen in the vibrational ground state ($H_2(0,0)S(2)$ at 12.28 microns and $H_2(0,0)S(1)$ at 17.03 microns) are observable from the ground, at least using high spectral resolution (>10,000) to find them between atmospheric lines. A variety of atomic lines are accessible from ground-based observations in the mid-IR, such as the forbidden lines of [Ne II] at 12.8 microns, the [S IV] line at 10.5 microns, and [Ar III] at 8.99 microns.

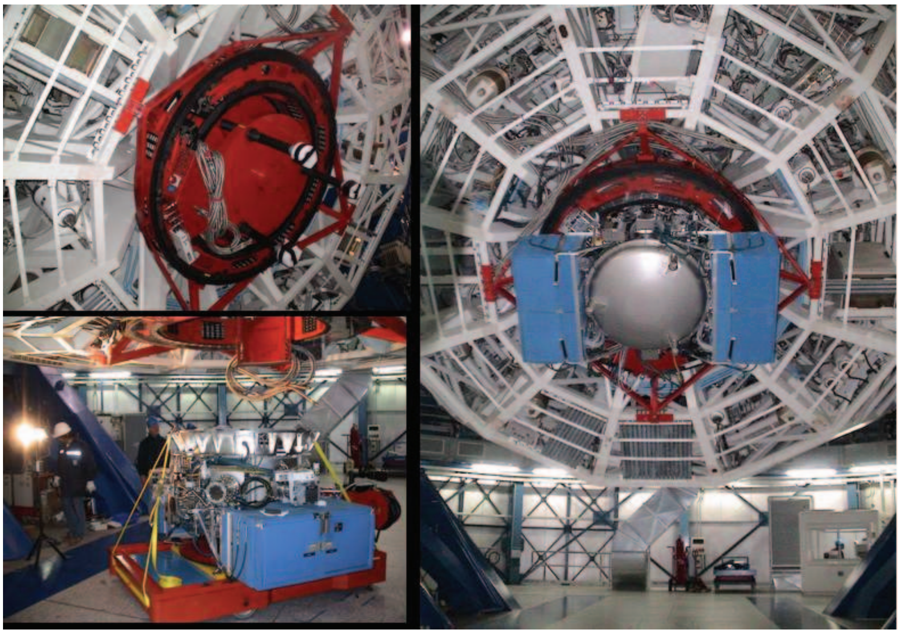

Figure 2: Top left: VISIR cable wrap mounted at the Cassegrain focus of MELIPAL. The cable wrap carries the electrical cables and closed-cycle cooler hoses to the instrument and rotates with it as the telescope tracks objects on the sky. At that time, a mass dummy was mounted on the cable wrap instead of VISIR. Bottom left: the mass dummy has been removed and VISIR, on its carriage, is going to be mounted onto the cable wrap. We can recognize the vacuum vessel (cylindrical shape with a diameter of 1.2 m and a height of 0.7 m) and the blue cabinets containing electronics for controlling and monitoring the instrument functions. Just above the middle of the blue boxes, we can see one of the three cryocoolers, used to cool the instrument to about 20K and the detector arrays to 7K. Right: VISIR fully mounted behind the primary mirror of MELIPAL. The total weight of VISIR is 2.3 tons.

The main advantage when observing from the ground in the mid-IR is the high angular resolution achievable with large telescopes. Indeed, in this wavelength range, the angular resolution is mainly limited by the diffraction of the telescope. Until the launch of the James Webb Space Telescope (JWST), scheduled for 2011, the angular resolution achievable using ground-based facilities will be 10 times higher than from space facilities. With VISIR the diffraction Airy pattern of the Spitzer Space Telescope (formerly known as SIRTF, the Space Infrared Telescope Facility) can be resolved into 100 elements (full width half maximum of 2.6 arcsec at 10 μm for a 80 cm telescope, to be compared to 0.26 arcsec for a 8-meter class telescope). Thus, the top priority in the VISIR specifications has been the image quality.

