## VERY LARGE TELESCOPE

## GRAVITY Pipeline User Manual

VLT-MAN-ESO-19500-XXXX

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## 1 Introduction

This manual is a complete description of the data reduction recipes implemented for the GRAVITY pipeline, reflecting the status of the GRAVITY pipeline as of now.

The main part of the document is focused on the main feature of the pipeline useful to the science user of GRAVITY. The detailled appendixes may be more useful to ESO staff for the purpose of long term re-calibration and data quality control.

### 1.1 Reference and applicable documents

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[1] OIFits Explorer. http://www.jmmc.fr/oifitsexplorer. 46
[2] QFitsView. http://www.mpe.mpg.de/ ott/QFitsView/. 46
[3] ESO/SDD/DFS, http://www.eso.org/cpl/. CPL home page. 88
[4] T. A. Pauls, J. S. Young, W. D. Cotton, and J. D. Monnier. A Data Exchange Standard for Optical (Visible/IR) Interferometry. PASP, 117:1255-1262, November 2005. 16, 51, 52, 91
[5] C.Sabet P.Ballester. VLTI Data Interface Control Document. ESO, 1.0 edition, 3 June 2002. VLT-SPE-ESO-15000-2764. 46, 49

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## 2 GRAVITY Instrument Description

The GRAVITY instrument has been developed under ESO contract by the GRAVITY consortium.
The main purpose of the instrument is to measure the angular separation between stars in the vicinity of the Galactic Center black hole, and even the position and motion of the infrared emission of the black hole itself during flares.

GRAVITY recombines the light beams collected by either the four 8.2 m Unit Telescopes or the four VLTI Auxiliary Telescopes. The general principle of the instrument is to recombine the light coming from one (single field mode) or two (dual field mode) astronomical targets in two different beam combiners: the Fringe Tracker (FT) and the Science Combiner (SC). In single field mode, the light from the target is split between the FT and SC channels using a beam splitter, while in dual field mode a mirror directs the light from each target to their respective beam combiners. The FT is optimized to record fringes at very high frequency (up to 1 kHz ), in order to measure and compensate in real time the atmospheric piston effect using a dedicated actuator in the instrument. As the observed targets are both within the atmospheric isoplanetic patch, the correction of the atmospheric piston by the FT stabilizes the fringes of the SC channel. This gives the possibility to integrate for up to several tens of seconds, and therefore reach a high sensitivity, even at relatively high spectral dispersion, on the SC channel.

The properties of the interference fringes are measured separately in the FT and SC beam combiners. GRAVITY measures the classical interferometric observables of any source, as the previous VLTI instruments (VINCI, MIDI, AMBER and PIONIER). The FT spectral resolution is limited to 5 spectral channels over the $K$ band. The SC has three available spectral resolutions: low (20), medium (500) and high (4000), providing approximately 10, 200 and 1800 spectral channels over the $K$ band.

The phases of the SC beam combiner are referenced to the FT using a metrology system that encompasses the optics of the VLTI up to the secondary mirror of the telescopes. Thanks to this link between the two beam combiners, GRAVITY provides very accurate measurements of the differential position of the fringe pattern obtained, for each baseline, between a reference star (in the FT channel) and the target star (in the SC channel). Given the VLTI FOV, the angular separation between the reference object and the science target is limited to 5 arcsec with the ATs and 2 arcsec with the UTs. Within this restricted separation, the final accuracy on the relative astrometry is expected to be of a few tens of $\mu$ arcsec.

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## 3 Data flow overview

### 3.1 The concept of recipe

The pipeline is built over "recipes" that implement the basic steps of the reduction. The recipe input is a Set Of Files (SOF), which contains the list of files to reduce, associated with the required calibrations. Each recipe has a list of possible options. Each recipe produces one or several products. The recipes can be triggered by several mechanisms:
gasgano is the ESO user interface to classify, select files (= construct a SOF) and launch recipes.
esorex is the ESO command line tool to launch a recipe on any SOF manually written by the user.
reflex is the ESO environment allowing to reduce an entire directory in batch mode.
The GRAVITY consortium has also built a dedicated python script which browses the content of the current directory, classifies the files, writes the SOFs and automatically triggers the corresponding recipes via esorex.

### 3.2 The concept of SOF

A SOF is a consistent list of files to be sent to a recipe. Each file in the list shall be assigned a DO Category, which tells the recipe its purpose in the reduction. In the GRAVITY pipeline, the DO categories are trivially built from the DPR.TYPE, DPR.CATG and PRO.CATG keywords in the FITS header.

### 3.3 Instrument calibrations

In order to reduce interferometric observations, it is mandatory to calibrate the detectors and the combiners. These calibrations are obtained via dedicated observations of the internal source with all shutters closed, one shutter open at a time, two shutters open at a time, and all shutters open.

The recipe gravity_dark creates the DARK calibration product, which contains the mean detector bias and the detector readout noise. It is associated matching the detector and the optical setup of the observation. The dark phisically doesn't depend on the optical setup, however in GRAVITY the detector gain is setup based on the resolution mode used.

The recipe gravity_p2vm creates the BAD (bad pixel), FLAT (internal transmission), P2VM (internal phase and contrast) and WAVE (wavelength map) calibration products. They shall match the optical setup of the observation for the SC and the FT, as well as the detector gain for the FT.

These products are all needed in order to reduce the interferometric observations of science target.

### 3.4 From raw data to raw visibilities

The first step is to reduce the raw interferometric observations into uncalibrated measurement of the visibilities and closure phases. This step is generally done file-per-file, that is each OBJECT exposure in the raw directoryhas a corresponding files in product directory (although it is possible to reduce several files together). Note that

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this step includes the averaging over all the frames that compose a standard exposure. This step is rather long (several hours for an entire night).

The recipe is gravity_vis.
The product (*_VIS) is an uncalibrated OIFITS file, containing the flux, the square visibilities, the complex visibilities and the closure phases for both the SC and the FT combiners.

The recipe produces an optional product, called P2VMRED, which contains many intermediate signals of the processing. It is very useful to assess the data quality. It is also possible to restart the reduction from the P2VMRED product, thus saving time for users who want to explore several values of recipe parameters.


Figure 3.1: Data flow of gravity_vis recipe.

### 3.5 From raw visibilities to calibrated visibilities

The second step is to calibrate the observation of science objects with the observation of calibration stars. This step could be performed "globally", that is all the uncalibrated *_VIS oifits can be loaded first, then the pipeline searches for consistent sequences (same setup, same DIT, same wavelength table...), and then each sequence is calibrated independently with the calibration stars that could be found within it. This step is rather short (1min for an entire night).

The recipe is gravity_viscal.
The product (*_VIS_CALIBRATED) is a calibrated OIFITS file, ready for science.


Figure 3.2: Data flow of gravity_viscal recipe.

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## 4 Instrument Data Description

### 4.1 RAW science data

The RAW frames created when observing have the following DPR.TYPE:

OBJECT,DUAL

OBJECT,SINGLE

SKY,SINGLE
SKY,DUAL
are observations of a nearby pair of objects, one feeding the fringetracker (FT) and the other feeding the science combiner (SC). It can be of category SCI or CAL.
are observations of a single object, feeding both the fringe-tracker (FT) and the science combiner (SC). It can be of category SCI or CAL.
are observation of an empty patch of the sky near the object in order to measure the sky brightness.

The OBJECT,DUAL and OBJECT,SINGLE types have a category DPR.CATG=SCI when observing a science target, and a category DPR.CATG=CAL when observing a calibration star used to monitor the transfer function.

### 4.2 RAW calibration data

The RAW frames used to calibrate the instrument on a daily-basis have the following DPR.TYPE:

DARK

FLAT

WAVE
WAVESC
are observations with all shutters closed, in order to calibrate the detector dark level and the detector + dark level noise.
are observations of the internal source with one shutter open, in order to calibrate the positions of the spectra on the detectors and the internal transmission of the instrument.
are observations of the internal source with two shutters open, in order to calibrate the internal contrasts and phases of the instrument.
are observations of the internal source with all shutters open, in order to calibrate the wavelength table, and the internal closure phases. The WAVE data are recorded by scanning on both SC and FT, with FDDL in open loop and no fringe tracking (in order to calibrate the FT wavelengths). The WAVESC data are recorded by scanning only SC, and FDDL in close-loop and fringe tracking (to calibrate the SC wavelengths).

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### 4.3 STATIC calibration

The STATIC calibration frames have the following DPR.TYPE:

| DISP_MODEL | is the model of the optical dispersive index $n(\lambda)$ of the fiber differential <br> delay lines (FDDL) of the instrument. |
| :--- | :--- |
| DISP_VIS | is an intermediate product when building DISP_MODEL, used to visu- <br> alise the quality of the FDDL stretching sequence. <br> is the catalog of stellar diameters used to estimate the transfer function. |
| DIAMETER_CAT | is a list of Earth Orientation Parameters (EOP) and DUT1 versus time. <br> These corrections are only needed for the most demanding astrometric <br> measurements. <br> contains the position of the metrology receivers |

### 4.4 PRODUCT calibration data

The PRODUCT of the calibration by the recipes gravity_dark and gravity_p2vm are identified by the following PRO.CATG keyword:

DARK

BAD

FLAT

WAVE

## P2VM

contains images with the dark level and variance for the SC and FT detectors.
contains images with the identified bad pixels for the SC and the FT detectors.
contains images of the profiles used to extract the SC spectra from the detector. There is one extracted spectrum per output of the detector and per polarisation if split (thus 24 or 48 spectra for each SC and FT combiners).
contains tables with the effective wavelengths of each channel of every spectra extracted with the profile. These tables are necessary to re-align the different spectra (outputs of the detector) onto a common wavelength grid.
contains tables with the internal transmission, contrast and phase of every output of the detector versus wavelength. These form the so-called pixel2 -visibility matrix used to extract the interferometric visibility from the spectra.

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### 4.5 PRODUCT science data

The products of the science reduction by the recipe gravity_vis are identified by the following PRO.CATG keywords:

SINGLE_SKY
DUAL_SKY

SINGLE_SCI_VIS
SINGLE_CAL_VIS
DUAL_SCI_VIS
DUAL_CAL_VIS
SINGLE_SCI_P2VMRED
SINGLE_CAL_P2VMRED
DUAL_SCI_P2VMRED
DUAL_CAL_P2VMRED

SPECTRUM
PREPROC
contains the mean brightness of the sky and its variance. Contrarily to DARKs, these quantities possibly depend on the instrument mode because different optics are used.
are OIFITS files [4] with the uncalibrated flux, squared visibilities, complex visibilities and closure phases extracted from the raw observation of an object. SCI/CAL corresponds to a science target or a calibration star used to monitor the transfer function.
are the raw data already processed through the P2VM algorithm. They contain flux per beam, and coherent flux per baseline, for each individual frame of the exposure. As such, they are intermediate products between the RAW data and the final, averaged, OIFITS. They also contain many intermediate results of the processing. The file size is huge ( $>200 \mathrm{Mb}$ ). It is meant to assess the overal data quality and tune the reduction parameters. It is not used for science. Its format is inspired by OIFITS, but it is not strictly compliant.
contains the RAW data already corrected for cosmetic and collapsed into one spectrum per combiner output. In SPECTRUM, the data are not yet re-interpolated into a common spectral wavelength grid, while this step is done in PREPROC. As such, they are debug-level intermediate products between the RAW data and the final, averaged, OIFITS.

