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Very Large Telescope

Paranal Science Operations

MIDI Calibration Plan

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81	29 August, 2007	All	P81 version
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78	1 October, 2006	All	P78 version

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Contents

List of Abbreviations

ADU Analog-to-Digital converter Unit
DIT Detector Integration Time
ESO European Southern Observatory
IRAS Infra-Red Astronomy Satellite
MIDI MID-infrared Interferometric instrument
MSX Mid-course Space eXperiment
OB Observation Block
OPD Optical Path Difference
OT Observation Toolkit
QC Quality Control
VLTI Very Large Telescope Interferometer

Reference documents

	Document number	Issue	Date	Name
1	VLT-MAN-ESO-15820-3519	79	2006-08-31	MIDI User manual
2	VLT-MAN-ESO-15820-3521	1.1	2006-06-26	MIDI Operation manual

1 INTRODUCTION

1.1 Scope

This document lists all the calibration and instrument characterization procedures that are applied to the MIDI instrument. The aim of calibration is to remove the "instrument signature" that may bias the final quantity measured by MIDI: the interferometric visibility as a function of the wavelength over the N-band, of the observed celestial infrared source to study (the "scientific target"), or the correlated flux (still as a function of the wavelength over the N-band) of the scientific target.

This document should be used:

- By the ESO astronomers working on MIDI: as a reference manual for the calibrations and instrument characterizations that must periodically be carried out. It is a supplement of the MIDI operation manual (RD 2).
- By the external astronomers ("users") who have obtained observing time on the VLTI with MIDI: as a description of the MIDI calibrations that are carried out by ESO to calibrate the scientific data at reduction time, and to certify the quality of the data that have been acquired. It is a supplement to the MIDI user manual (RD 1).

All the MIDI detector exposures which do not correspond neither to "fringes on a celestial object of scientific interest" nor to "acquisition on a celestial object" (beam overlap and zero OPD search) are therefore described in this document.

1.2 What MIDI measures

As stated earlier, the purpose of MIDI is to measure interferometric visibilities at different wavelengths of the N-band (from 8 to 13 μm).

We remind that, at a given wavelength λ, the "interferometric visibility" is:

$$V = |\hat{I}(\mathbf{u})|,$$

where $\hat{I}$ is the Fourier transform of the function plotting the intensity vs. the angle of incidence $\mathbf{a}$. The point of sampling $\mathbf{u}$ of $\hat{I}$ is defined by:

$$\mathbf{u} = \mathbf{B}/\lambda,$$

where $\mathbf{B}$ is the on-the-ground baseline (vector spanning between the two VLTI telescopes that are being used by MIDI) projected onto the plane that is perpendicular to the line-of-sight of the observed target.

In MIDI, visibility measurements are affected by:

- MIDI detector artifacts.
- MIDI transmission.
- Atmospheric turbulence.

- Atmospheric transmission.
- Atmospheric thermal emission.

Moreover, the wavelength calibration of MIDI is required in order to know what wavelength is represented by each illuminated pixel of the detector. Also, flux calibrations are required for correlated flux measurement, in order to relationship, at a given wavelength, between the flux, usually expressed in Jansky (1 Jy=10^{-26} $\mathrm{Wm^{-2}Hz^{-1}}$) of the target and pixel levels (in ADUs).

1.3 Summary of the MIDI calibrations

Some of the calibrations are carried out everyday by the VLTI day-astronomer, by executing a calibration-block. They cover the following parameters:

- MIDI detector readout noise.
- MIDI detector linearity of the response.
- MIDI prism and grism transmission.
- MIDI wavelength calbration (for prism/grism, HIGH_SENS/SCI_PHOT).
- MIDI reference pixel positions.

