Calibration of VISIR, the VLT Mid-Infrared Imager/Spectrometer

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ABSTRACT

Since the beginning of the VISIR project, the calibration aspects have been taken into account as an integral part of the design. In order to provide the user and the archive with high quality and well-controlled data, it is mandatory to have, during the routine observation phase, all calibration observations as part of the instrument set-up activities and as part of the actual Astronomical Observing Template. We propose here to review the calibration of VISIR observations. After a description of the various hardware tools which have been introduced for calibration purposes (warm calibration unit, distortion grid, pupil imaging optics, wavelength calibration modules), we will present the calibrations in four astronomical categories (spatial resolution, photometry, astrometry and wavelength calibration). Cross-calibrations between the Imager and Spectrometer subsystems will also be addressed.

Keywords: Infrared, instrumentation, imager, spectrometer, VLT

1. INTRODUCTION

VISIR is the mid-infrared instrument to be installed in march 2003 at the Cassegrain focus of MELIPAL, the telescope unit number 3 of the European Very Large Telescope (VLT). VISIR is a cryogenic instrument optimized for the mid-infrared atmospheric windows (N and Q bands). This instrument combines imaging capabilities at the diffraction limit of the telescope and also spectroscopic capabilities in the same spectral band. The Imager offers a field of view up to ≈1 arcmin, with 3 different spatial resolutions (0.2, 0.127 and 0.075 arcsec/pixel). The filter wheel can receive 40 filters for which the spectral resolution is between 2 and $\geq$60. The grating Spectrometer provides various spectral resolutions up to 25000 at 10 μm and 12500 at 20 μm. Full design and expected performances[1] have already been described. The current status[2] of the instrument can be found in this proceedings.

For mid-infrared observations from the ground, the influence of Earth's atmosphere is very large and can be problematic, particularly for spectrometric observations. It is therefore essential to have a thorough and accurate calibration of the instrument itself in order to isolate the adverse atmospheric effects. For this purpose,

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VISIR design includes an extensive set of built-in calibration tools which enable the observer/operator to make calibration measurements and checks.

In this paper, we propose to describe first the various hardware tools which have been introduced for calibration purposes: the warm calibration unit (Sect. 2.1), the distortion grid and pupil imaging optics of the Imager subsystem (Sect. 2.2), the wavelength calibration modules of the Spectrometer subsystem (Sect. 2.3). Then, the calibration plan of VISIR is presented in terms of objectives, accuracy and type of device used to fulfill the requirement (Sect. 3 and Sect. 4 respectively for the Imager and Spectrometer subsystems). Finally, the cross calibration between the Imager and Spectrometer is addressed (Sect. 5).

2. HARDWARE TOOLS FOR CALIBRATION OF VISIR

2.1. Warm calibration unit

On top of the VISIR vacuum enclosure lies the warm calibration unit, also called star simulator (Figure 1). Artificial calibration sources of the warm calibration unit can be used instead of astrophysical sources, even when VISIR is mounted on the telescope. The warm calibration unit simulates a monochromatic point source (with adjustable wavelength) and an extended uniform source seen through the VLT unit telescope. A selection mirror allows switching from the telescope beam to the simulator beam. This facility is currently used in CEA-Saclay in order to verify the instrument performances and to calibrate it. It will also be used intensively at the observatory for calibrations and tests even during daytime. The structure supporting the whole facility is attached isostatically (3 points) to the VISIR warm flange. The star simulator main components are (see Figure 2):

- A chopped infrared source imaged onto the input slit of a monochromator. A 50 μm hole located at the monochromator output is the infrared monochromatic source point source. The size of 50 μm corresponds to less than one third of the airy pattern given by the VLT in the image plane at 10 μm range. The monochromator has a resolving power R $\approx$ 500. The output wavelength can be chosen in the 6-24 μm range.
- An extended blackbody based on a Peltier device. Its temperature can be set in order to adjust the flux level received by the detector. The temperature can be adjusted between -85°C and +85°C with a precision of 0.1°C relatively of the cooling fluid (glycol at Paranal, temperature slightly below ambient). The focus of the extended source is adjustable manually by ±15 mm, allowing to increase the flux homogeneity if needed.
- The optical system based on a 2 mirrors Offner system, plus a flat folding mirror (SS-M3 on Figures 1 and 3) to feed in VISIR. This flat mirror is mounted on a motorized table to switch from the simulator beam to the telescope beam. This table allows focus adjustment. Two screws are used to align the simulator pupil with respect to the VISIR cold stops.
- Two motorized tables allowing the movement of the point source in the whole field (51.2×51.2 arcsec^2). One of those motorized tables is used to select either the extended source or the point source in front of the Offner system.