The PRODUCT of the final calibration step by the recipe gravity_viscal are identified by the following PRO.CATG keywords:

## SINGLE_SCI_VIS_CALIBRATED DUAL_SCI_VIS_CALIBRATED

SINGLE_CAL_TF<br>DUAL_CAL_TF

are the final OIFITS file of the reduction, science ready. They contain the interferometric observations calibrated with the transfer function.
are OIFITS files containing the transfer function value estimated by the corresponding observation of a calibration star. It is the observed visibility of a calibrator divided by its visibility estimated from its diameter.
are OIFITS files containing the estimated (interpolated) value of the transfer function at the time of the corresponding science target observation.

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## 5 Data Reduction

### 5.1 Graphical overview of the cascade



Figure 5.1: Data reduction cascade for observations in mode SINGLE. As of now, the cascade is the same for the mode DUAL.

### 5.2 Using Gasgano

Gasgano, provides a graphic interface for data browsing, classification and association, and offers several other utilities such as easy access to recipes documentation and preferred data display tools.

Gasgano can be started from the system prompt in the following way:

```
gasgano &
```

Use the Add/Remove Files entry of the File menu to load data. The data are hierarchically organised as preferred by the user. More information about a single frame can be obtained by clicking on its name.

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Frames can be selected from the main window for being processed by the appropriate recipe. Before launching the recipe, its configuration may be modified on the Parameters panel (on top). The window contents might be saved for later use by selecting the Save Current Settings entry from the File menu.

Please refer to the Gasgano User's Manual [7] for a more complete description of the Gasgano interface.

### 5.3 Using EsoRex

EsoRex is a command line utility for running pipeline recipes. It may be embedded by users into data reduction scripts for the automation of processing tasks. Users are free to define manually the input SOF and the appropriate configuration parameters.

A SOF for EsoRex is a simple ASCII file listing the files and their DO Category. Examples of SOF are given in the description of each recipe. Note that ' $\#$ ' is the comment character.

The basic syntax to use EsoRex is the following:

```
esorex [esorex_options] recipe_name [recipe_options] set_of_frames.sof
```

To get more information on how to customise EsoRex (see also [7]), or on a specific recipe, run the commands:

```
esorex -h
esorex -h recipe_name
esorex --man-page recipe_name
```

For more information on EsoRex, see http://www.eso.org/cpl/esorex.html.

### 5.4 Using run_gravi_reduce.py python script

The consortium has written a simple python script that classifies the files in the current directory, associates them with calibrations, and runs the corresponding recipes.

Instrument calibration and data reduction is triggered by the following script:

```
run_gravi_reduce.py [options]
```

The script performs the following steps:

1. Trigger the recipe gravity_dark on all standalone DARK.
2. Trigger the recipe gravity_p2vm on all sequences of $1 \times$ DARK, $4 \times$ FLAT, $6 \times$ P2VM, $1 \times$ WAVE, $1 \times$ WAVESC.
3. Trigger the recipe gravity_vis on all OBJECT,* files.

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The script will search for (static) calibrations in the current directory if any. It will also search in the upper directory . ./common_calibration/. The products are created in the reduced/subdirectory.

Before triggering a recipe, the script writes the corresponding SOF and the esorex command in the reduced/ subdirectory. Thus one can manually reproduce a given reduction by executing:

```
./reduced/GRAVI.XXXX_esorex.sh
```

To get more information on syntax and options, run the commands:

```
run_gravi_reduce.py -h
```

Transfer function and trending can be then triggered with the following script:

```
cd reduced/
run_gravi_trend.py [options]
```

The script performs the following steps:

1. Trigger the recipe gravity_viscal on all *CAL_VIS.
2. Trigger the recipe gravity_viscal on all *SCI_VIS.
3. Produce trending plots to check the transfer function.

The products are created in the calibrated/ and trend/ subdirectories.

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## 6 Known Problems

### 6.1 Spectral calibration

The spectral calibration between baselines is accurate to 0.1 nm . It corresponds to half a pixel in spectral direction (thus $1 / 4$ of the spectral resolution element) in HR.

This uncertainty can generate biases in the closure phase, which amount to $\approx 3$ deg when observing at a groupdelay of $40 \mu \mathrm{~m}$.

The absolute spectral calibration is accurate to 0.5 nm , which corresponds to one spectral resolution elements in HR.

### 6.2 Uncertainties in products

The uncertainty of product data contains the statistical noise only, computed by bootstrapping over the NDIT samples when possible. It does not contain the calibration uncertainty.

When the number of valid DIT within an exposure is lower than 5, the statistic to compute the final error bars also include additional MonteCarlo realisation of the theoretical photon and detector noise (to reach 5 samples). These uncertainties are thus less realistic.

### 6.3 Metrology and polarization

The metrology snr does not follow strictly the polar. $\mathrm{s} / \mathrm{polar}$. p brightness ratio of the beam combiners when inserting the linear polarizer and rotating the half-wave plates. The reason is that the final polarization alignment is a compromise between best possible SC/FT s/p nulling of a polarized source, and the metrolgy snr (= alignment between FT/SC metrology and 3rd beam). In the "detector real time display reference frame" the metrology polarization is therefore aligned with the left FT channels and the lower SC channels, that is, with the P1 polarization signals in the GRAVITY data files.

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## 7 Pipeline Recipe Interfaces

### 7.1 List of all recipes

We here list the role of each recipe. The input, output, options and QC parameters are detailled in each dedicated subsection.

| gravity_badpix | Detect the bad pixels on the detectors. |
| :---: | :---: |
| gravity_biasmask | *Not Offered* Determine which pixels can be used to measure the bias of SC detector. |
| gravity_dark | Calibrate the detector noise and background level. |
| gravity_disp | Calibrate the linearity and the dispersion of the differential delay lines. |
| gravity_eop | Download the last values of the Earth Orientation Parameters and DUT from IERS. |
| gravity_p 2 vm | Detect the bad pixels on the detectors, calibrate the wavelength tables, calibrate the interferometric contrast and phase. |
| gravity_piezo | Calibrate the response of the piezo actuators. |
| gravity_postprocess | Post-process the products, to fine-tune their content. |
| gravity_vis | Compute the visibilities from raw observation of OBJECT. |
| gravity_vis_from_p2vmred | Compute the visibilities from P2VMRED intermediate product. |
| gravity_viscal | Calibrate visibilities with the transfer function (atmospheric interferometric response). |
| gravity_wavelamp | Measure the position of the Argon lines in the spectra. |

## 7.2 gravity_badpix

The recipe creates a BAD calibration map from raw DARKs and raw FLATs observations. Since it is not associated with the calibration of the instrumental transmission, more specific darks or flats can be used. Such as very long darks, fore better statistic; and/or defocused flats to illuminate more pixels. The create BAD map can then be used as an input for further calibration (P2VM) and observations.

1. Load input files

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2. Compute badpixel from dark rms, dark median, and flat value
3. Save the product)

## Input

| DO.CATG | short description |
| :--- | :--- |
| DARK_RAW | raw dark, all shutters closed (DPR.TYPE=DARK) |
| FLAT_RAW $x 4$ | raw flats, one sutter open (DPR.TYPE=FLAT) |

## Output

| PRO.CATG | short description |
| :--- | :--- |
| BAD | badpixel calibration (PRO.CATG=BAD) |

## Parameters

| Name | short description |
| :--- | :--- |
| -static-name <br> -bad-dark-threshold | Use static names for the products (for ESO). [FALSE] <br> the rms factor for dark bad pixel threshold. [10] |

## 7.3 gravity_biasmask

*UNOFFERED* The recipe creates a binary mask (BIASPIX) indentifying which pixels of the SC detector are not illuminated, and thus could be used as bias-pixels in further processing. The idea would be to input such a mask, as static calibration, in all reductions. However this is not yet implemented, nor demonstrated as necessary.

1. Load the input files
2. Identify the mask
3. Write product

## Input

| DO.CATG | short description |
| :--- | :--- |
| DARK_RAW | raw dark, all shutters closed (DPR.TYPE=DARK) |
| FLAT_RAW $x 4$ | raw flats, one sutter open (DPR.TYPE=FLAT) |


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## Output

| PRO.CATG | short description |
| :--- | :--- |
| BIASMASK | biaspixel mask calibration |

## Parameters

| Name | short description |
| :--- | :--- |
| - -static-name | Use static names for the products (for ESO). [FALSE] |

## 7.4 gravity_dark

This recipe computes the DARK calibration for the SC, the FT and the ACQ detectors. The SC detector is first debiased using the biaspixels, before computing the dark mean and rms. For detectors, the mean dark level of each pixel and the stdev of each pixel are saved in the output product.

1. Loop on input dark files and concatenate them
2. Compute the median and rms of these concatenated files
3. Save the product (FT, SC, ACQ camera into same product)

## Input

| DO.CATG | short description |
| :--- | :--- |
| DARK_RAW | raw dark, all shutters closed (DPR.TYPE=DARK) |

## Output

| PRO.CATG | short description |
| :--- | :--- |
| DARK | dark calibration |

## Parameters

| Name | short description |
| :--- | :--- |
| -static-name | Use static names for the products (for ESO). [FALSE] |


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| -bias-method | Method to average the biaspixels when cleaning-up the <br> SC detector (only applied to MED and LOW). Ideally the <br> same value shall be used when reducing the DARK with <br> gravity_dark and the OBJECT with gravity_vis. UTO |
| :--- | :--- |
| is equivalent to MASKED_MEDIAN_PER_COLUMN |  |
| if the data ontains in the IMAGING_DETECTOR_SC |  |
| extension the EFT, HALFLEFT, CENTER, HALFRIGHT |  |
| and RIGHT columns. therwise it is like MEDIAN. |  |
| <AUTO I MEDIAN I MEDIAN_PER_COLUMN । |  |
| MASKED_MEDIAN_PER_COLUMN> [AUTO] |  |
| Save the BIAS_SUBTRACTED intermediate product. |  |
| Lias-subtracted-file |  |
| [FALSE] |  |

## Pseudo code

reference 10.1

```
    frameset = recipe_input_frameset
    parameters = recipe_input_parameters
/* Extract DARK frameset */
dark_frameset = gravi_frameset_extract_dark_data (frameset)
    nb_dark = size(dark_frameset)
    /* Merge the dark frames */
for i in nb_dark :
    data = gravi_data_load_rawframe (dark_frameset[i])
    gravi_data_detector_cleanup (data, parameters) // see algo 10.1
    if i=0 :
        raw_dark = data
    else :
            gravi_data_append(raw_dark, data)
/* compute the reduced dark and save product */
    dark_map = gravi_compute_dark (raw_dark) // see algo 10.2
    gravi_data_save_new(dark_map, parameters)
```


## 7.5 gravity_disp

This recipe is associated to the template GRAVI_all_disp. It measures the phases obtained on the internal source at the position of the Argon lines and various positions (= fiber stretch) of the Fibered Differential Delay Lines (FDDL). It deduces the linearity model and the dispersion model of the differential delay lines. These models are stored as polynomials versus wavelength.