Of course, the huge atmospheric and telescope background dramatically limits the sensitivity achievable with ground-based mid-IR instruments. Thus the “niche” for ground-based mid-IR astronomy is the observation of relatively bright sources (a few mJy) for which high angular resolution is needed. Examples of such programs are the study of circumstellar environments, the study of multiplicity in early stages of star formation, …

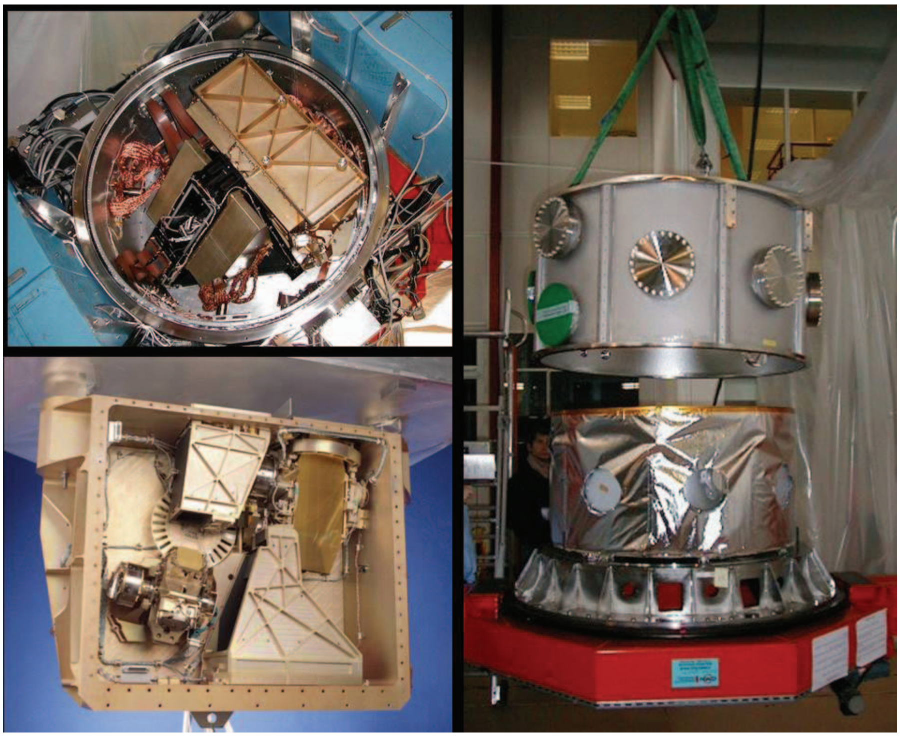

Figure 3: Top left: inside the cryostat; after removing the dome at the back of the cryostat, as shown in Figure 2 (right), one can see two sub-units: the imager (bottom left) and the spectrometer (top right). Bottom left: inside the spectrometer, partly integrated; one can see the slit wheel, the high-resolution duo-echelle grating (top right) and the grating carrousel carrying the 4 gratings including one scanner each for the low- and medium- spectral resolution arm (bottom left). Right: VISIR cryostat being assembled; the cryostat consists of a vacuum vessel and radiation screens; the vessel is composed of a flange to interface VISIR with the telescope adapter rotator (bottom of the image), a cylinder and a dome. The vessel is equipped with a radiation screen with superinsulation to lower the temperature of the surface radiating towards the cold optical bench.

To conduct the various observing programs with VISIR, several observing modes were implemented :