The other calibrations (which are the most important to determine accurate visibilities on the scientific targets) are carried out every night by the VLTI night-astronomer:

- Full MIDI observation of a spectrophotometric calibrator ("star-of-the-month") at the beginning of the night.
- Photometry exposures (automatically performed by the OBs).
- Observation of calibrators for each scientific target.
- Splitting-ratios ("kappa-matrix") of the SCI_PHOT beam combiner.

2 INTERNAL CALIBRATIONS

2.1 Introduction

This sections refers to the calibrations that are performed with MIDI alone, normally during the day. Except for the wavelength calibration, the internal calibrations are mostly performed for an instrument health-check, and cannot be used to remove the instrument signature of MIDI. The internal calibrations are processed by the ESO MIDI pipeline. The resulting pipeline products that correspond to the night of astronomical observations are made available to the users.

2.2 Detector readout noise

As any other electronic detector, the MIDI detector features a readout noise that affects the pixel levels. Though this noise has been minimized by very-low temperature cooling, shielding and tuning of the readout electronics, its value may affect the data quality of MIDI.

We remind that the detector of MIDI is used to take "exposures" consisting of several (typically 200 to 20000) frames in "integrate-then-read" mode. The frames can be full (all the detector area is read out) or windowed (some selected regions of the detector are read out). In the following, we refer as "detector integration time" (DIT), the integration time of an individual frame in an exposure.

The readout noise of MIDI is monitored by taking a full-frame exposure with a large number of frames, with the MIDI shutter closed, and with a minimum DIT. The standard deviation of the pixel level over the frames is computed by the pipeline for each pixel, as well as the standard deviation over all the pixels and all the frames.

A map of the standard deviation of the level for each pixel is therefore produced, and the median (expressed in detector ADUs) of the level standard deviation over the whole detector area is given in the reduced files by the keyword :

- `QC.DETRON.MEDIAN`

Note: No detector bias exposures are taken for data calibration, since they are not really needed: to process fringe exposures, the interferometric beams are subtracted, and the spectral channel for the same wavelength has a similar bias in both interferometric beam. To process photometry exposures, chopping is used and performs a systematic bias subtraction.

Frequency of the calibration: The detector readout noise is normally measured everyday.

Data destination: ESO Instrument health-check. Data can be distributed to the users as certification of the detector quality.

2.3 Detector linearity

The linearity of the MIDI detector is an indicator of the quality of its response curve (number of ADUs vs. integration time when the detector is illuminated by a constant flux source). The response curve of a pixel (x, y) is the function:

$$I_{(x,y)}(T) = a_0 + a_1 T + a_2 T^2 + a_3 T^3,$$

where T is the frame integration time (in ms) that has been setup. It is obvious that the response curve should be as linear as possible, i.e. a_2 and a_3 must be as close to zero as possible. The detector linearity (hence the values of the coefficients a_0, a_1, a_2, a_3) is measured everyday with the following procedures:

1. Due to the optical system of MIDI (not designed for full-frame imaging), it is difficult to have all the pixels illuminated, moreover with a homogeneous level. The optical elements inside the MIDI cryostat are therefore moved to optimize the detector illumination (the setup is: SCI_PHOT beam-combiner + grism + open slit + field camera). The detector is illuminated by the black-screen of MIDI (lying on the warm optics bench), heated at a stable temperature.

2. A set of N exposures is taken. Considering that one of the exposures has a frame integration time T, the next exposure will have an integration time $T + \Delta T$.

3. After the N exposures have been taken, a second-order polynomial fit is performed for each pixel: the average level of the pixel in each exposure is used for the fit, only if this level is below the saturation (65535 ADUs).

Because the pixels are not illuminated with the same flux, a large number of exposures have to be taken. Of course, most of the pixels are already saturating in the last exposures (the ones with the largest integration times). The integration time increment ΔT and the frame integration time T_0 of the first exposure are adjusted so the polynomial fit can be performed on the most illuminated pixels which are the first to reach the saturation level. The number of exposures for a polynomial fit of these pixels has therefore to be large enough. For the moment, 3 different instrument set-ups are used to assess the linearity of the pixels: open (imaging mode), prism, and grism. The HIGH_SENS beam-combiner is used for the prism and the grism.