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1. Reduce all the input DISP files (see gravity_vis), write each product
2. Compute the dispersion parameters from this entire dataset
3. Write product

## Input

| DO.CATG | short description |
| :--- | :--- |
| FLAT | flat calibration (PRO.CATG=FLAT) |
| BAD | badpixel calibration (PRO.CATG=BAD) |
| WAVE | wave calibration (PRO.CATG=WAVE) |
| P2VM | p2vm calibration (PRO.CATG=P2VM) |
| DARK | dark calibration (PRO.CATG=DARK) |
| WAVELAMP | spectrum of Argon, with position of lines |
| DISP_RAW $(>50)$ | raw dispersion |

## Output

| PRO.CATG | short description |
| :--- | :--- |
| DISP_VIS | intermediate product |
| DISP_MODEL | dispersion model of FDDL |

## Parameters

| Name | short description |
| :--- | :--- |
| -static-name | Use static names for the products (for ESO). [FALSE] |
| -bias-subtracted-file | Save the BIAS_SUBTRACTED intermediate product. |
|  | [FALSE] |
| -spectrum-file | Save the SPECTRUM intermediate product. [FALSE] |
| -preproc-file | Save the PREPROC intermediate product. [FALSE] |
| -astro-file | Save the P2VMRED intermediate product. [FALSE] |
| -vis-file | Save the ASTROREDUCED intermediate product. [FALSE] |
| -ditshift-sc | Save the VIS intermediate product. [FALSE] |
|  | Shift the time of SC DITs by an integer value to account for |
|  | lost frames in exposure (issue on the instrument side, report |
|  | to instrument team). The time of all DITs in exposure are in- |
|  | creased by ditshift x PERIOD. ditshift can be 0, positive (sys- |
|  | tem has lost one SC DIT), or negative (SC desynchronized). |
|  | [0] |
|  | Include the 6th pixels ot the FT. [TRUE] |
|  | Delay between the end of ACQ frame and correction offset |
| -extra-pixel-ft | seen by the metrology diodes, in seconds. [0.25] |


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| -use-fiber-dxy |
| :---: |
| -use-met-rtc |
| -smooth-faint |
| -preswitch-delay |
| -postswitch-delay |
| -chi2r-threshold |
| -chi2r-sigma |
| -nsmooth-snr-ft |
| -phase-ref-sc-maxdeg <br> -use-met-zero |
| -imaging-ref-met |
| -snr-min-ft |
| -global-state-min-ft |
| -global-state-max-ft |
| -state-min-ft |
| -tracking-min-sc |
| -vfactor-min-sc <br> -opd-pupil-max-sc |

Use the fiber position when computing OPD_TEL_CORR. [FALSE]
Reduce metrology voltage with the real time algorithm nstead of using the pipeline's algorithm. [FALSE]
Adds an additional factor to the smoothing of he metrology voltages in faint mode. [1]
Delay where metrology values are ignored before aser brightness is switched in faint mode, ms. [50]
Delay where metrology values are ignored after aser brightness is switched in faint mode, ms. [200]
Threshold in chi2 2 of the fringe-fit to declare a bad value. This is usefull to detect outliers or cosmic in individual frames. [50.0]
Threshold in chi2r of the fringe-fit (in unit of the the std of chi 2 r in the spectral direction) to declare a bad value. This is usefull to detect outliers or cosmic in individual frames. [100.0]
Number of samples to average coherently when computing the real-time SNR and GDELAY of the FT (shall correspond to the atmospheric coherence time). The integration window runs from -nsmooth -> +nsmooth. [5]
Maximum deg for the fit of PHASE_REF. [3]
Flag to add a constant value to OPD_DISP. This constant value is taken from the header. [FALSE]
Metrology source used for IMAGING_REF calculation: Use fibre coupler metrology (FC); Use fibre coupler metrology corrected from pupil motion (FC_CORR); Use telescope metrology (TEL). <FC I FC_CORR I TEL> [FC]
SNR threshold to accept FT frames ( $>0$ ). It raises the first bit («0) of column REJECTION_FLAG of FT. [30.0]
Minimum OPDC state to accept FT frames ( $>=0$ ) It raises the second bit ( $<1$ ) of column REJECTION_FLAG of FT. [2.0]
Maximum OPDC state to accept FT frames ( $>=0$ ) It raises the second bit ( $<1$ ) of column REJECTION_FLAG of FT. [4.0]
Minimum OPDC state per baseline to accept FT frames ( $>=0$ )
It raises the second bit ( $<1$ ) of column REJECTION_FLAG of FT. [1.0]
Minimum ratio of accepted FT frames in order to accept a SC frames (0..1), that is, for each SC DIT, the fraction of the time the REJECTION_FLAG of the FT is not 0 . It raises the first bit ( $<0$ ) of column REJECTION_FLAG of SC. [0.8]
vFactor threshold to accept SC frame (0..1). [0.8]
Maximum OPD_PUPIL (abs) to accept SC frames. It raises the third bit («2) of column REJECTION_FLAG of SC. [9999.0]

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| -opd-pupil-stddev-max-sc | Maximum OPD_PUPIL_STDDEV to accept SC frames. It raises the fourth bit («3) of REJECTION_FLAG of SC. [2.9e07] |
| :---: | :---: |
| -max-frame | Maximum number of frames to integrate coherently into an OIFITS entry. [10000] |
| -force-same-time | Force all baseline/quantities to have strictly the same TIME and MJD columns. [FALSE] |
| -debias-sc | Subtract the V2 bias from SC. [TRUE] |
| -debias-ft | Subtract the V2 bias from FT. [TRUE] |
| -nboot | Number of bootstraps to compute error (1..100). [1] |
| -vis-correction-sc | Correction of SC visibility from losses due to long integration, using the measured visibility losses with the FT (VFACTOR and/or PFACTOR) or by forcing the SC visibilities to match those of the FT (FORCE). Possible choices are: <VFACTOR I PFACTOR I VFACTOR_PFACTOR I FORCE \| NONE> [NONE] |
| -phase-ref-sc | Reference phase used to integrate the SC frames. Use a selfestimate of the phase, fitted by poly. (SELF_REF) Use the FT phase only, interpolated in lbd (PHASE_REF) Use the FT+MET-SEP.UV phase (IMAGING_REF). <SELF_REF PHASE_REF \| IMAGING_REF | AUTO | NONE $>$ [AUTO] |
| -output-phase-sc | With DIFFERENTIAL, the mean group-delay and mean phases are removed from the output VISPHI in the final OIFITS file. With ABSOLUTE, the VISPHI is kept unmodified. With SELF_VISPHI, the internal differential phase between each spectral channel and a common reference channel is computed. <DIFFERENTIAL \| ABSOLUTE I AUTO SELF_VISPHI> [AUTO] |
| -output-phase-channels | range (string in the form [min, max]) of channels o use a SELF_VISPHI phase reference. [0,0] |
| -outlier-fraction-threshold | Flag channels with more than this fraction of the frames affected by outliers or cosmics. These are typically detected with the thresholds options in chi2 of the fringe-fit. [0.5] |

## 7.6 gravity_eop

This recipe downloads the latest version of the Earth Orientation Parameter and DUT from the IERS site. File is created in the current directory. A web connection is required.

1. Download the IERS data
2. Convert into CPL table
3. Write product

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## Input

| DO.CATG | short description |
| :--- | :--- |
| None | No input |

## Output

| PRO.CATG | short description |
| :--- | :--- |
| EOP_PARAM | EOP calibration file (gravity_eop_calib.fits) |

## Parameters

| Name | short description |
| :--- | :--- |
| -eop_host | FTP Host to retrieve the EOP from. [ftp.iers.org] |
| -eop_urlpath | FTP URL path of the EOP file to retrieve. [/product- |
| s/eop/rapid/standard/finals2000A.data] |  |

## 7.7 gravity_p2vm

This recipe reduces the internal calibrations. As a special sequence of shutter opening is required, it is advised to always build the SOF with a complete sequence of files obtained within a single execution of the p 2 vm calibration template. However it is still possible to input a SOF with DARK_RAW only, or DARK_RAW and FLAT_RAW only. It is also possible to input a SOF with some already processed calibration (e.g WAVE).

1. Compute the dark, write product
2. Compute the flat, write product
3. Compute the badpixels, write product
4. Compute the spectral calibration, write product
5. Compute the p 2 vm , write product

## Input

| DO.CATG | short description |
| :--- | :--- |
| DARK_RAW | raw dark, all shutters closed (DPR.TYPE=DARK) |
| FLAT_RAW $x 4$ | raw flats, one shutter open (DPR.TYPE=FLAT) |
| P2VM_RAW x6 | raw p2vms, two shutters open (DPR.TYPE=P2VM) |
| WAVE_RAW | raw wavelength calibration for FT (DPR.TYPE=WAVE) |
| WAVESC_RAW | raw wavelength calibration for SC (DPR.TYPE=WAVE,SC) |


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## Output

| PRO.CATG | short description |
| :--- | :--- |
| DARK | dark calibration |
| FLAT | flat calibration |
| BAD | badpixel calibration |
| WAVE | wave calibration |
| P2VM | p2vm calibration |

## Parameters

| Name | short description |
| :---: | :---: |
| -static-name | Use static names for the products (for ESO). [FALSE] |
| -debug-file | Save additional debug file(s). [FALSE] |
| -preproc-file | Save the PREPROC intermediate product. [FALSE] |
| -bias-method | Method to average the biaspixels when cleaning-up the SC detector (only applied to MED and LOW). Ideally the same value shall be used when reducing the DARK with gravity_dark and the OBJECT with gravity_vis. UTO is equivalent to MASKED_MEDIAN_PER_COLUMN if the data ontains in the IMAGING_DETECTOR_SC extension the EFT, HALFLEFT, CENTER, HALFRIGHT and RIGHT columns. therwise it is like MEDIAN. <AUTO \| MEDIAN | MEDIAN_PER_COLUMN | MASKED_MEDIAN_PER_COLUMN $>$ [AUTO] |
| -acq-correction-delay | Delay between the end of ACQ frame and correction offset seen by the metrology diodes, in seconds. [0.25] |
| -use-fiber-dxy | Use the fiber position when computing OPD_TEL_CORR. [FALSE] |
| -use-met-rtc | Reduce metrology voltage with the real time algorithm nstead of using the pipeline's algorithm. [FALSE] |
| -smooth-faint | Adds an additional factor to the smoothing of he metrology voltages in faint mode. [1] |
| -preswitch-delay | Delay where metrology values are ignored before aser brightness is switched in faint mode, ms. [50] |
| -postswitch-delay | Delay where metrology values are ignored after aser brightness is switched in faint mode, ms. [200] |
| -bad-dark-threshold | the rms factor for dark bad pixel threshold. [10] |


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\(\left.\left.$$
\begin{array}{|l|l}\text {-profile-mode } & \begin{array}{l}\text { Method to compute the extraction profile. PROFILE corre- } \\
\text { sponds to the pixel intensities measured in the FLAT files } \\
\text { (Gaussian like with FWHM of approx 1.5 pixel). This is }\end{array} \\
\text { the AUTO option for the Low and Med spectral resolution. }\end{array}
$$\right\} \begin{array}{l}GAUSS corresponds to a Gaussian fit of the (non-zero) pixel <br>
intensities measured in the FLAT files. BOX corresponds to <br>
a box-card of 6 pixels centered on the spectra measured in <br>
the FLAT files. This is the AUTO option for High spectral <br>

resolution. <AUTO I PROFILE I GAUSS I BOX> [AUTO]\end{array}\right\}\)| Force the badpixel to zero in profile. [TRUE] |
| :--- |
| -force-badpix-to-zero |
| -profile-width of the detector window extracted around the default |
| -force-wave-ft-equal |
| position of each spectrum, and on which the profile will be |
| applied to perform the extraction. [6] |

## Quality control

| QC in BAD | short description |
| :--- | :--- |
| BADPIX ACQ | Total number of bad pixels on the ACQ detector |
| BADPIX SC | Total number of bad pixels on the SC detector |
| BADPIX FT | Total number of bad pixels on the FT detector |
| BADPIX_DARK SC/FT | Pixels with weird mean level |
| BADPIX_RMS SC/FT | Pixels with weird noise level |