- imaging with a choice of 3 magnifica-

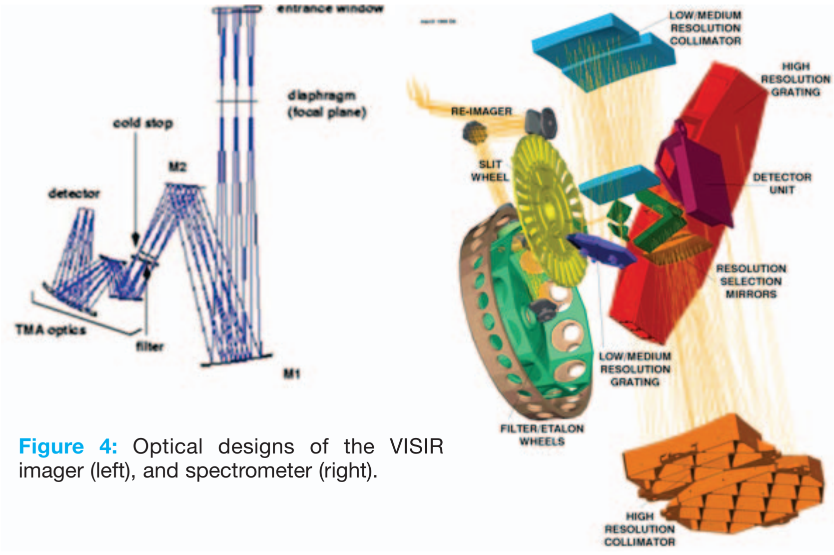

Figure 4: Optical designs of the VISIR imager (left), and spectrometer (right).

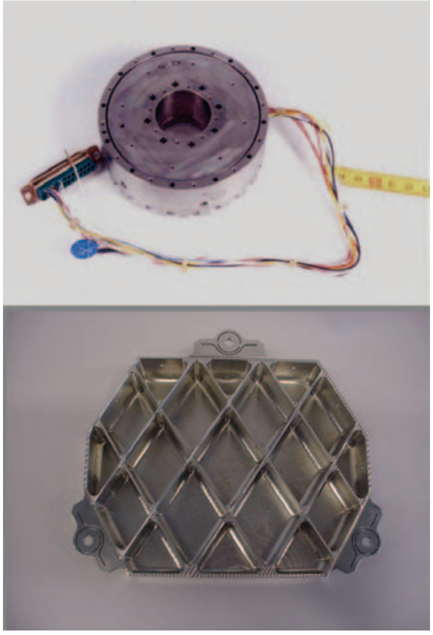

Figure 5: Top: Novel compact, precise and cryogenic motor/clutch unit actuator of VISIR. Such compactness was a key requirement to achieve a very compact mechanical design, imperative for a cryogenic instrument. Bottom: light-weighted structure on the back of one of the mirrors of the spectrometer. Also shown are the special mounting 'ears' for stress-free isostatic mounting.

tions and 24 narrow- and broad-band filters. The three Pixel Fields Of View (PFOV) are 0.075 arcsec, 0.127 arcsec and 0.2 arcsec. The corresponding fields of view are 19.2×19.2 arcsec^2, 32.5×32.5 arcsec^2 and 51.2×51.2 arcsec^2.

- slit grating spectroscopy with various spectral resolutions (R=$\lambda/\delta\lambda$), given for an entrance slit width set to $2\lambda/D$, (where, as usual, λ is the wavelength and D the telescope diameter). Three spectral resolutions are available in the *N* band: low (R = 350 at 10 µm), medium (R = 3200 at 10 µm) and high (R = 25,000 at 10 µm). Two spectral resolutions are available in the *Q* band: medium (R = 1600 at 20 µm) and high (R = 12,500 at 20 µm). There is also the possibility to have a low resolution mode in *Q* band (R = 175 at 10 µm) but the usefulness of such a mode in the poor *Q* band atmospheric window has to be proven. The PFOV along the slit is 0.127 arcsec. There are 28 slits with selectable width between 0.3″ and 4″. In low and medium resolution the slit length is 32 arcsec. The nominal high-resolution echelle spectroscopy mode is performed with cross-dispersion grisms for order separation. With these low-dispersion grisms four to five echelle orders are imaged simultaneously on the detector. To avoid order overlap the slit length is reduced to 4.5 arcsec for the cross-dispersed mode. Alternatively, for astrophysically important isolated lines, long slit Echelle spectroscopy observations are possible. At the moment four order-selection filters are available to perform long-slit high-resolution echelle spectroscopy: H_2 at 8.02 microns, [Ne II] at 12.81 microns, H_2 at 17.03 microns and [S III] at 18.68 microns.