The results of the pipeline processing are contained in the keywords that represent the $\{a_i\}$ coefficient of the polynomial fit of the average pixel value (over the windowed area) of the detector, for the different configurations:

- `QC.DETLIN.IM.A0`
- `QC.DETLIN.IM.A1`
- `QC.DETLIN.IM.A2`
- `QC.DETLIN.IM.A3`
- `QC.DETLIN.PR.A0`
- `QC.DETLIN.PR.A1`

- `QC.DETLIN.PR.A2`
- `QC.DETLIN.PR.A3`
- `QC.DETLIN.GR.A0`
- `QC.DETLIN.GR.A1`
- `QC.DETLIN.GR.A2`
- `QC.DETLIN.GR.A3`

Note: One should take into account that the thermal background is the main contributor to the detector signal level (compared to the photons from the observed object). The background is removed by processing (by subtraction of interferometric beams, or by chopping), and the dynamic of the useful signal is much smaller than the total dynamic of the detector, on which the linearity is measured.

Frequency of the calibration: The detector linearity is normally measured everyday.

Data destination: ESO Instrument health-check. Data can be distributed to the users as certification of the detector quality.

2.4 Dispersive element transmission

MIDI has two dispersive elements: the prism ($R = 30$) and the grism ($R = 230$). The transmission of each element is measured through narrow-band filters at three different wavelengths ([ArIII]=9.00 μm, [SIV]=10.46 μm, and [NeII]=12.80 μm). Measurement through the same filters but without dispersion are also performed to normalize the transmission. The results (transmission from 0 to 1 at different wavelengths) are stored in the following keywords of the reduced files:

- `QC.DSPTRN.ARIII.PR.TRANS`
- `QC.DSPTRN.SIV.PR.TRANS`
- `QC.DSPTRN.NEII.PRISM.TRANS`
- `QC.DSPTRN.ARIII.GRISM.TRANS`
- `QC.DSPTRN.SIV.GRISM.TRANS`
- `QC.DSPTRN.NEII.GRISM.TRANS`

Frequency of the calibration: The transmission of the prism and of the grism are normally measured everyday. The results are published in the ESO health-check page.

Data destination: ESO Instrument health-check. Data can be distributed to the users as certification of the optical quality.

2.5 Wavelength calibration

The spectral dispersion inside MIDI is performed horizontally on the detector. There is therefore a relationship between the x-coordinate of an illuminated pixel and the wavelength. This relationship can be written:

$$\lambda(X) = C_2 X^2 + C_1 X + C_0$$

where X is the pixel position (1 = left edge column, 320 = right edge column in the displayed image). The coefficients C_0, C_1, and C_2 have to be determined from the wavelength calibration procedure.

There should be one calibration for each instrument spectrometric ((prism or grism) and (HIGH_SENS or SCI_PHOT). The results are stored in the reduced file as a table giving the wavelength corresponding to each "channel" and each "region". A channel refers to a column in a detector window. Its value ranges from 0 (=left edge of the window as it appears on RTD), to the maximum value (=right edge of the window). A "region" is actually a window (there are two regions in HIGH_SENS, and four regions in SCI_PHOT). In the pipeline product, an array of keywords like:

- `QC.WAVECAL.CH<i>.R<j>`

gives the wavelength corresponding to the channel `<i>` in the region `<j>`.

The procedure that is used to internally calibrate the wavelength consists in using the MIDI heated blackscreen, and taking three exposures through different MIDI narrow-band filters ([NeII], [ArIII], [SIV—) having central wavelengths accurately measured in laboratory by the manufacturer. Also, an exposure is taken through a polycarbon foil that has several absorption lines in its N-band spectrum. Exposures without filters and with closed shutter are also taken to process the exposures with filters. From the spectra obtained through the filters, a fit of the $\lambda(X)$ function is performed.