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| BADPIX_FLAT SC/FT | Pixels non-responding to illumination |
| :--- | :--- |
| QC in FLAT | short description |
| PROFILE_CENTER SC1 MED | [pixel] position of the first spectra on SC detector |
| PROFILE_WIDTH SC1 MED | [pixel] width of the first spectra on SC detector |
| PROFILE_CENTER SC13 MED | [pixel] position of the 13d spectra on SC detector |
| PROFILE_WIDTH SC13 MED | [pixel] width of the 13d spectra on SC detector |
| MEANGAIN SC | Mean gain [ADU/e] for SC detector |
| MEANGAIN FT | Mean gain [ADU/e] for FT detector |
| QC in P2VM | short description |
| FLUX_SCi AVG | [e/DIT/chanel/output] flux in SC (mean of files) |
| FLUX_FTi AVG | [e/DIT/chanel/output] flux in FT (mean of files) |
| P2VM_COHERENCE_AVG_SC | Average instrumental contrast of SC |
| P2VM_COHERENCE_AVG_FT | Average instrumental contrast of FT |
| P2VM_COHERENCE_SCij | Average instrumental contrast of SC for pair ij |
| P2VM_COHERENCE_FTij | Average instrumental contrast of FT for pair ij |
| QC in WAVE | short description |
| REFWAVE1 | Reference wavelengh [m] for the below parameters |
| REFPOS1 SCi | Position [pix] of the REFWAVE1 in output SCi |
| REFPOS1 FTi | Position [pix] of the REFWAVE1 in output FTi |
| REFWAVE2 | Reference wavelengh [m] for the below parameters |
| REFPOS2 SCi | Position [pix] of the REFWAVE2 in output SCi |
| REFPOS2 FTi | Position [pix] of the REFWAVE2 in output FTi |
| WAVE_CORR | Model to convert the glass wavelength in vacuum wavelength |
| WAVE_CORR N0 | Paramater of above model |
| WAVE_CORR N1 | Paramater of above model |
| WAVE_CORR N2 | Paramater of above model |
| MINWAVE SC/FT | Min wavelength [m] of SC/FT channels |
| MAXWAVE SC/FT | Max wavelength [m] of SC/FT channels |
| RMSWAVE SC/FT | Rms of residuals during polynomial wavelength fit |

## Pseudo code

reference 10.1

```
    frameset = recipe_input_frameset
    parameters = recipe_input_parameters
/* Extract DARK frameset */
dark_frameset = gravi_frameset_extract_dark_data (frameset)
darkcalib_frameset = gravi_frameset_extract_dark_map (frameset)
/* Extract FLAT frameset */
flat_frameset = gravi_frameset_extract_flat_data (frameset)
flatcalib_frameset = gravi_frameset_extract_flat_map (frameset)
```

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```
/* Extract BAD frameset */
badcalib_frameset = gravi_frameset_extract_bad_map (frameset)
/* Extract WAVE frameset */
wave_frameset = gravi_frameset_extract_wave_data (frameset)
wavesc_frameset = gravi_frameset_extract_wavesc_data (frameset)
wavecalib_frameset = gravi_frameset_extract_wave_map (frameset)
/* Extract P2VM frameset */
p2vm_frameset = gravi_frameset_extract_p2vm_data (frameset)
/*(1) Compute or load the DARK file */
if (dark_frameset) then
    data = gravi_data_load_rawframe (dark_frameset[0])
    gravi_data_detector_cleanup (data, parameters) // see algo 10.1
    dark_map = gravi_compute_dark (data) // see algo 10.2
    gravi_data_save_new(dark_map, parameters)
elseif (darkcalib_frameset) then
    dark_map = gravi__data_load_frame (darkcalib_frameset[0])
/*(2) Compute or load the BAD pixel file */
if (badcalib_frameset) then
    badpix_map = gravi__data_load_frame (badcalib_frameset[0])
elseif (dark_frameset & flat_frameset)
    for i in nb_flat_frameset
        raw_flat[i] = gravi_data_load_rawframe (flat_frameset[i])
        gravi_data_detector_cleanup (raw_flat[i], parameters)
                // see algo 10.1
        badpix_map = gravi_compute_badpix (dark_map, raw_flat)
    gravi_data_save_new (badpix_map, parameters)
/*(3) Compute or load the FLAT file */
if (flatcalib_frameset) then
    profile_map = gravi_data_load_frame (flatcalib_frameset[0]);
elseif (flat_frameset)
    for i in nb_flat_frameset
        raw_flat[i] = gravi__data_load_rawframe (flat_frameset[i])
        gravi_data_detector_cleanup (raw_flat[i], parameters)
            // see algo 10.1
    profile_map = gravi_compute_profile (raw_flat, dark_map, badpix_map,
        nb_frame_gain, parameters) // see algo 10.3
    gain = gravi_compute_gain (raw_data, nb_frame_gain, dark_map)
    cpl_propertylist_append (profile_map_header, gain)
    gravi_data_save_new (profile_map, parameters)
```

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```
/*(4) Compute or load the WAVE file */
if (wavecalib_frameset) then
    wave_map = gravi__data_load_frame (wavecalib_frameset[0]);
elseif (wave_frameset)
    wave_data = gravi_data_load_rawframe_ext (wave_frameset)
    gravi_data_detector_cleanup(wave_data, parameters) // see algo 10.1
    spectrum_data = gravi_extract_spectrum (wave_sc_data, profile_map,
        dark_map, badpix_map, parameters) // see algo 10.3
    wave_map.p2vm_met = gravi_metrology_compute_p2vm (wave_data.met_table)
    gravi__wave_compute_opds (spectrum_data, wave_data.met_table)
    gravi_compute_wave (wave_map, spectrum_data, GRAVI_FT, parameters);
    if (wavesc_frameset)
        wavesc_data = gravi_data_load_rawframe_ext (wavesc_frameset)
        gravi_data_detector_cleanup(wavesc_data, parameters)
            // see algo 10.1
        spectrum_data = gravi_extract_spectrum (wavesc_data, profile_map,
            dark_map, badpix_map, parameters) // see algo 10.3
        gravi_wave_compute_opds (spectrum_data, wavesc_data.met_table)
    gravi_compute_wave (wave_map, spectrum_data, GRAVI_SC, parameters)
    gravi_data_save_new (wave_map, parameters)
/* (5) Compute the p2vm */
check(dark_map + bad_map + flat_map + wave_map)
p2vm_frameset = p2vm_frameset + wave_frameset + flat_frameset
check(size(p2vm_frameset) == 11)
p2vm_map = gravi_create_p2vm (wave_map)
for i in size(p2vm_frameset)
    data = gravi_data_load_rawframe_ext(p2vm_frameset[i])
    if (gravi_data_check_shutter (hdr_data, 1,1,1,1))
        i_wave = i
        skip_file
    gravi_data_detector_cleanup (data, parameters) // see algo 10.1
    preproc_data = gravi_extract_spectrum (data, profile_map, dark_map,
        badpix_map, parameters) // see algo 10.3
    gravi_align_spectrum(preproc_data, wave_map, p2vm_map, parameters)
        // see algo 10.5
    gravi_compute_p2vm (p2vm_map, preproc_data, valid_trans, valid_CP,
        GRAVI_DET_SC) // see algo 10.6
/* (7) P2VM normalization */
gravi_p2vm_normalisation (p2vm_map)
```

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```
/* (8) Analyse the WAVE to get the phase correction
    * and the internal spectrum to latter correct */
data = gravi__data_load_rawframe_ext(p2vm_frameset[i_wave])
gravi_data_detector_cleanup (data, parameters)
preproc_data = gravi_extract_spectrum (data, profile_map, dark_map,
    badpix_map, parameters)
gravi_align_spectrum(preproc_data, wave_map, p2vm_map, parameters)
p2vmred_data = gravi_compute_p2vmred(preproc_data, p2vm_map, parameters)
if (parameters.phase-calibration == "CLOSURE")
    gravi_p2vm_phase_correction (p2vm_map, p2vmred_data, 0)
    if (parameters.phase-calibration == "DISP")
    gravi_p2vm_phase_correction (p2vm_map, p2vmred_data, 1)
    if (parameters.phase-calibration == "FULL")
    gravi_p2vm_phase_correction (p2vm_map, p2vmred_data, 2)
    gravi_p2vm_transmission (p2vm_map, p2vmred_data);
    gravi_data_save_new (p2vm_map, parameters)
```


## 7.8 gravity_piezo

This recipe compute the response (open loop transfer function) of the piezo actuators used to fringe-track in GRAVITY.

1. Compute the piezo TF QC parameter* Write product

## Input

| DO.CATG | short description |
| :--- | :--- |
| PIEZOTF_RAW | dedicated observations (DPR.CATG=PIEZOTF) |

## Output

| PRO.CATG | short description |
| :--- | :--- |
| PIEZOTF | Response of the piezo |

## Parameters

| Name | short description |
| :--- | :--- |
| -static-name | Use static names for the products (for ESO). [FALSE] |


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## Quality control

| QC in PIEZOTF | short description |
| :--- | :--- |
| FT KAL PZ_FIT | Standard deviation of the residual of the fit of the piezo re- <br> sponse [rad]. |
| FT KAL PX_GAIN | Static gain of Piezo number X [rad/Volts] <br> FT KAL PX_DELAY |
| FT KAL PX_STDEV | standard of Peviation error between the value calculated and the <br> value which are used by the Kalman RTC [rad] <br> Response value of Piezo number X at step number Y (AR5 <br> (ecomposition) [rad/Volts]. |

## 7.9 gravity_postprocess

This recipe allows to manipulate the product of the GRAVITY pipeline, mostly the VIS. It permits to merge several files together into a single VIS file with all observations; to average the observations of one or several VIS file to increse the SNR; to remove some data (FT, SC); and to resample the SC observation with spectral binning. The list of input files can be P2VMRED, VIS, VIS_CALIBRATED (or even RAW for some parameters). However they should all be compatible in term of setup and observed objets !! Note that the recipe performs only litle checks of the input file content and structure. Thus the user shall ensure the input files are conformable (same polarisation and spectral mode for instante)

1. Load the files
2. Execute request from user
3. Write product

## Input

| DO.CATG | short description |
| :--- | :--- |
| Input files | see above |

## Output

| PRO.CATG | short description |
| :--- | :--- |
| POSTPROCESSED | Output file |

## Parameters

| Name | short description |
| :--- | :--- |


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```
-average-vis
-fluxerr-sc
-visamperr-sc
-visphierr-sc
-vis2err-sc
-copy-fluxdata
-force-merge
-remove-ft
-remove-sc
-remove-opdc
-remove-met
-nbin-lambda-sc
```

```
Average the results from the different input files (if any) in the
```

Average the results from the different input files (if any) in the
output product, instead of simply appending them. [FALSE]
output product, instead of simply appending them. [FALSE]
Force the uncertainty in FLUX of SC. [0.0]
Force the uncertainty in FLUX of SC. [0.0]
Force the uncertainty in VISAMP of SC. [0.0]
Force the uncertainty in VISAMP of SC. [0.0]
Force the uncertainty in VISPHI of SC. [0.0]
Force the uncertainty in VISPHI of SC. [0.0]
Force the uncertainty in VIS2 of SC. [0.0]
Force the uncertainty in VIS2 of SC. [0.0]
Duplicate FLUX into FLUXDATA for OIFITS2 grav-
Duplicate FLUX into FLUXDATA for OIFITS2 grav-
ity.postprocess. [TRUE]
ity.postprocess. [TRUE]
Force merging even if inconsistent data. [FALSE]
Force merging even if inconsistent data. [FALSE]
Remove FT extensions. [FALSE]
Remove FT extensions. [FALSE]
Remove SC extensions. [FALSE]
Remove SC extensions. [FALSE]
Remove OPDC extensions. [FALSE]
Remove OPDC extensions. [FALSE]
Remove METROLOGY related extensions. [FALSE]
Remove METROLOGY related extensions. [FALSE]
Bin SC extensions in spectral dimension. [0]

```
Bin SC extensions in spectral dimension. [0]
```


### 7.10 gravity_vis

This recipe is associated to the observations template. Its reduces the raw data acquired on calibrator or science targets and computes the uncalibrated visibilities, saved in an OIFITS file. If several OBJECT are provided, the recipe will reduce all of them and merge the resulting data into a single OIFITS. If several SKY_RAW are provided, the recipe reduces the first OBJECT with the first SKY file. Then each new OBJECT with the next SKY. When the number of SKYs is reached, the recipe loops back to first SKY file (so if the number of SKYs is larger than the number of OBJECTs, the last SKY won't be used). The recipe will reduce the data even if no SKY or no DARK is provided. However this will lead to wrong estimate of the visibility and squared visibility of the object. If the file DIAMETER_CAT is not provided, the recipe will use the diameter provided in the header to compute the transfer function QC parameters. The tag in the DO category can be SINGLE/DUAL and CAL/SCI. They should reflect the instrument mode (SINGLE or DUAL) and the DPR.CATG of the observation (SCIENCE or CALIB). The tag in the PRO.CATG category will be SINGLE/DUAL and CAL/SCI depending on the input tag.