DESIGN AND DEVELOPMENT

The choice was made in the early stage of the ESO VLT instrumentation plan to have only one VLT instrument in the mid-IR, able to combine imaging and spectroscopy. This decision resulted in VISIR being a rather complex multi-mode instrument. On top of that, in order to limit the contribution of the optical bench to the photon background to less than 1%, the optical bench has to be cooled to a temperature lower than 60 K for the imager and lower than 32 K for the spectrometer. Thus VISIR is a cryogenic instrument (Fig. 3).

VISIR is made of two subsystems: an imager and a spectrometer. Each subsystem has its own detector array. The detectors are both 256×256 Si:As BIB arrays developed by DRS Technologies (Galdemard et al. 2003). The acquisition system is the common-user IRACE system developed by ESO. The software is based on the general VLT software. The detectors have to be cooled down to ~8K to avoid prohibitive dark current.

The optical design of the imager is an all-reflective system made of five mirrors (Fig. 4). The first mirror images the telescope pupil onto a cold stop (18 mm in diameter) to block extra background. The second mirror is a folding flat to ease the mechanical implementation. The last three mirrors form a Three Mirror Anastigmat (TMA) configuration. They ensure the re-imaging of the field onto the detector. The three magnifications of the imager are implemented by a set of three TMA systems mounted on a wheel, named TMA wheel. Near the focal plane another wheel (the diaphragm wheel) is used to adapt the entrance field aperture to the selected magnification, in order to limit possible extra-background. Three positions of the wheel are occupied by aperture masks and folding flats to deflect the telescope beam into the spectrometer. The third wheel of the imager is a filter wheel, which is located just after the cold stop and which can hold up to 40 filters.

In the spectroscopic mode the telescope beam enters the spectrometer via the 're-imager' unit with a cold stop, two filter wheels (with order-selection filters and fixed Fabry-Perot etalons for wavelength calibration) and an entrance slit wheel (Fig. 4). The actual spectrometer has two arms, one for Low- and Medium- Resolutions (LMR) and one for the High-Resolution (HR) mode. Like the imager, the spectrometer makes use of Three Mirror Anastigmat systems, but now in double pass: in the first pass the TMA acts as a collimator, in the second pass as a camera. Each arm has its own TMA, with a collimated beam diameter of 125 mm in the HR arm and 53 mm in the LMR arm. Via switchable folding flats the spectra from both arms are imaged onto the spectrometer detector. The LMR arm gives a choice between four small reflective gratings. All are used in 1st order in the *Q*-band and in 2nd order in the *N*-band. The HR arm is built around the 'duo-echelle': two large echelle gratings mounted back-to-back on an aluminium blank of 350×130 mm. Both echelles have slightly different rulings (80.0 and 77.3 grooves/mm), resulting in two sets of "interlaced" grating orders. By choosing either the 'A' or the 'B' side of the duo-echelle, one can select for each wavelength the grating order with optimum blaze efficiency.

Given that VISIR is a cryogenic instrument and given the number of modes, the leading mechanical design criteria were high