Frequency of the calibration: The wavelength calibration is normally performed everyday. The results are published in the ESO health-check page.

Data destination: ESO Instrument health-check. Data should be distributed to the users.

2.6 Reference pixels

The reference pixels of MIDI are the two pixels of the detector (in imaging mode, without beam-combiner) onto which the photocenters of the target images must be located, in order to ensure a proper beam overlap (that generated interference fringes). It is determined by measuring by a 2-D gaussian fit the position of the center of a special pinhole (INS.SLIT.NAME=T_0.11C) in different beam-combiner setups (OPEN, HIGH_SENS, SCI_PHOT). The pipeline produces from the exposures a set of keywords:

- `QC.REFPIX.OPEN.A.X`
- `QC.REFPIX.OPEN.A.Y`
- `QC.REFPIX.OPEN.B.X`
- `QC.REFPIX.OPEN.B.Y`
- `QC.REFPIX.HS.A1.X`
- `QC.REFPIX.HS.A1.Y`
- `QC.REFPIX.HS.A2.X`
- `QC.REFPIX.HS.A2.Y`
- `QC.REFPIX.HS.B1.X`
- `QC.REFPIX.HS.B1.Y`
- `QC.REFPIX.HS.B2.X`
- `QC.REFPIX.HS.B2.Y`
- `QC.REFPIX.SP.A1.X`
- `QC.REFPIX.SP.A1.Y`
- `QC.REFPIX.SP.A2.X`
- `QC.REFPIX.SP.A2.Y`
- `QC.REFPIX.SP.PA.X`
- `QC.REFPIX.SP.PA.Y`
- `QC.REFPIX.SP.B1.X`
- `QC.REFPIX.SP.B1.Y`
- `QC.REFPIX.SP.B2.X`
- `QC.REFPIX.SP.B2.Y`
- `QC.REFPIX.SP.PB.X`
- `QC.REFPIX.SP.PB.Y`

It is important also to monitor the shifts introduced by the beam-combiner plate:

- `QC.REFPIX.OPEN.A.X-QC.REFPIX.HS.A1.X`
- `QC.REFPIX.OPEN.A.Y-QC.REFPIX.HS.A1.Y`
- `QC.REFPIX.OPEN.B.X-QC.REFPIX.HS.B2.X`
- `QC.REFPIX.OPEN.B.Y-QC.REFPIX.HS.B2.Y`

and the shifts introduced by the photometric beam-splitters:

- `QC.REFPIX.OPEN.A.X-QC.REFPIX.SP.A1.X`
- `QC.REFPIX.OPEN.A.Y-QC.REFPIX.SP.A1.Y`
- `QC.REFPIX.OPEN.B.X-QC.REFPIX.SP.B2.X`
- `QC.REFPIX.OPEN.B.Y-QC.REFPIX.SP.B2.Y`

Frequency of the calibration: The reference pixel calibration is normally performed everyday, to monitor the mechanical stability of MIDI. The values of the reference pixels (DET.NRTS.TARG keywords) are modified by the IS whenever the drift is too important (more than 0.3 pixels).

Data destination: ESO Instrument health-check.

3 ON-SKY CALIBRATIONS

3.1 Photometry

The general expression of the interference fringe at the output of the interferometric channels of MIDI is:

$$\begin{aligned} I_1(\lambda) &= I'_{A1}(\lambda) + I'_{B1}(\lambda) + 2V(\lambda)\sqrt{I_{A1}(\lambda)I_{B1}(\lambda)}sin(2\pi\text{OPD}/\lambda + \phi) \\ I_2(\lambda) &= I'_{A2}(\lambda) + I'_{B2}(\lambda) - 2V(\lambda)\sqrt{I_{A2}(\lambda)I_{B2}(\lambda)}sin(2\pi\text{OPD}/\lambda + \phi) \end{aligned}$$

where:

- $I_1(\lambda)$ and $I_2(\lambda)$ are the intensities from the two outputs of the beam-combiner.
- $I_{xy}(\lambda)$ the stellar intensity collected by telescope x mixed for the channel y of the combiner.
- $I'_{xy}(\lambda)$ is the total intensity (stellar flux + background) collected by telescope x mixed for the channel y of the combiner.
- OPD is the path difference introduced by the atmospheric turbulence and by the optomechanical modulator (used to produce interferograms).