The point source and the monochromator are used during the construction phase to calibrate the filters, to check the image quality, to determine the instrument efficiency and sensitivity, to calibrate the wavelength shift as a function of the position in the field (for every combination of filter and magnification), to study the detector response as a function of the wavelength. The instrument efficiency and sensitivity can be checked at Paranal during the instrument lifetime. Filter aging will be monitored with the point source. The point source will also be useful for functional tests during maintenance periods.

The role of the extended source is flatfielding the detectors. It can be heated in order to produce high fluxes necessary to perform flat-fields for the Spectrometer subsystem, allowing to perform flat fields much faster than on the sky (20 times more flux than the sky at 10 μm and 5 times more at 20 μm). For the Imager subsystem,

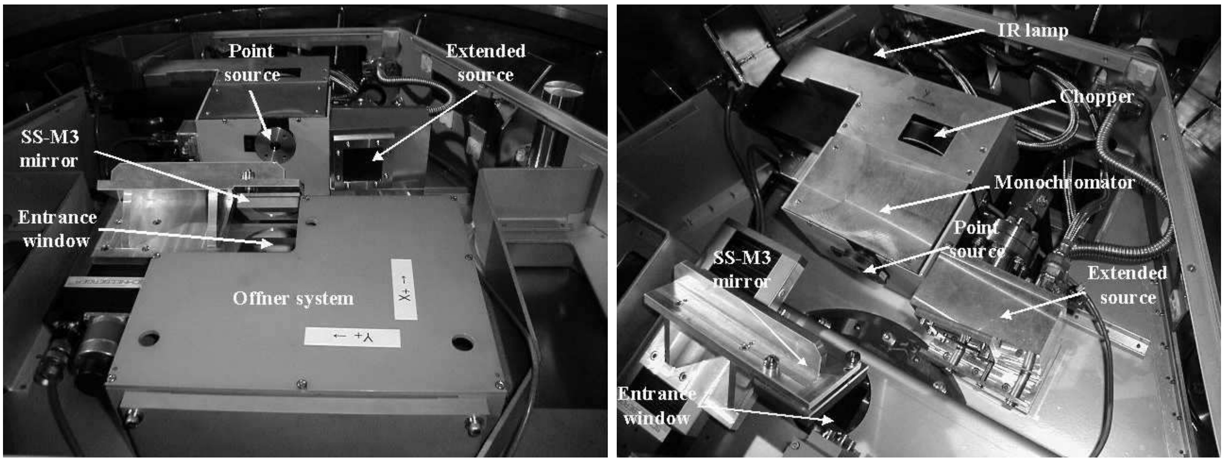

Figure 1. VISIR warm calibration unit. For illustration purpose, the cover that is placed on the whole facility has been removed. This cover has only one aperture to allow the telescope beam to enter the instrument.