## 1. Load the input file (loop on input OBJECT files)

2. Extract the spectra (use BAD, DARK, SKY, FLAT files)
3. Interpolate the spectra into a common wavelength table (use WAVE file)
4. Compute the real-time visibilities (use P2VM file)
5. Compute additional real-time signals (SNR, GDELAY...)
6. Compute selection flags (= flag frames with SNR lower than threshold, vFactor lower than threshold...)
7. Average the real-time visibilities, considering the selection flag
8. Write the product

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## Input

| DO.CATG | short description |
| :--- | :--- |
| FLAT | flat calibration (PRO.CATG=FLAT) |
| BAD | badpixel calibration (PRO.CATG=BAD) |
| WAVE | wave calibration (PRO.CATG=WAVE) |
| P2VM | p2vm calibration (PRO.CATG=P2VM) |
| DARK | dark calibration (PRO.CATG=DARK) |
| SINGLE_SCI_RAW | raw object (DPR.TYPE=OBJECT,SINGLE) |
| SINGLE_SKY_RAW | raw sky (DPR.TYPE=SKY,SINGLE) |
| DISP_MODEL (opt) | fiber dispersion model (PRO.CATG=DISP_MODEL) |
| DIODE_POSITION (opt) | met receiver position (PRO.CATG=DIODE_POSITION) |
| DIAMETER_CAT (opt) | catalog of diameter (PRO.CATG=DIAMETER_CAT) |

## Output

| PRO.CATG | short description |
| :--- | :--- |
| SINGLE_SCI_VIS | OIFITS file with uncalibrated visibilities |
| SINGLE_SKY (opt) | sky map |
| SINGLE_SCI_P2VMRED (opt) | intermediate product (see detailled description of data) |
| SPECTRUM (opt) | intermediate product (see detailled description of data) |
| PREPROC (opt) | intermediate product (see detailled description of data) |

## Parameters

| Name | short description |
| :--- | :--- |
| -static-name | Use static names for the products (for ESO). [FALSE] |
| -bias-subtracted-file | Save the BIAS_SUBTRACTED intermediate product. |
|  | [FALSE] |
| -spectrum-file | Save the SPECTRUM intermediate product. [FALSE] |
| -preproc-file | Save the PREPROC intermediate product. [FALSE] |
| -p2vmreduced-file | Save the P2VMRED intermediate product. [FALSE] |
| -astro-file | Save the ASTROREDUCED intermediate product. [FALSE] |
| -average-vis | Average the results from the different input files (if any) in the |
|  | output product, instead of simply appending them. [FALSE] |


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Method to average the biaspixels when cleaning-up the SC detector (only applied to MED and LOW). Ideally the same value shall be used when reducing the DARK with gravity_dark and the OBJECT with gravity_vis. UTO is equivalent to MASKED_MEDIAN_PER_COLUMN if the data ontains in the IMAGING_DETECTOR_SC extension the EFT, HALFLEFT, CENTER, HALFRIGHT and RIGHT columns. therwise it is like MEDIAN. <AUTO | MEDIAN | MEDIAN_PER_COLUMN | MASKED_MEDIAN_PER_COLUMN > [AUTO]
Delay between the end of ACQ frame and correction offset seen by the metrology diodes, in seconds. [0.25]
Use the fiber position when computing OPD_TEL_CORR. [FALSE]
Reduce metrology voltage with the real time algorithm nstead of using the pipeline's algorithm. [FALSE]
Adds an additional factor to the smoothing of he metrology voltages in faint mode. [1]
Delay where metrology values are ignored before aser brightness is switched in faint mode, ms. [50]
Delay where metrology values are ignored after aser brightness is switched in faint mode, ms. [200]
Threshold in chi2 r of the fringe-fit to declare a bad value. This is usefull to detect outliers or cosmic in individual frames. [50.0]
Threshold in chi2r of the fringe-fit (in unit of the the std of chi2 2 in the spectral direction) to declare a bad value. This is usefull to detect outliers or cosmic in individual frames. [100.0]
Number of samples to average coherently when computing the real-time SNR and GDELAY of the FT (shall correspond to the atmospheric coherence time). The integration window runs from -nsmooth -> +nsmooth. [5]
Maximum deg for the fit of PHASE_REF. [3]
Flag to add a constant value to OPD_DISP. This constant value is taken from the header. [FALSE]
Metrology source used for IMAGING_REF calculation: Use fibre coupler metrology (FC); Use fibre coupler metrology corrected from pupil motion (FC_CORR); Use telescope metrology (TEL). <FC I FC_CORR I TEL> [FC]
SNR threshold to accept FT frames ( $>0$ ). It raises the first bit ( «0) of column REJECTION_FLAG of FT. [3.0]
Minimum OPDC state to accept FT frames ( $>=0$ ) It raises the second bit («1) of column REJECTION_FLAG of FT. [2.0]

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| -global-state-max-ft | Maximum OPDC state to accept FT frames ( $>=0$ ) It raises the second bit ( $« 1$ ) of column REJECTION_FLAG of FT. [4.0] |
| :---: | :---: |
| -state-min-ft | Minimum OPDC state per baseline to accept FT frames ( $>=0$ ) It raises the second bit ( $<1$ ) of column REJECTION_FLAG of FT. [1.0] |
| -tracking-min-sc | Minimum ratio of accepted FT frames in order to accept a SC frames ( $0 . .1$ ), that is, for each SC DIT, the fraction of the time the REJECTION_FLAG of the FT is not 0 . It raises the first bit ( $« 0)$ of column REJECTION_FLAG of SC. [0.8] |
| -vfactor-min-sc | vFactor threshold to accept SC frame (0..1). [0.1] |
| -opd-pupil-max-sc | Maximum OPD_PUPIL (abs) to accept SC frames. It raises the third bit ( $<2$ ) of column REJECTION_FLAG of SC. [9999.0] |
| -opd-pupil-stddev-max-sc | Maximum OPD_PUPIL_STDDEV to accept SC frames. It raises the fourth bit («3) of REJECTION_FLAG of SC. [2.9e07] |
| -max-frame | Maximum number of frames to integrate coherently into an OIFITS entry. [10000] |
| -force-same-time | Force all baseline/quantities to have strictly the same TIME and MJD columns. [FALSE] |
| -debias-sc | Subtract the V2 bias from SC. [TRUE] |
| -debias-ft | Subtract the V2 bias from FT. [TRUE] |
| -nboot | Number of bootstraps to compute error (1..100). [20] |
| -vis-correction-sc | Correction of SC visibility from losses due to long integration, using the measured visibility losses with the FT (VFACTOR and/or PFACTOR) or by forcing the SC visibilities to match those of the FT (FORCE). Possible choices are: <VFACTOR I PFACTOR \| VFACTOR_PFACTOR I FORCE | NONE> [VFACTOR] |
| -phase-ref-sc | Reference phase used to integrate the SC frames. Use a selfestimate of the phase, fitted by poly. (SELF_REF) Use the FT phase only, interpolated in lbd (PHASE_REF) Use the FT+MET-SEP.UV phase (IMAGING_REF). <SELF_REF । PHASE_REF I IMAGING_REF I AUTO I NONE $>$ [AUTO] |
| -output-phase-sc | With DIFFERENTIAL, the mean group-delay and mean phases are removed from the output VISPHI in the final OIFITS file. With ABSOLUTE, the VISPHI is kept unmodified. With SELF_VISPHI, the internal differential phase between each spectral channel and a common reference channel is computed. <DIFFERENTIAL \| ABSOLUTE | AUTO | SELF_VISPHI> [AUTO] |
| -output-phase-channels | range (string in the form [min,max]) of channels o use a SELF_VISPHI phase reference. [0,0] |


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| -outlier-fraction-threshold | Flag channels with more than this fraction of the frames af- <br> fected by outliers or cosmics. These are typically detected <br> with the thresholds options in chi2 of the fringe-fit. [0.5] <br> Normalize the flux (stored in OI_FLUX binary extension) <br> with instrument transmission recorded in the nput P2VM cal- <br> ibration map. Consequently, the flux quantity is either the <br> intensity level recorded n the detector, thus including the in- <br> strument transmission (FALSE); or the intensity level at the <br> instrument entrance (TRUE). [FALSE] |
| :--- | :--- |
| -flat | Average the SKYs into a master SKY. If FALSE, the recipe <br> loops over the SKY to reduce each OBJECT with a different |
| -average-sky | SKY. [FALSE] <br> If TRUE, reduced ACQ_CAM images. [FALSE] |
| If TRUE, creates a new OI_WAVELENGTH_EFF with cor- |  |
| rected wavelength. [FALSE] |  |

### 7.11 gravity_viscal

This recipe calibrates the visibilities acquired on science target using visibilities acquired on a calibrator target. If the DIAMETER_CAT is not provided, the recipe will use the diameter provided in the header to compute the transfer function QC parameters. The corresponding keywords are INS.SOBJ.DIAMETER and FT.ROBJ.DIAMETER. The OI_FLUX data are not yet calibrated. The tag in the DO category can be SINGLE/DUAL and CAL/SCI. The tag in the PRO.CATG category will be SINGLE/DUAL and CAL/SCI depending on the input tag.