Since the N-band intensity in each beam that feeds MIDI mostly contains thermal sky background, the fringe is detected by subtracting I_1 and I_2. Supposing $I_{A1} = I_{A2}$ and $I_{B1} = I_{B2}$ (the ZnSe beam-combiner plate of MIDI acts like a 50/50 beamsplitter):

$$I_1(\lambda) - I_2(\lambda) = 4V(\lambda)\sqrt{I_{A1}(\lambda)I_{B1}(\lambda)}sin(2\pi\text{OPD}/\lambda + \phi)$$

Therefore MIDI only measures a fringe amplitude. To get the visibility $V(\lambda)$, it is necessary to measure $I_{A1}(\lambda)$ and $I_{B1}(\lambda)$, which means that $I_A(\lambda)$ and $I_B(\lambda)$ have to be measured. This is called "photometric" measurement (though it is a spectrophotometric measurement actually).
If the HIGH_SENS beam combiner is used, the photometric measurement is performed by taking an exposure with beam A open only, and then with beam B open only, with telescope chopping (to remove the thermal background). If the SCI_PHOT beam-combiner is used, 30/70 ZnSe beamsplitter plates take 30% of the light from each telescope upstream of beam combination. The two resulting "photometric" beams are dispersed and imaged on the detector next to the interferometric beams. In this case, if the grism is used, photometric channels show a lot of dispersion at the top and bottom of the detector. It is therefore useful to take one-beam-only exposures (as if HIGH_SENS were used) to process the photometric channels. It has been shown that one-beam-only exposures can be used to refine the data in SCI_PHOT+PRISM setup. However, neither the current MIDI data reduction package nor the pipeline support yet the processing of SCI_PHOT data using one-beam-only exposures.

Frequency of the calibration: photometry exposures of beam A and beam B are automatically taken after the fringe exposure by the observation template script of any MIDI OB, whatever the beam combiner (HIGH_SENS or SCI_PHOT). In case of technical problem during the photometry exposures, the downtime should not exceed 10 minutes (otherwise, the fringe exposure will be repeated).

Data destination: Photometry data are indeed distributed to the users for their targets and for the calibrators of the night. Visibility obtained by fringe+photometry on a standard at the beginning of each night ("star-of-the-month") will be used for health-checks (monitoring of the transfer function). Also, the photometry levels of the star-of-the-month will be monitored.

3.2 "Kappa-matrix" (SCI_PHOT splitting ratios)

The kappa-matrix defines the relationship between the intensity in the interferometric channels and the intensity in the photometric channels. It depends on the splitting ratios of the ZnSe plates that form the beam-combiner, and is chromatic. It is defined by:

$$[\kappa] \text{ such that : } \mathbf{I} = [\kappa]\mathbf{P} \Longleftrightarrow \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{bmatrix} \kappa_{11} & \kappa_{12} \\ \kappa_{21} & \kappa_{22} \end{bmatrix} \begin{pmatrix} P_1 \\ P_2 \end{pmatrix}$$

The kappa-matrix has to be established for each dispersive element (prism and grism). It can be measured from the one-beam-only exposures taken on a calibrator. Normally, a kappa-matrix computed on a bright calibrator ("star-of-the-month") at the beginning of each night for quality control purpose.