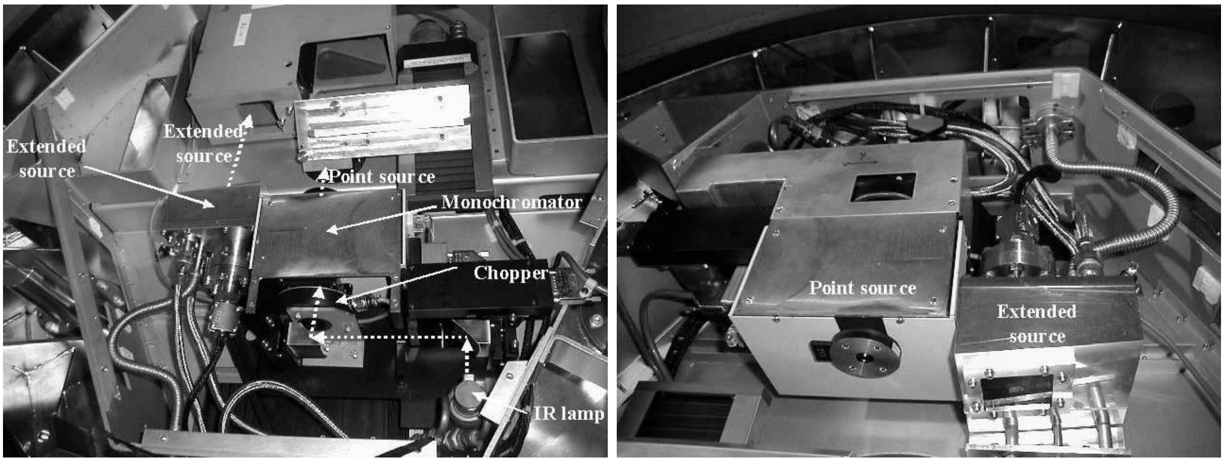

Figure 2. Source bench of the calibration unit. The point source is movable in both horizontal and vertical directions. Its focus is adjusted thanks to the SS-M3 mirror (Fig. 1 and 3). The extended source is movable only in the horizontal direction. Its focus is adjustable manually.

it should be possible to perform flat fields directly on the sky, by taking images at two different sky airmasses to obtain different fluxes (provided that the flexures are negligible). But the extended source can also be cooled down in order to reproduce the infrared flux given by the telescope. The extended source can be used to check the vignetting of the instrument.

2.2. Imager internal devices

In the cold part of VISIR, several sub-systems have been introduced for calibration purposes.

2.2.1. Distortion grid

The entrance wheel of VISIR located in the telescope focal plane has several roles:

- diaphragm mask to adapt the entrance field according to the VISIR imaging configuration (various magnifications),

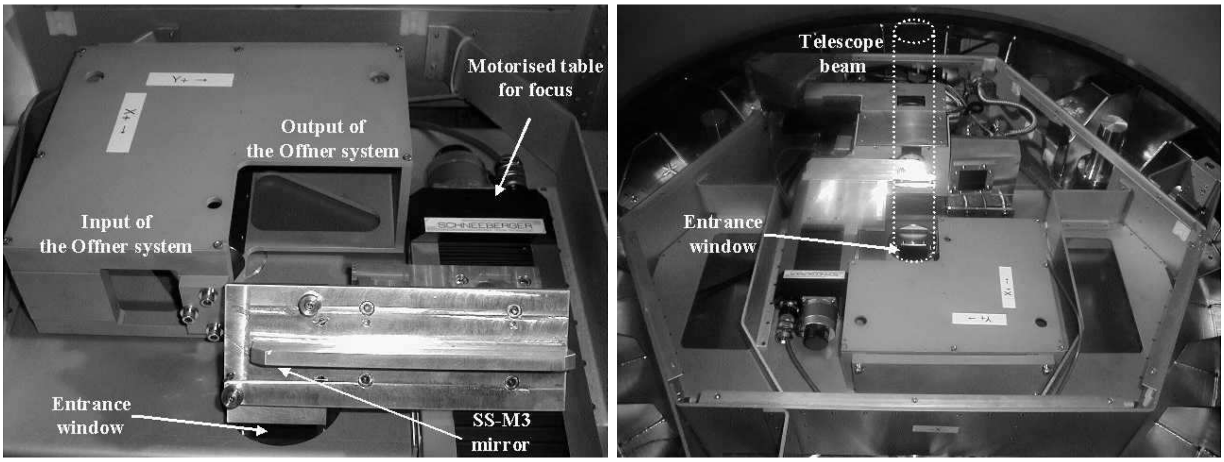

Figure 3. The Offner system and the flat folding mirror (SS-M3). Left panel corresponds to the feed in with the star simulator beam (SS-M3 mirror is above the entrance window). Right panel corresponds to the feed in with the telescope beam (SS-M3 mirror is beside the entrance window).

- holding the selection mirror to switch from Imager to Spectrometer subsystems,
- holding a grid of holes to calibrate or check the distortion, the image quality, the flexions ...

The distortion grid is an array of holes regularly spaced with respect to eachother. Each hole is 20 μm in diameter and the distance between holes is 662 μm. Figure 4 shows the distortion grid and an example of image as recorded by the Imager detector.