1. Loop on all input CALIB files, compute the TF for each of them and write the corresponding product
2. Loop on all input SCIENCE files, interpolate the TF at that time, calibrate, and write the corresponding product

### 7.11.1 Input

| DO.CATG | short description |
| :--- | :--- |
| SINGLE_SCI_VIS $(>=1)$ | visibilities on sciences |
| SINGLE_CAL_VIS $(>=1)$ | visibilities on calibrators |
| DIAMETER_CAT $(\mathrm{opt})$ | catalog of stellar diameters |

### 7.11.2 Output

| PRO.CATG | short description |
| :--- | :--- |
| SINGLE_SCI_VIS_CALIBRATEDcalibrated science visibilities |  |
| SINGLE_CAL_TF | Transfer Function (TF) estimated on calibrators |
| SINGLE_SCI_TF | TF interpolated at the time of sciences |


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## Parameters

| Name | short description |
| :--- | :--- |
| -static-name | Use static names for the products (for ESO). [FALSE] |
| -delta-time-calib | Delta time to interpolate the TF [s] |
| -force-calib |  |
| -nsmooth-tfvis-sc | Force the calibration, don't check setup. [FALSE] |
|  | Smooth the TF spectrally by this number of spectral bin, <br> to enhance SNR (only apply to VIS2, VISPHI, VISAMP, <br>  <br> -nsmooth-tfflux-sc <br> T3PHI, T3AMP). This parameter is ignored in spectral mode |
|  | LOW. [0] <br> Smooth the TF spectrally by this number of spectral bin, to <br> enhance SNR (only apply to FLUX, RVIS, IVIS). This pa- <br> -maxdeg-tfvis-sc |
|  | rameter is ignored in spectral mode LOW. [0] <br> Fit the TF spectrally by a polynomial to enhance SNR (only <br> apply to VIS2, VISPHI, VISAMP, T3PHI, T3AMP). This pa- |
|  | rameter is ignored in spectral mode LOW. [5] <br> -calib-flux |
|  | Normalize the FLUX by the calibrator. [FALSE] <br> control smoothing of transfer function (TF) TRUE do <br> smoothing FALSE Skip smoothing. [TRUE] |

### 7.12 gravity_vis_from_p2vmred

This recipe averages the real-time data of P2VMRED files into a VIS product. It allows to run the reduction with different parameters (for instance for SNR thresholding) without having to re-reduce the files from scratch. Typically the reduction is 4 x faster when started from this intermediate product. The tag in the DO category can be SINGLE/DUAL and CAL/SCI. They should reflect the mode (SINGLE or DUAL) and the DPR.CATG of the observation (SCIENCE or CALIB). The tag in the PRO.CATG category will be SINGLE/DUAL and CAL/SCI depending on the input tag.

1. Load the input file (loop on input files)
2. Update the selection flag
3. Average the real-time visibilities
4. Write the product

## Input

| DO.CATG | short description |
| :--- | :--- |
| SINGLE_SCI_P2VMRED | Input intermediate product |


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## Output

| PRO.CATG | short description |
| :--- | :--- |
| SINGLE_SCI_VIS | OIFITS with uncalibrated visibilities |

## Parameters

| Name | short description |
| :---: | :---: |
| -static-name | Use static names for the products (for ESO). [FALSE] |
| -average-vis | Average the results from the different input files (if any) in the output product, instead of simply appending them. [FALSE] |
| -chi2r-threshold | Threshold in chi2r of the fringe-fit to declare a bad value. This is usefull to detect outliers or cosmic in individual frames. [50.0] |
| -chi2r-sigma | Threshold in chi2r of the fringe-fit (in unit of the the std of chi2r in the spectral direction) to declare a bad value. This is usefull to detect outliers or cosmic in individual frames. [100.0] |
| -nsmooth-snr-ft | Number of samples to average coherently when computing the real-time SNR and GDELAY of the FT (shall correspond to the atmospheric coherence time). The integration window runs from -nsmooth -> +nsmooth. [5] |
| -snr-min-ft | SNR threshold to accept FT frames ( $>0$ ). It raises the first bit («0) of column REJECTION_FLAG of FT. [3.0] |
| -global-state-min-ft | Minimum OPDC state to accept FT frames (>=0) It raises the second bit ( $« 1$ ) of column REJECTION_FLAG of FT. [2.0] |
| -global-state-max-ft | Maximum OPDC state to accept FT frames (>=0) It raises the second bit ( $« 1$ ) of column REJECTION_FLAG of FT. [4.0] |
| -state-min-ft | Minimum OPDC state per baseline to accept FT frames ( $>=0$ ) It raises the second bit ( $« 1$ ) of column REJECTION_FLAG of FT. [1.0] |
| -tracking-min-sc | Minimum ratio of accepted FT frames in order to accept a SC frames ( $0 . .1$ ), that is, for each SC DIT, the fraction of the time the REJECTION_FLAG of the FT is not 0 . It raises the first bit ( $« 0)$ of column REJECTION_FLAG of SC. [0.8] |
| -vfactor-min-sc | vFactor threshold to accept SC frame (0..1). [0.1] |
| -opd-pupil-max-sc | Maximum OPD_PUPIL (abs) to accept SC frames. It raises the third bit ( $<2$ ) of column REJECTION_FLAG of SC. [9999.0] |
| -opd-pupil-stddev-max-sc | Maximum OPD_PUPIL_STDDEV to accept SC frames. It raises the fourth bit ( $« 3$ ) of REJECTION_FLAG of SC. [2.9e07] |
| -max-frame | Maximum number of frames to integrate coherently into an OIFITS entry. [10000] |


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$\left.\begin{array}{l|l}\text {-force-same-time } & \begin{array}{l}\text { Force all baseline/quantities to have strictly the same TIME } \\ \text { and MJD columns. [FALSE] } \\ \text {-debias-sc }\end{array} \\ \begin{array}{l}\text {-debias-ft } \\ \text {-nboot }\end{array} & \begin{array}{l}\text { Subtract the V2 bias from SC. [TRUE] } \\ \text {-vis-correction-sc } \\ \text { Subtract the V2 bias from FT. [TRUE] }\end{array} \\ \text { Number of bootstraps to compute error (1.100). [20] } \\ \text { Correction of SC visibility from losses due to long integra- } \\ \text { tion, using the measured visibility losses with the FT (VFAC- } \\ \text { TOR and/or PFACTOR) or by forcing the SC visibilities } \\ \text { to match those of the FT (FORCE). Possible choices are:. } \\ \text { <VFACTOR I PFACTOR I VFACTOR_PFACTOR I FORCE }\end{array}\right]$

### 7.13 gravity_wavelamp

This recipe is associated to the template gravity_wavelamp. It reduces the raw file obtained with the Argon lamp (WAVELAMP) and process it so that it can be used to calibrate the fiber dispersion (recipe gravity_disp).

1. Extract the spectra of the Argon exposure
2. Interpolate the spectra into a common wavelength table
3. Measure the wavelength position of known Argon lines
4. Write the product

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## Input

| DO.CATG | short description |
| :--- | :--- |
| FLAT | flat calibration (PRO.CATG=FLAT) |
| BAD | badpixel calibration (PRO.CATG=BAD) |
| WAVE | wave calibration (PRO.CATG=WAVE) |
| P2VM | p2vm calibration (PRO.CATG=P2VM) |
| WAVELAMP_RAW | long exposure of Argon lamp |
| DARK_RAW | dark of Argon exposure |

## Output

| PRO.CATG | short description |
| :--- | :--- |
| WAVELAMP | spectrum of Argon, with position of lines |

## Parameters

| Name | short description |
| :--- | :--- |
| -static-name | Use static names for the products (for ESO). [FALSE] |


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## 8 Re-creating the Static Calibration

### 8.1 Dispersion model

The DISP_MODEL static calibration can be recomputed with the recipes gravity_wavelamp and gravity_disp. The principle is to accurately measure the interferometric phases obtained for various position of the FDDL (= various strechting of the fibers) at the wavelengths of known Argon lines. The following dedicated RAW data are required:

WAVELAMP is a spectrum of the internal argon lamp.
DISP are interferometric observations of the internal source for various position of the FDDL (= different strech of the fibers).

### 8.2 Earth Orientation Parameters

The EOP_PARAM static calibration can be recomputed with the recipe gravity_retrieve_eop, which shall query the IERS webpage to obtain the best estimate of the past and futur EOP.

### 8.3 Metrology diode positions

There is no recipe to create a new calibration file, but the DIODE_POSITION static calibration can be update by editing the fits file.

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## 9 Detailed description of the data content

### 9.1 Recommended tools to browse data

RAW files can be conveniently opened with the last version of QFitsView [2] from Thomas Ott.
OIFITS product files can be conveniently open with the last version of OIFits Explorer [1] from the JMMC.
The consortium has built a python script to visualise most of the GRAVITY data, run_gravi_visual.py.

### 9.2 Table structure common to all data

The INSNAME header keyword specifies the combiner to which a table refers to, and thus allows to crossreference with other tables. The EXTVER keyword specifies the instance of a table repeated in the OIFITS file to allow fast search in the tables (see python FITS class for instance). They can take the values: GRAVITY_SC' (10), GRAVITY_SC_P1' (11), GRAVITY_SC_P2' (12), GRAVITY_FT' (20), GRAVITY_FT_P1' (21), GRAVITY_FT_P2' (22).

The polarisation 'P1' in output products correspond to the 'S' regions in IMAGING_DETECTOR tables. The polarisation ' P 2 ' in output products correspond to the ' P ' regions in IMAGING_DETECTOR tables.

The IMAGING_DETECTOR_SC and IMAGING_DETECTOR_FT tables store the detector configurations based on the VLTI interface control document [5].

The IMAGING_DATA_SC and IMAGING_DATA_FT extensions store the detector data. The SC data are stored as image list, while the FT data are stored as tables.

The OI_WAVELENGTH tables store the wavelength table following the OIFITS standard. They shall be associated to the SC or FT using the INSNAME or EXTVER keywords.

OIFITS tables storing quantities per-beam (OI_FLUX) have a total of NDIT x 4 rows (or NEXP x 4 rows for final product). In these tables, the four beams are always ordered following 12341234...

OIFITS tables storing quantities per-baseline (OI_VIS, OI_VIS2) have a total of NDIT x 6 rows (or NEXP x 6 rows for final product). In these tables, the six baselines are always ordered following 123456123456... The baselines 1 to 6 are always the pair of the beams 1-2,1-3,1-4,2-3,2-4,3-4.

### 9.3 RAW calibration data

RAW calibration data are set of data acquired on internal calibration source to be reduced by the recipe gravi_all_dark and gravi_all_p2vm in order to produce master calibration frame (DARK, FLAT, BAD PIXEL and WAVE maps) characterising the detector pixels and P2VM.

The data contain the following tables :

OPTICAL_TRAIN : Optical train configuration (see [5])
IMAGING_DATA_ACQ : Data of the imaging camera (image cube)

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IMAGING_DETECTOR_SC : Configuration of the SC detector
IMAGING_DETECTOR_FT : Configuration of the FT detector
IMAGING_DATA_SC : Images of the SC camera (image cube)
IMAGING_DATA_FT : Images of the FT camera
OPDC: OPD Controler data (fringe tracker)
FDDL : Fiber Delay Line position
METROLOGY : Metrology data

## IMAGING_DETECTOR_SC and IMAGING_DETECTOR_FT

The REGNAME column must refer to an output of the integrated optic. It is defined as the following [1..3][2.4]-[A,B,C,D]-[S-P]. The 2 first numbers define the 2 entrance ports connected to the output, the median letter correspond to the phase shift A, B, C or D, and the final letter is the polarisation of the region (S or P). Ex : 13-A-S is the A output of the T1-T3 pair with the polarisation S. The IMAGING_DETECTOR_SC tables contain the following columns:

| Column | Size | Unit | Description |
| :--- | :--- | :--- | :--- |
| REGION | I |  | The region number that is being described by this row. |
| DETECTOR | I |  | The detector that is on this region, index defined in <br> INS_DESCRIPTION. |
| CORRELATION | I |  | Correlation type: <br> $0=$ background (no signal), <br> $1=$ photometric, <br> $2=$ interferometric. |
| REGNAME | 16A |  | Detector region name, to match the IMAGING_DATA ta- <br> ble. |
| CENTER | 2I | PIXEL | This gives the position of the centre of the spectrum in the <br> x and y dimension. |
| LEFT | 2I | PIXEL | SC ONLY - This gives the position of the left of the spec- <br> trum in the $x$ and y dimension. |
| HALFLEFT | 2I | PIXEL | SC ONLY -This gives the position of the halfleft of the <br> spectrum in the $x$ and y dimension. |
| RIGHT | 2I | PIXEL | SC ONLY - This gives the position of the right of the spec- <br> trum in the $x$ and y dimension. |
| HALFRIGHT | 2I | PIXEL | SC ONLY - This gives the position of the half right of the <br> spectrum in the x and y dimension. |

## IMAGING_DATA_FT

The IMAGING_DATA_FT tables contain the following columns:

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| Column | Size | Unit | Description |
| :--- | :--- | :--- | :--- |
| REGION | I |  | The region number that is being described by this row. |
| REGNAME | 16 A |  | Detector region name, to match the IMAGING_DATA ta- <br> ble. |

## OPDC

This table contains the data coming from the OPD controller. It is mainly the command applied to the PIEZO and VLTI delay lines.