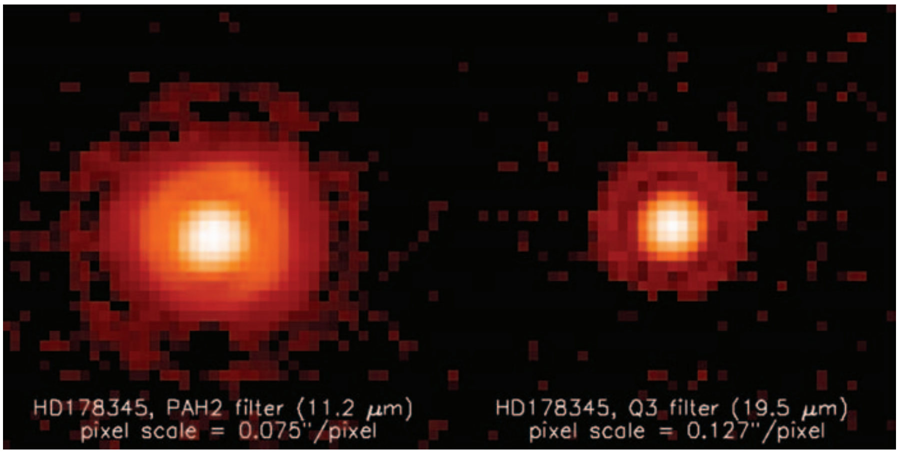

Figure 6: Point source with diffraction rings at 11.2 microns and 19.5 microns.

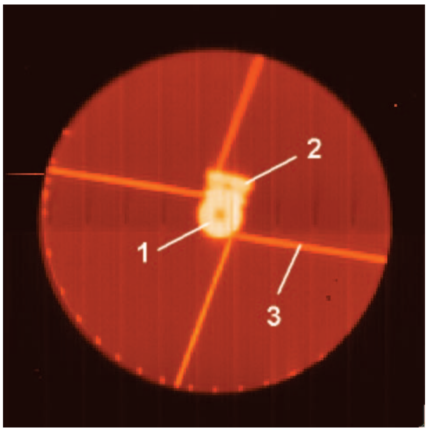

Figure 7: *N*-band pupil image for the spectrometer. In the thermal infrared, the pupil-image is an inverse of an 'optical' pupil image. What would show up dark in an optical image is radiating strongly at 10 microns. We can see thermal emission of 1) the (circular) M3-tower, 2) the rectangular attachment of the M3-tower in the stow-position and 3) the spiders of the VLT-M2 with their V-shaped geometry.

stiffness to weight ratio, low mass and high thermal stability. Such criteria have led to the development of a novel type of cryomechanism by the CEA/DAPNIA (Fig. 5). These devices have to actuate, at cryogenic temperature, optical devices with a very high accuracy and positioning repeatability (5 arcsec). By design, the cryomechanisms are very rigid and can be used in a cantilever position. The concept allows open loop control by use of a stepper motor with high torque and direct drive and includes a zero position switch as well. The power dissipation is zero when the cryomechanism is locked in position. Eleven such cryomechanisms are used in VISIR: three for the imager and eight for the spectrometer. The low mass criterion has also led to light-weighting of the opto-mechanic parts of VISIR, such as the mirrors (Fig. 5).

PERFORMANCE

The image quality of the imager was checked to be diffraction limited both in *N* and *Q* band (Fig. 6), at least under good seeing conditions. In the mid-IR at 10 microns the influence of atmospheric turbulence on image quality is obviously much less than at optical wavelengths. However, it is important to note that, when the optical seeing is worse than about 0.6 arcsec, a departure from diffraction limited performance at 10 microns is also observed.

The pupil alignment was also checked and found to be correct within a few percent (Fig. 7).

The sensitivity depends considerably on the weather conditions, especially in the *Q* band. While we achieved reasonable sensitivities in the *N* band (for example, down to 3.6 mJy 10σ 1 hour for the 11.3 μm PAH filter in good weather conditions), we were far off (an order of magnitude) in the *Q* band. The origin of such bad sensitivity is probably bad weather conditions.

To achieve the required sensitivity, the huge photon background has to be removed. This is done following the classical chop-