2.2.2. Pupil imaging optic

The wheel used to change of pixel field of view configuration (TMA wheel) also holds a special configuration which allows to image the cold stop pupil onto the detector. This facility is used to check the alignment between the Imager subsystem and the telescope (Figure 5).

2.3. Spectrometer internal devices

2.3.1. Fabry-Perot etalon wheel

For wavelength calibration purposes, a wheel holding 5 Fabry-Perot etalons is located near the pupil cold stop of the re-imager sub-unit of the Spectrometer. In addition to the etalons, the wheel holds Hartmann pupil masks for focus determinations.

2.3.2. Slit wheel

To calibrate the distortion along the slit, an extra aperture in the slit wheel with 20 pin holes is implemented.

2.3.3. Imaging the pupil

On the resolution selection mirrors mechanism there is a small auxiliary lens which allows imaging of the cold-stop pupil of the Spectrometer re-imager onto the detector.

2.3.4. Detector unit

The detector unit can move by ±5 mm in the direction perpendicular to the detector plane in order to check the position of the internal focus of the Spectrometer.

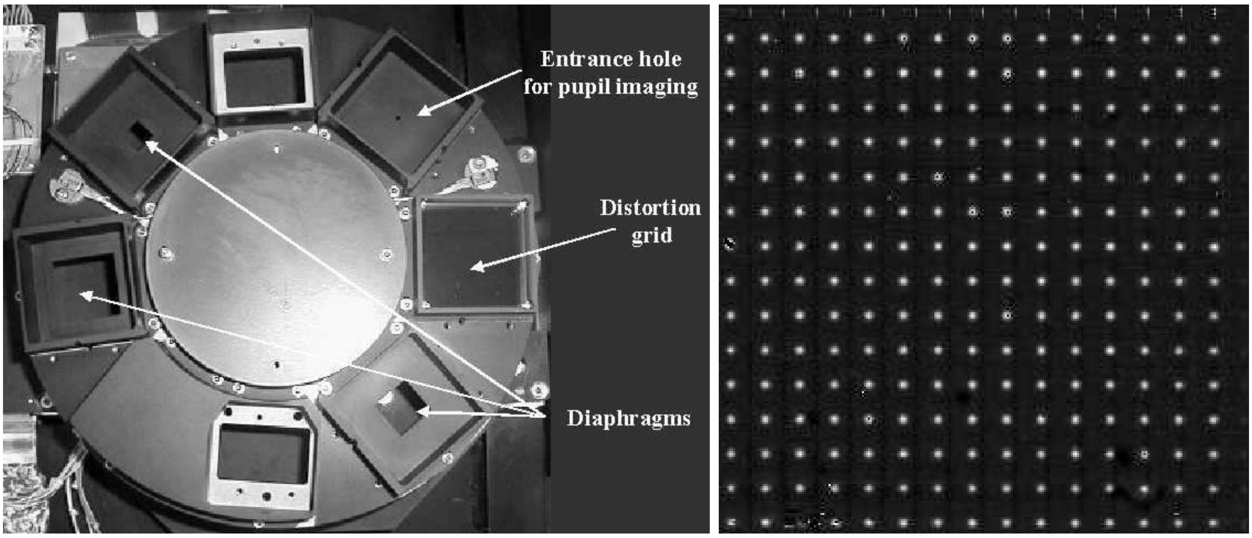

Figure 4. Distortion grid of the entrance wheel (left panel). For illustration purpose, the cover that is placed on the entrance wheel has been removed. This cover has only one aperture to allow the telescope beam to enter the instrument. Image of the distortion grid (right panel) as seen by the Imager detector in the small field of view configuration (0.075 arcsec/pixel).