The OPDC tables contain the following columns:

| Column | Size | Unit | Description |
| :--- | :--- | :--- | :--- |
| TIME | J | $\mu \mathrm{s}$ | Time tag for this exposure, the effective centroid from the <br> MJD_OBS date. |
| STATE | J |  |  |
| STEPS | J |  |  |
| BASELINE_STATE | J |  |  |
| PIEZO_DL_OFFSET | 4 E | V | Command sent to GRAVITY's internal actuator at the cur- <br> rent iteration. |
| VLTI_DL_OFFSET | 4 E | m | Command sent to the main VLTI delay lines at the current <br> iteration. |
| KALMAN_PIEZO | 4 E | rad | Impact of GRAVITY's internal actuator on OPD at the cur- <br> rent iteration. |
| OPD | 6 E | rad | Phase residual measured at the current iteration. |
| KALMAN_OPD | 6 E | rad | Phase residual predicted by the Kalman for the current it- <br> eration. |

The T2B matrix converts telescope quantities to baseline quantities.

$$
\mathrm{T} 2 \mathrm{~B}=\left(\begin{array}{cccc}
1 & -1 & 0 & 0  \tag{1}\\
1 & 0 & -1 & 0 \\
1 & 0 & 0 & -1 \\
0 & 1 & -1 & 0 \\
0 & 1 & 0 & -1 \\
0 & 0 & 1 & -1
\end{array}\right)
$$

The internal modulation of GRAVITY is derived from

$$
\begin{equation*}
\text { modulation }=\frac{\pi}{8}((\mathrm{STEPS} \gg 4 i) \& 15) \quad i \in[0,1,2,3] \tag{2}
\end{equation*}
$$

where $\gg$ is the bitwise "right shift" operator, and \& is the bitwise "and" operator.
The phase residuals, without the modulation, wrapped in the interval $[-\pi ;+\pi]$, are obtained with

$$
\begin{equation*}
\text { residuals }=(\mathrm{OPD}-\mathrm{T} 2 \mathrm{~B} \cdot \text { modulation }+\pi) \%(2 \pi)-\pi . \tag{3}
\end{equation*}
$$

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The pseudo open loop disturbances are reconstructed with
disturbances $=\mathrm{T} 2 \mathrm{~B} \cdot \mathrm{KALMAN} \mathrm{\_PIEZO}+\left(\mathrm{OPD}-\left(\mathrm{KALMAN} \_\mathrm{OPD}-\pi\right)\right) \%(2 \pi)+\left(\mathrm{KALMAN} \_\mathrm{OPD}-\pi\right)$.

## FDDL

This table contains the data coming from the FDDL controller. It is mainly the command applied to the fibered differential delay lines.

The FDDL tables contain the following columns:

| Column | Size | Unit | Description |
| :--- | :--- | :--- | :--- |
| TIME | J | $\mu \mathrm{s}$ | Time tag for this exposure, the effective centroid from the <br> MJD_OBS date. |
| FT_POS | 4 E | V |  |
| SC_POS | 4 E | V |  |
| OPL_AIR | 4 E | m |  |

## METROLOGY

This table contains metrology measurement: phase differences between reference star and target star as function of time.

The METROLOGY tables contain the following columns:

| Column | Size | Unit | Description |
| :--- | :--- | :--- | :--- |
| TIME | J | $\mu \mathrm{s}$ | Time tag for this exposure, the effective centroid from the <br> MJD_OBS date. |
| VOLT | 80 E | V |  |
| POWER_LASER | E | mV |  |
| LAMBDA_LASER | E | m |  |

### 9.4 RAW science data

RAW science data are produced during on sky observation of calibrator or science target by the instrument. They are reduced by the recipe gravity_vis.

The data contain the following tables :

ARRAY_DESCRIPTION : Description of the telescope array (see [5])
ARRAY_GEOMETRY : Positions of the used telescope (see [5])
OPTICAL_TRAIN : Optical train configuration (see [5])

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IMAGING_DATA_ACQ : Data of the imaging camera (image cube)
IMAGING_DETECTOR_SC : Configuration of the SC detector
IMAGING_DETECTOR_FT : Configuration of the FT detector
IMAGING_DATA_SC : Images of the SC camera (image cube)
IMAGING_DATA_FT : Images of the FT camera
OPDC : OPD Controler data (fringe tracker)
FDDL: Fiber Delay Line position
METROLOGY : Metrology data

### 9.5 P2VM product

Visibility to pixels matrix contains the beam combiner calibration matrix in P2VM table (transmission, coherence and phase) for the three data sources (P2VM_SC, P2VM_FT and P2VM_MET).

The products contain the following tables :

IMAGING_DETECTOR_SC : copied from raw data
IMAGING_DETECTOR_FT : copied from raw data
OI_WAVELENGTH : computed from the minimum and the maxiumum wavelength and the spectral resolution of the mode

OI_FLUX : store the internal instrument transmission, measured on the internal light, following the OIFITS standard, in arbitrary units. These tables are used to later calibrate the measured flux of the object using the spectral shape of the internal transmission.

P2VM_SC : P2VM of the SC beam combiner
P2VM_FT : P2VM of the FT beam combiner
P2VM_MET : P2VM of the metrology

## P2VM_SC and P2VM_FT tables

The P2VM_SC and P2VM_FT tables contain the following columns:

Column $\quad$ Size $\quad$ Unit | Description |
| :--- |

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| REGNAME | 16A |  | Detector region name, to match the IMAGING_DATA ta- <br> ble. |
| :--- | :--- | :--- | :--- |
| TRANSMISSION | ntel $\times$ nwave [E] | For each region (= output of the combiner), a ntel $\times$ nwave <br> image with the transmission of each input beam in this re- <br> gion. Since the combination scheme is pairwise, normaly <br> only 2 rows of this image shall be non-zero. |  |
| COHERENCE | nbase $\times$ nwave [E] | For each region (= output of the combiner), a nbase $\times$ <br> nwave image with the instrumental visibility of each pair of <br> input beam in this region. Since the combination scheme is <br> pairwise, normally only one single rows of this image shall <br> be non-zero. |  |
| PHASE | nbase $\times$ nwave [E] | For each region (= output of the combiner), a nbase $\times$ <br> nwave image with the instrumental phase in radian of each <br> pair of input beam in this region. Since the combination <br> scheme is pairwise, normaly only one single rows of this <br> image shall be non-zero. |  |
| C_MATRIX | nbase $\times$ nwave [E] | Normalisation matrix |  |

## 9.6 *_VIS and *_TF products

The files with PRO.CATG=*_VIS and *_TF follow the OIFITS standard, version 2. All information can be found in [4].

The OI_VIS, OI_VIS2 and OI_T3 tables contain one row per baseline and per corresponding RAW exposure, that is all the frames from the individual exposure are averaged together.

The OI_FLUX tables contain one row per telescope and per corresponding RAW exposure.
The OIFITS tables are associated to the SC or FT using the INSNAME (and/or EXTVER) keywords.

### 9.7 SPECTRUM, PREPROC products

These are intermediate products used to debug the pipeline.
Both files contain the extracted spectra of each output of the combiners. In SPECTRUM, the spectra are in pixel space, thus on different wavelength grids. In PREPROC, the spectra have been re-interpolated into a common wavelength grid.

The products contain the following tables :

IMAGING_DETECTOR_SC/FT : copied from raw data
SPECTRUM_DATA_SC/FT : Computed spectra in pixels space for SPECTRUM product, or re-interpolated in PREPROC product.

SPECTRUM_FLAT_SC : Computed spectra from the FLAT in pixels space for SPECTRUM product, or re-interpolated in PREPROC product.

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OI_WAVELENGTH : Only for PREPROC file, this table is copied form the WAVE used for re-interpolation.

## Columns in the SPECTRUM_DATA tables

| Column | Size | Unit | Description |
| :--- | :--- | :--- | :--- |
| TIME | J | $\mu \mathrm{s}$ | time of the frame, in [us], from the PRC.ACQ.START time <br> from header (RMN recording start). |
| DATAi | NWAVE*D | e | The spectrum of the flux from output i of the combiner. |
| DATAERRi | NWAVE*D | e | The spectrum of the theoretical error of the flux from out- <br> put i of the combiner, including detector and photonic vari- <br> ances. |

## Columns in the SPECTRUM_FLAT_SC tables

| Column | Size | Unit | Description |
| :--- | :--- | :--- | :--- |
| DATAi | NWAVE*D | e | The spectrum of the flux from output i of the combiner. |
| DATAERRi | NWAVE*D | e | The spectrum of the theoretical error of the flux from out- <br> put i of the combiner, including detector and photonic vari- <br> ances. |

## 9.8 *_P2VMRED products

The files with PRO.CATG=*_P2VMRED use elements of the OIFITS format [4], but are non-standard for the TIME colums. They also include many additional columns to store intermediate signal.

Beware that the OIFITS tables contain one row per frame: the number of row can be huge for the FT tables.
The product contains the following tables :

OI_WAVELENGTH : copied form the WAVE used for re-interpolation.
OI_TARGET : created by the pipeline from the template parameters (see [4] for description).
OI_ARRAY : created by the pipeline from ARRAY_GEOMETRY table of the raw data (see [4] for description).

OI_VIS : computed visibilitites adapted from [4] see below.
OI_FLUX : computed flux adapted from [4] see below.
METROLOGY : copied form the RAW data
OI_VIS_MET : computed phase of the metrology see below.
FDDL : copied form the RAW data
OPDC : copied form the RAW data

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If the ACQUISITION camara data are reduced :

IMAGING_DATA_ACQ : reduced images of the acquisition camera (see below)
OI_VIS_ACQ : computed data from the acquisition camera images (see below)

## Columns in the OI_VIS table of the SC

TARGET_ID : id listed in OI_TARGET
TIME $[\mu \mathrm{s}]$ : time of the frame, in [us], from the PRC.ACQ.START time from header (RMN recording start).
MJD [day] :
INT_TIME [s]: integration time of this frame
VISDATA [e,e] : complex coherent flux of SC in this frame
VISERR [e,e] : theoretical complex error on the coherent flux
UCOORD [m]: uv-plane of this SC frame
VCOORD [m] : uv-plane of this SC frame
STA_INDEX : station index in the OI_ARRAY
FLAG : T if flagged, F if not flagged
$\mathbf{E} \_\mathbf{U}, \mathbf{E} \_\mathbf{V}, \mathbf{E} \_\mathbf{W}$ : Local celestial $\{\mathbf{u}, \mathbf{v}, \mathbf{w}\}$ (East, North, Toward observer = OIFITS standard) expressed in local terrestrial (East, North, Up) at Paranal reference. It is useful for recomputing the projected baseline from physical baseline.
$\mathbf{E} \_\mathbf{A z}$ : Vector product of the E_W and the Zenith directions, expressed in the local terrestrial (East, North, Up) at Paranal reference. Sitting on telescope, looking at the target, E_Az points toward left in the horizontal plane.
$\mathbf{E} \_\mathbf{Z d}$ : Vector product of the E_W and E_Az, expressed in the local terrestrial (East, North, Up) at Paranal reference. Sitting on telescope, looking at the target, E_Az points toward Nadir in the plane perpendicular to pointing direction.