Frequency of the calibration: One-beam-only exposures for kappa-matrix are taken for each SCI_PHOT OB. Kappa-matrix for quality control is computed each night.

Data destination: Kappa-matrix exposures are distributed to the users. The values obtained are monitored for health-check.

3.3 Visibility calibration

The measured visibility $\mu(\lambda)$ of a target is always lower than the expected theoretical visibility $V(\lambda)$. The main reasons are the atmospheric turbulence (piston and tip-tilt) and slight misalignment in beam overlap. The instrumental transfer function is defined by:

$$T(\lambda) = \frac{\mu(\lambda)}{V(\lambda)}$$

To determine T, a star with a known and fixed visibility V_0, called a “calibrator” has to be observed with MIDI, yielding a measured visibility μ_0. The calibrator should preferably be unresolved ($V_0 = 1$), be as close as possible to the science target on the celestial sphere, and have a spectral type similar to the one of the science target.

Though the users are free to use as calibrators for their scientific targets the objects of their choice, we recommend them to use the calibrators from the ESO CalVin database. These calibrators have been selected by the MIDI consortium as follows:

1. A first batch of 511 candidates has been selected from the IRAS and MSX point-source catalogs (on the criteria of observability at VLTI with MIDI: coordinates and magnitudes).
2. Spectrophotometric observations in the mid-IR of these candidates were performed. For each candidate, a χ^2 was calculated on the discrepancy between the observed spectrum and the spectrum predicted by a stellar model (according to the spectral type of the star). The quality of a calibrator is given by this χ^2 (the smaller the better). A χ^2 too high indicates an infrared excess in the calibrator, which is not therefore suitable for MIDI. Keeping only the candidates having $\chi^2 < 5$, the list has been reduced to 178 calibrators.
3. The spectrophotometric observations allowed also to estimate the diameter of the calibrators.

The CalVin database is periodically refreshed: calibrators that are found to have a visibility abnormally low with MIDI are removed from CalVin.

Frequency of the calibration: In service mode, a calibrator is systematically observed after or before each scientific target to be observed. The MIDI setup (beam combiner, dispersive element, integration time) for the calibrator observation should be identical to the one of the scientific target observation. The difference of observation time is in general between 20 and 30 minutes, and should not exceed 45 minutes. In visitor mode, the user is free to observe calibrators whenever wanted within the allocated time. It is therefore possible, for example, to “frame” a scientific target observation by the same calibrator observed twice: before and after the scientific target. Special calibrations like that can be carried out in service mode after application for a waiver. The calibration time is counted in the total time allocated for the program.

Data destination: All the calibrator data of a given night are made available.

3.4 Correlated flux calibration

In order to convert the visibility vs. wavelength curve into flux vs. visibility (with the flux expressed in Jansky), a source with a flux which is known and constant over the whole N-band spectrum has to be observed with MIDI (taking fringe + photometry exposures). Such a source is called a "spectrophotometric calibrator". The catalog of spectrophotometric calibrators for MIDI is available at:

`http://www.eso.org/instruments/midi/tools/spectrophot_std.html`

The spectrophotometric calibrators that are used for MIDI have N-band flux spectra known with a precision of 3%. They are entries common to the MIDI consortium calibrator catalog, and to the Cohen infrared calibrator catalog or the ISO GBPP catalog. More information about these targets (including flux vs. wavelength tables) can be found at:

`http://www.iso.vilspa.esa.es/users/expl_lib/ISO/wwwcal/isoprep/cohen/templates/`

`http://www.iso.vilspa.esa.es/users/expl_lib/ISO/wwwcal/isoprep/gbpp/model/HD/`

Frequency of the calibration: Users wishing spectrophotometric calibrations have to select one as a calibrator for their targets. As for any other calibrator, it is recommended to select the spectrophotometric calibrator so its airmass is close to the one of the scientific targets.

Data destination: Spectrophotometric calibrators are available to the users following the rules applying to normal calibrators (see previous section).

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