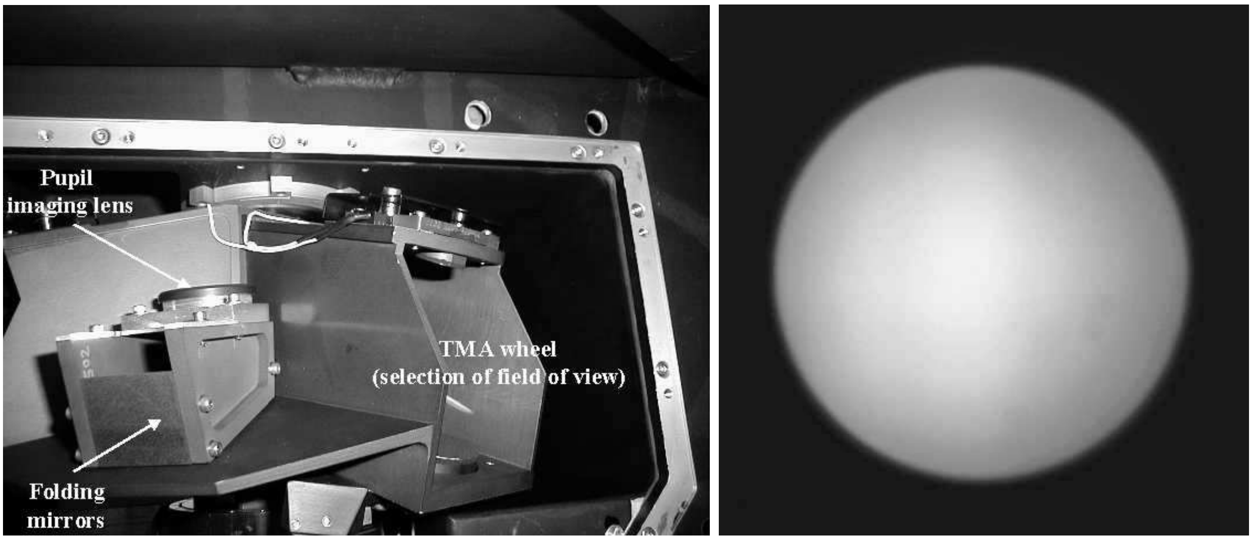

Figure 5. Pupil imaging system mounted on the TMA wheel (left panel). Image of the pupil (right panel) as seen by the Imager detector.

3. CALIBRATION PLAN OF THE IMAGER SUBSYSTEM

We have classified the calibrations of the Imager subsystem under three astronomical categories: spatial resolution, photometry and astrometry. The detector linearity is not addressed here because the detector is expected to be all the time stabilized on the high flux of the atmosphere. Large VLT mirrors will provide higher fluxes than smaller mirrors, but these fluxes will be sampled by detector with smaller pixels. So the background flux is still much higher than the source flux in VISIR observing configurations. Nevertheless, one should be sure to use the detector in its linear domain, and thus it may be preferable to avoid using the brightest standard stars.

3.1. Spatial resolution

The image of a point source is not a point, but is spread over several pixels. The reasons for such a spread are: atmospheric seeing, telescope diffraction, image quality, tracking error, defocus, focus stability, chopper jitter, instrument image quality, detector cross talk ... In the mid-infrared the dominant effect is the diffraction by the telescope.

3.1.1. Focus check

The absolute focus is determined by observing a bright point source and by scanning the telescope focus.

3.1.2. Pixel Field of Views (PFoVs)

The portion of the sky seen by a pixel of the detector needs to be characterized. PFoVs will be determined by three methods which will be cross checked:

1. In the laboratory, by moving the point source of the VISIR calibration unit over ± 50 pixels along each axis of the detector array.
2. On the sky:
   (a) by offsetting a bright star over each axis of the detector array,
   (b) by observing binary stars or asterism for which accurate coordinates are known independently (even if this is not available in the mid-infrared).

The last method has the advantage of being independent of external variables. This calibration has to be done for each of the 3 magnifications of the Imager. Precision on PFoVs should be better than $\approx 2\%$. PFoVs are inputs for the point spread functions.

3.1.3. Point Spread Functions (PSFs)

The knowledge of PSF is of outmost importance for many scientific programs and they are also input for the photometry. Calibrating the PSF is easily done by taking an image of a bright point source. Unfortunately, this is more or less rare in the mid-infrared. The PSF depends on the wavelength and on the PFoV, so that a calibration has to be done for each instrumental configuration implying a change of wavelength or PFoV. We assume that it does not depend on the chopper throw and chopper frequency (TBC). We also assume that the PSF is independent of the position on the array (TBC). This is not completely true due the distortion effect. But since the effect on PSF goes as the derivative of the distortion field, it should be very small. Precision of $\approx$10% should be reached.