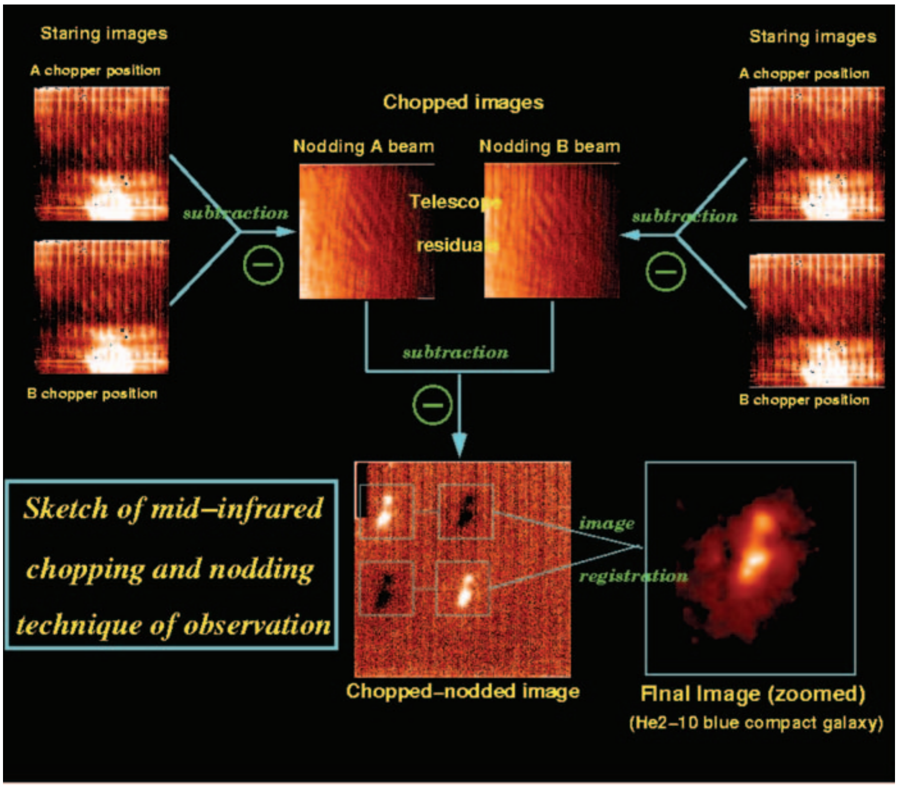

Figure 8: Illustration of the chopping-nodding technique when observing the He2-10 blue compact galaxy (see ESO press release about VISIR for more information about the object). The basic idea to remove the huge photon background generated by the atmosphere and the telescope is to make the difference between two observations: one on-source (background plus source) and the other off-source (background alone). Given the background fluctuation time scale, the on- and off-source measurements have to be done at a rate typically in the Hz range. Such a high rate cannot be achieved by moving the telescope. That is why it is done by moving the secondary mirror of the telescope (positions A and B on the left of the illustration); this is called *chopping*. The chopping technique allows us to remove the sky background and most of the telescope background. However the optical path on the primary mirror is not exactly the same according to the chopper position. That is why a residual background remains after chopping and one cannot detect the galaxy (see image labeled *nodding A beam* in the illustration). The time scale for the fluctuations of the residual background is long and can be monitored by moving the telescope off source and doing the same chopping observation sequence as in the preceding telescope position (resulting in the image labeled *nodding B beam*). After subtracting beams A and B, the galaxy is detected. If the chopping throw and nodding throw are small enough, the source is always present in the field of view of the instrument, so that we end up with four sources on the final image (two positive and two negative).

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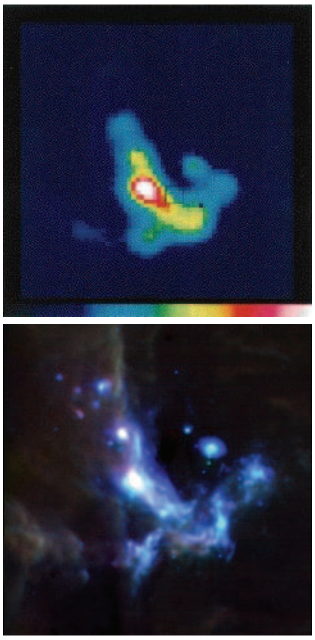

Figure 9: Top : image of the galactic centre obtained with the TIMMI instrument mounted on the 3.6-meter telescope on La Silla (H. Zinnecker et al. 1996). Bottom: image of the galactic centre obtained with VISIR. This illustrates the huge improvement when going from a 3-meter class to a 8-meter class telescope.