3.2. Photometry

We consider in this section the way of relating the number of counts generated in the detector by photons from an astrophysical source to the source flux. The relation depends on: atmospheric transmission, telescope transmission, instrument transmission and alignment (position of the pupil cold stop), detector response, PSF. The calibration is done in three steps:

1. Observing a bright star at a given position on the array.
2. Observing a flat field to get the photometry at the other position on the array.
3. Taking into account distortion and illumination effects.

We aim at ensuring a photometry precision of 10% at 10 μm, 15% at 20 μm, allocating the error budget as follows:

- 7% at 10 μm, 12% at 20 μm for the photometry at a given position (see Sect. 3.2.1).
- 1% for flat field (see Sect. 3.2.2).
- 2% due to illumination effects (see Sect. 3.2.3).

In this section, we also discuss the way of checking the pupil alignment (Sect. 3.2.4), monitoring the instrument transmission (Sect. 3.2.5) and checking of filter wavelength as function of the position in the field (Sect. 3.2.6).

3.2.1. Photometry at a given position in the field

7% at 10 μm, 12% at 20 μm is not the error of the measurement, but rather the variation range acceptable according to the sky transmission temporal variations, and to the difference between the position in the sky of the source and of the photometric standard star. The error in the absolute flux of the standard star is not included in that budget.

The calibration is done by observing a photometric standard star from a reference star catalogue. In principle, the standard star and the source should be observed at the same air mass. However, we can expect that an atmosphere extinction model could be built and provide the air mass correction, so that only the zero point of the model should be calibrated by observing only a standard star at zenith. There is little experience about such a model in the mid-infrared, especially at Paranal. Such an experience should be acquired on site during the first months of VISIR use. Given the poor quality of the 20 μm atmospheric window, the observations at 20 μm should always be done when the source is near the meridian. This calibration has to be done for each Imager configuration implying a change of wavelength or PFoV.

3.2.2. Flat field

To allow the calibration star and the science object to have different positions on the detector, we use a flat field procedure which relates the pixel response at the location of the standard star to the pixel response at any other location on the array. The precision to be reached is $\approx$1%.

In the mid-infrared, the sky is a very good homogeneous source. However the flux received on the detector is not homogeneous because, on top of the sky emission, there is also the non homogeneous flux emitted by the telescope mirror. To get rid of the telescope pattern, the flat field is done by performing sky observations at two different air masses. The difference of air mass should be sufficient to have a good signal over noise ratio over the difference of counts between the two sky positions. Of course this method works only if there is no flexion (telescope or instrument) between the two sky positions. A solution may be to obtain observations at a range of air masses (e.g. by trailing the telescope from zenith to the appropriate air mass) in which flexion effects could be isolated (if they show a continuous dependence on elevation for instance). This has to be determined during commissioning. In case of problems with this method, we still have the possibility to use the extended source of the warm calibration unit. The behavior of the detector (relative pixel response as a function of flux, wavelength) will determine if we have to do a flat field for each configuration of the instrument.

3.2.3. Illumination

The flat field cannot fully correct effects like distortion. Even if we do not expect to have much distortion, we need to check it. This calibration is done by scanning a bright star or the point source of the calibration unit across the field. Thus we need to have the photometry of the same star at several positions on the array with a relative precision better than 2%.

3.2.4. Alignment check

From the finite element mechanical calculations, we do not expect alignment problems. However we know that the telescope may have some vignetting. Checks of the pupil alignment by observing a bright star and looking at the pupil with the pupil-imaging lens. The required precision is 1% of the cold stop area.

3.2.5. Monitoring the instrument transmission

We propose to monitor the instrument transmission at 1% precision level. This is done by measuring the signal level when observing the extended source and the point source of the calibration unit. Absolute flux calibration of warm sources is not necessary, but this method requires that they are very stable in time. Otherwise, flux variation on the detector can be attributed to a variation of flux emitted by warm sources rather than to the instrument transmission. Hopefully, it is very unlikely that the two warm sources have the same variation. The use of the two sources allows to disentangle possible calibration source variations from instrumental transmission variations.

3.2.6. Check of filter wavelength as function of the position in the field

For all filters, a slight shift of the central wavelength according to the position in the field occurs. It is necessary to calibrate this effect at least for the narrow band filters. This is done by moving in the field the monochromatic source of the warm calibration unit. The required relative precision is 10% of the filter bandwidth.

3.3. Astrometry

This section deals with the determination of the scales, the relative source position as a function of magnification, the source position as a function of telescope position, the distortion.

3.3.1. Relative source position according to the magnification

We do not expect change of position when changing of filter but it is necessary to characterize the relative position of a point source on the array when changing of magnification. The required level of precision is 0.5 pixel.

This calibration can be done by observing the point source of the calibration unit (or a star) and changing the PFoV. It is also possible to do astrometric calibration by observing a rich asterism. The advantage of the latter method is that it allows to determine both the geometric distortion and the flexure effects by a recursive analysis of the relative displacements of the asterism at various adjacent pointings. In this way, external effects (e.g. wheel stability) would be reduced. The problem is that it should not be very easy to find an asterism in the mid-infrared.

3.3.2. Source position as function of VISIR position

It is necessary to characterize the relative position of a point source on the array according to the telescope position. Finite element mechanical calculations and calculations about the stiffness of mechanisms have shown that the source position is not expected to vary significantly ($\leq$1 pixel) according to the telescope position in normal observing conditions (air mass $\leq$2). Nevertheless, as it is allowed in the technical specifications to have a shift by 1 pixel per hour, we discuss hereafter how the calibration will be done in case of flexions. The required level of precision is 0.2 arcsec.

If needed, a flexion model will be built from finite element calculations and laboratory measurements with the star simulator and the large VISIR integration support which can reproduce any telescope position. Instead of the star simulator, we may use the distortion grid. Such a model will be validated on sky during commissioning by observing stars at different positions.

3.3.3. Distortion

The PFoV is slightly varying as a function of position in the field but the variation is small enough to stay within the uncertainties in the determination of the PFoV. The cumulative systematic variation of the PFoV implies a shift by only one pixel for the Imager in the worst case (source at the corner of the field in the configuration with the largest PFoV, 0.2 arcsec).

The absence of significant distortion in the system will be tested by using the distortion grid (see Sect. 2.2) located on the entrance diaphragm wheel of the Imager. This can be cross-checked by moving the point source of the calibration unit or by offsetting the telescope when observing a bright star.

4. CALIBRATION PLAN OF THE SPECTROMETER SUBSYSTEM

Many aspects of the Imager calibration are also valid for the Spectrometer. This section only deals with items that are specific to the Spectrometer: wavelength calibration, photometric calibration, focusing, slit-viewing and distortion.

4.1. Wavelength calibration

The wavelength calibration is one of the most essential calibrations for the Spectrometer. The Spectrometer has many configurations with individual wavelength scales: 2 low- and 2 medium-resolution gratings used in two orders and two echelles used in a dozen orders. In principle the wavelength scales in all these different grating orders are very accurately known from the Spectrometer optical model. A few zeropoints checks per night would therefore probably be sufficient to calibrate the wavelengths. However, we have chosen a different strategy since the wavelength calibrations can be done very quickly and because redundancy is an advantage for quality control. A wavelength calibration will be made at the beginning of each new spectroscopic configuration (i.e. choice of grating/order), and also within a given configuration at least once per hour.

This calibration is done by turning one of the 5 fixed Fabry-Prot (FP) etalons of the etalons-wheel into the collimated beam behind the cold-stop. This will usually be done with the sky background as light source, but use of the astronomical source or the artificial light sources is also possible. The etalons will always produce a minimum number (>5) of FP-peaks on the detector for which the wavelengths are very accurately known. The shape of the wavelength calibration curve (i.e. the local polynomial fit) will always be taken from the spectrometer optical model. A least squares fit to the pattern of FP-peaks is used to fix the zeropoint. The FP wavelength calibration is less straightforward towards the ends of the slit (there is a wavelength shift of the FP-peaks of typically 0.4% from center to end of the slit). We therefore plan to use the FP calibration at the slit center and use the spectrometer model - after careful verification, of course - to extend the calibration to the rest of the detector plan. The level of precision is within 10% of the FWHM of the instrumental profile corresponding to:

$$\begin{aligned}
\delta\lambda/\lambda &= 2.8\ 10^{-6} \text{ in the high resolution N band mode} \\
&= 5.6\ 10^{-6} \text{ in the high resolution Q band mode} \\
&= 2.0\ 10^{-5} \text{ in the medium resolution N band mode} \\
&= 1.0\ 10^{-5} \text{ in the medium resolution Q band mode} \\
&= 1.8\ 10^{-4} \text{ in the low resolution N band mode}
\end{aligned}$$

4.2. Spectro-photometric calibration

This is basically similar to the photometric calibration of the Imager, but with the main difference that the pixel-to-pixel calibrations in the field and wavelength directions on the detector are done separately.