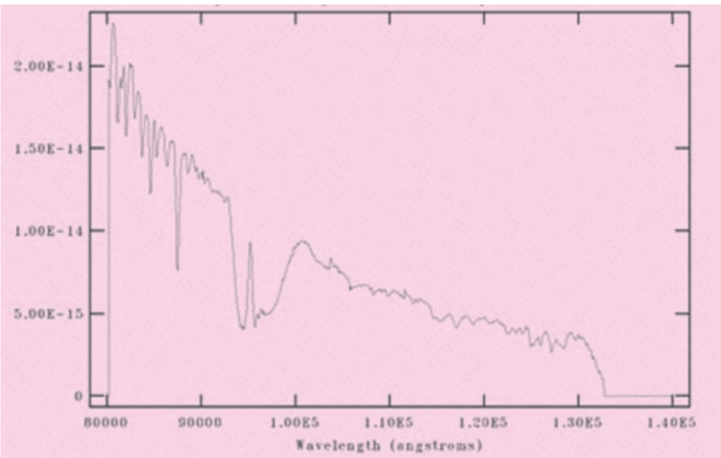

Figure 10: Full low-resolution *N*-band spectrum of standard star HD175775 (20.2 Jy at 12 μm). Note that the spectra have not been corrected for atmospheric effects.

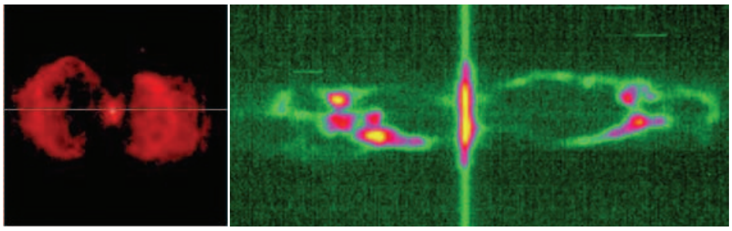

Figure 11: Left: image in the [NeII] line at 12.8 microns of the "Ant" Planetary Nebula (Mz3). Right: long-slit high-resolution spectrum around the [NeII] line; spatial direction is horizontal and spectral direction vertical. The slit was located as indicated by the line on the left image. The velocity resolution is about 17km/s.

ping-nodding technique illustrated in Fig. 8. While the VLT secondary mirror assembly allows chopping up to typically 5 Hz, substantially lower frequencies are being used, so that active field-stabilisation with the VLT-secondary mirror (M2) while chopping becomes possible. This is necessary for ultimate image quality under typical wind conditions. For the commissioning runs chopping frequencies as low as 0.25Hz were used to detect sources at a level of a few tens of mJy in imaging. Further tests are pending, to see whether these low frequencies compromise the sensitivity.

With VISIR a huge hurdle in improving ground-based mid-IR observation has been passed. We knew that with observations on a 3-meter class telescope we were only seeing the "tip of the iceberg" and that improvements should be achieved with VISIR. But, we were surprised by what we saw (Fig. 9)! With VISIR, we can obtain from the ground, mid-IR images with a quality rivalling that of shorter wavelength observations.

The spectrometer is also performing very well. Complete low-resolution *N*-band spectra were taken on July 4 and 6 in four settings (two with the LSW grating and two with the LLW grating) for various standard stars. The result for HD 175775 is shown in Fig. 10. In general the different parts of the spectrum join up quite well. The ratio of the spectra of two standard stars is reasonably close to the ideally flat distribution, except at wavelengths with strong atmospheric features like in the ozone band around 9.5 microns, where the atmospheric contributions do not cancel sufficiently due to difference in air mass and atmospheric variations.

Of special interest is the high spectral resolution mode, which has, so far, no equivalent in the Southern hemisphere (Fig. 11).

OBSERVING WITH VISIR

VISIR is one of the instruments which will generally be used during bright time. Given the international competition (for example the T-ReCS instrument on Gemini South), VISIR will be offered to the community as soon as possible. The VISIR modes that have been sufficiently tested during the first two commissionings will be offered to the community in the call for proposals for Period 75 (proposal due date: October 1st).

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