4.3. Focusing

The focusing procedures in the Spectrometer are essentially different from those in the Imager because the Spectrometer has two image-planes, of which only one can be controlled by the VLT-focus. For this reason the Spectrometer detector has an independent focusing mechanism.

- The slit plane: this is done by moving the pupil-imaging lens on the resolution selection mirror mechanism into the beam and performing a knife-edge test on a bright star in the slit plane. When moving the VLT focus from inside to outside the slit while moving the star across one of the slit edges, the sense of the pupil shadow movements reverses. Interpolation in a short series of pupil images with different VLT focus settings gives a very precise focus.
- The detector plane: once the correct slit focus has been established, the detector can be focused by means of Hartmann pupil-screens in the etalon-wheel, just behind the cold stop. For this we use the low/medium resolution arm in the imaging configuration. Covering alternately one or the other half of the pupil by the screens gives no image shift when the detector is exactly in focus. Again, interpolation in a short sequence of exposures on a bright star is needed.

4.4. Slit viewing

To make full use of the diffraction-limited performance of the spectrometer, very accurate centering of the targets in the entrance slit is necessary. For this centering we rely naturally on the accurate pointing and guiding of the VLT, but regular checks are desirable, especially during the initial setting on an object. Unfortunately it turned out to be extremely difficult to incorporate a true slit-viewing device in VISIR, but a very useful alternative is offered by the imaging mode of the low/medium resolution spectrometer arm, which allows *behind-the-slit-viewing.*

This calibration is done by moving the return flat on the low/medium-resolution grating carrousel into the beam and opening the slit (when needed to the maximum slit width of 15 arcsec). This gives a direct 1:1 image of the slit plane. Centering on the slit should be done with an accuracy of about 50 μm in the slit plane.

4.5. Distortion

There are two kinds of distortion in the spectrometer: distortion along the slit and slit curvature. Both distortions can be predicted very accurately from the spectrometer optical model. They should be extremely stable, but observational checks should be made now and then. Image distortion in the imager is calibrated by means of a pinhole grid in the primary focal plane on the entrance diaphragm wheel. Because the imager/spectrometer selection mirror M0 is on this wheel as well, this grid is not available in the spectroscopic modes. In order to calibrate distortions in the field direction of the spectrometer, a special mask with 20 pinholes will be included in the slit wheel.

- Slit curvature: sky background spectra with a normal (narrow) slit, in line-rich parts of the sky spectrum.
- Distortion along the slit: the same sky background spectra, but now with the 20-pinhole mask.

By comparing both observations with the spectrometer optical model, a complete distortion map for the whole detector field can be constructed. Both the slit curvature and the distortion along the slit should be known to within 0.5 pixel (25 μm) over the whole detector area.

5. CROSS-CALIBRATIONS BETWEEN THE IMAGER AND SPECTROMETER

In some observations, the imager might be used first to select the region to be observed with the spectrometer. Thus the relative position between imager array and spectrometer slit of the spectrometer has to be calibrated with a precision of 0.1 arcsec. This is done by observing a same source (star or artificial source of the calibration unit) alternatively with the imager and the spectrometer in its imaging mode.

In some cases cross checks between calibration from the spectrometer and the imager could be done. Hereafter we just give a few examples of such possible cross checks:

- photometry of lines observed with narrow band filters of the imager and with the spectrometer,
- two-dimensional images obtained by scanning the telescope in the direction perpendicular to the slit and two-dimensional images from the imager.

6. CONCLUSION

In this paper, we have presented the main aspect concerning the calibration of VISIR data. Calibration are mandatory to provide the user and the archive with high quality and well-controlled data even if they represent a significant amount of telescope time. Nevertheless, there should be frequent checks during the commissioning of the instrument and the first months of use of the instrument to validate the calibration plan, and later on, the need for instrumental calibrations will be reduced to a few percents of telescope time.

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