SNR : real-time SNR
GDELAY_BOOT [m] : best GD estimate, taking into account closing triangles
SNR_BOOT : best SNR estimate, taking into account closing triangles
FIRST_FT : first FT frame in this SC frame
LAST_FT : last FT frame in this SC frame
NFRAME_FT :

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FIRST_MET : first MET frame in this SC frame

LAST_MET : last MET frame in this SC frame

## NFRAME_MET :

P_FACTOR : predicted square visibility loss of this SC frame due to photometric flickering (based on the real-time photometry of the FT)

F1F2 Estimate of geometric flux of this frame.
PHASE_MET_FC [rad] : unwrapped FT-SC phase as computed by the DRS algorithm
PHASE_MET_TEL [rad] : unwrapped FT-SC phase as computed by the DRS algorithm, mean of 4 diodes
PHASE_MET_TELFC : differential phase between FC and TEL diodes, average in the complex phasor space. This correspond to an astrometric phase error to be applied to compute astrometry.

OPD_MET_FC [m] : unwrapped SC-FT delay as computed by the TAC algorithm
OPD_MET_TEL [m] : unwrapped SC-FT delay as computed by the TAC algorithm, 4 diodes
OPD_MET_FC_CORR : same as OI_VIS_MET table
OPD_MET_TELFC_MCORR : same as OI_VIS_MET table
OPD_MET_TELFC_CORR : same as OI_VIS_MET table
VISDATA_FT $[\mathrm{e}, \mathrm{e}]:<$ VISDATA $>$ spectra of FT (integrated in this SC frame)
VISVAR_FT $\left[\mathrm{e}^{* * 2}\right]:<|\mathrm{VISERR}|^{* *} 2>$ spectra of FT (integrated in this SC frame)
VISPOWER_FT $\left[\mathrm{e}^{* * 2}\right]:<|V I S D A T A| * * 2>$ spectra of FT (integrated in this SC frame)
V_FACTOR : predicted square visibility loss of this SC frame (re-interpolation of V_FACTOR_FT on the SC wavelengths)

V_FACTOR_FT : measured visibility loss on the FT
V_FACTOR_WL :predicted square visibility loss in white light for the SC.
OPD_DISP [m] : spectra of OPD introduced by fibers, including dispersion.
GDELAY_DISP [m] :
PHASE_DISP [m] :
GDELAY [m] : real-time GD computed from VISDATA
GDELAY_FT [m] : real-time GD computed from VISDATA_FT
SELF_REF [rad] : self-reference phase.
SELF_REF_COEFF [rad]:

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PHASE_REF [rad] : reference phase from FT, actually $-1 * \arg$ VISDATA_FT, re-interpolated in the SC wavelength.

PHASE_REF_COEFF [rad] : polynomial coefficients fit to argVISDATA_FT and used to extrapolate to the SC wavelengths, in units of $\left(\lambda_{\text {mean }} / \lambda-1\right) /\left(\lambda_{\max }-\lambda_{\min }\right) * \lambda_{\text {mean }}$.

IMAGING_REF [rad] : reference phase for dual-mode, which include the PHASE_REF, the metrology and the sidereal motion.

FRINGEDET_RATIO : fraction of FT frame accepted in this SC frame
REJECTION_FLAG : this frame is accepted/rejected
PUPIL_U [m] : lateral shift of pupil (in uv reference).
PUPIL_V [m] : lateral shift of pupil (in uv reference).
PUPIL_W [m] : focus shift of pupil (in uv reference).

## Columns in the OI_VIS table of the FT

TARGET_PHASE [rad] : target phase of the loop, including the Sylvester modulation
STATE : baseline tracking state as reported by OPDC
OPDC_STATE :
SNR : real-time SNR
GDELAY_BOOT [m] : best GD estimate, accounting closing triangles
SNR_BOOT : best SNR estimate, accounting closing triangles
F1F2 Estimate of geometric flux of this frame.
SELF_REF [rad]: self-reference phase.
GDELAY [m] : real-time GD computed from VISDATA
REJECTION_FLAG : this frame is accepted/rejected

## Columns in the OI_FLUX table of the SC

TARGET_ID : id listed in OI_TARGET
TIME [us] : time of the frame, in [us], from the PRC.ACQ.START time from header (RMN recording start).
MJD [day] :
INT_TIME [s]: integration time of this frame

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FLUX [e]: flux
FLUXERR [e] : theoretical error on flux
STA_INDEX : station index in the OI_ARRAY
CHI2 : reduced chi 2 of the fit of the raw data with the P2VM model
FLAG : T if flagged, F if not flagged
FIRST_FT : first FT frame in this SC frame
LAST_FT : last FT frame in this SC frame
NFRAME_FT :
FIRST_MET : first MET frame in this SC frame
LAST_MET : last MET frame in this SC frame

## NFRAME_MET :

FIRST_FDDL : first FDDL frame in this SC frame
LAST_FDDL : last FDDL frame in this SC frame
NFRAME_FDDL :
OPD_MET_FC [m] : unwrap SC-FT delay as computed by the TAC algorithm
OPD_MET_TEL [m] : unwrap SC-FT delay as computed by the TAC algorithm, 4 diodes.
PHASOR_MET_TELFC : average over the SC DIT of PHASOR_TELFC in OI_VIS_MET
OPD_MET_FC_CORR :
OPD_MET_TELFC_MCORR :
OPD_MET_TELFC_CORR :
FT_POS [V] : mean FT FDDL strain gauge voltage during this frame
SC_POS [V] : mean SC FDDL strain gauge voltage during this frame
OPL_AIR [m] : optical path length calculated as the scalar product between the telescope position and the target direction

TOTALFLUX_SC [e] : total flux of SC in this SC frame (integrated over spectrum)
TOTALFLUX_FT [e] : total flux of FT in this SC frame (integrated over spectrum)
FDDL [m] : The mean of SC_FDDL and FT_FDDL, where these value are the FDDL strain gauge measurements, corrected from non-linearity and converted in [m].

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## Columns in the OI_FLUX table of the FT

STATE : telescope state as reported by OPDC

## Columns in the OI_VIS_MET table

The table has the same structure as the OI_FLUX table, that is one row per beam (12341234124...), and thus nsample x 4 rows.

PHASE_FC_DRS [rad] : phases at combiner, unwrap by pipeline algorithm (FT-SC)
PHASE_TEL_DRS [rad] : 4 diodes phases at telescope, unwrap by pipeline algorithm (FT-SC)
PHASE_FC_TAC [rad] : phases at combiner, unwrap by TAC algorithm (FT-SC)
PHASE_TEL_TAC [rad] : 4 diodes phases at telescope, unwrap by TAC algorithm (FT-SC)
FLAG_FC, FLAG_TEL : flags computed by TAC algorithm
OPD_FC [m] : OPD at telescope, unwrap by TAC algorithm (SC-FT)
VAMP_FC_FT , VAMP_FC_SC, VAMP_TEL_FT, VAMP_TEL_SC: Volt amplitudes
OPD_TEL [m] : 4 diodes OPD at telescope, unwrap by TAC algorithm (SC-FT)
OPD_FC_CORR [m] : OPD error to astrometry caused by pupil displacements and static abberations
OPD_TEL_CORR [m] : OPD predicted on telescope diodes caused by astigmatism and tip-tilt
OPD_TELFC_CORR [m] : OPD measured on the telescope diodes with respect to FC and the 2 correction terms FC_CORR and TEL_CORR.

OPD_TELFC_MCORR [m] : mean of the 4 telescope diodes OPD_TELFC_CORR.
OPD_PUPIL [m] : Expected OPD introduced by the measured pupil shift, re-aligned in time with the MET sampling.

## Columns in the OI_VIS_ACQ table

The table has the same structure as the OI_FLUX table, that is one row per beam (12341234124...), and thus nsample x 4 rows.

TIME [us] : time of the frame, in [us], from the PRC.ACQ.START
PUPIL_NSPOT : number of spot detected in the pupil sensor (maximum is $16=4$ diodes x 4 sub-apertures).
PUPIL_X [pix] : horizontal shift of pupil (in detector).
PUPIL_Y [pix] : vertical shift of pupil (in detector).

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PUPIL_Z [pix] : focus shift of pupil (in detector).
PUPIL_R [deg] : rotation of pupil diode (in detector).
PUPIL_U [m] : lateral shift of pupil (in uv reference).
PUPIL_V [m] : lateral shift of pupil (in uv reference).
PUPIL_W [m] : focus shift of pupil (in uv reference).
OPD_PUPIL [m] : Expected OPD introduced by the measured pupil shift.

## Columns in the OPDC table

TIME [us] : time of the frame, in [us], from the PRC.ACQ.START time from header (RMN recording start).
STATE : global fringe tracking state
STEPS : target phase modulation per baseline (scrambled), in units of pi/8
BASELINE_STATE : fringe tracking state per telescope and baseline (scrambled)
PIEZO_DL_OFFSET : same as raw data
VLTI_DL_OFFSET : same as raw data
VLTI_FDDL_OFFSET : same as raw data
OPD : same as raw data
KALMAN_PREDICT : same as raw data

## 9.9 *_ASTROREDUCED products

This is a lighter version of the P2VMRED file. It is used for the astrometric mode of GRAVITY. For more detail on how to do it, see Section 10.26

### 9.10 DISP_MODEL

The data are stored in the table DISP_MODEL. There are one line per GRAVITY beam. They are used to calculate OPD_DISP (see section 10.23). The columns are:

WAVE0 : $\lambda_{0}$, reference wavelength to calculate OPD_DISP model.
NMEAN : Mean optical index of the SC and FT fibers. The vector contains the $n$ mean ${ }_{i}$ coefficients such that the index at wavelength $\lambda$ is given by : $n(\lambda) / n\left(\lambda_{M E T}\right)=\sum_{i}\left(\operatorname{nmean}_{i}\left(\frac{\lambda_{0}}{\lambda}-1\right)^{i}\right)$.

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NDIFF : Differential optical index between the SC and the FT fibers. The vector contains the $n d i f f_{i}$ coefficients such that the differential index at wavelength $\lambda$ is given by : $n(\lambda) / n\left(\lambda_{M E T}\right)=\sum_{i}\left(\operatorname{ndiff}_{i}\left(\frac{\lambda_{0}}{\lambda}-\right.\right.$ $\left.1)^{i}\right)$.

LIN_FDDL_FT : Linearity coefficients to convert the FDDL signal in [V] to stretching length in [m]. The vector contains the $a_{i}$ coefficients such that $L(V)=\sum_{i} a_{i} V^{i}$.

LIN_FDDL_SC : Same for the SC.

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## 10 Algorithms

In the following, $f$ is the index of individual DIT (that is from 0 to NDIT-1, whose typicall values are 30 for SC and 300000 for FT ), $i j$ are the pixel indices on the detector ( $i$ being the spatial direction, and $j$ being the spectral direction), $l$ is for the spectral channel, $o$ is the combiner output (so called region in the code, [0..23] or [0..47] if polarisations are split), $b$ is the baseline [0..5], and $t$ is the telescope/beam [0..4].

### 10.1 Correction of detector bias

The SC frames are corrected for the detector bias using the value of some specific pixels, supposedly nonilluminated. In LOW and MED spectral mode, the bias per frame is estimated as the mean over all the pixels of the bias lines interleaved between the spectra of each region.

In HIGH spectral mode, the bias per frame is estimated as the mean over all pixles of the bias columns at the edge of the detector.

In both case, there is thus a single, scalar bias value for the entire frame for each frame.

### 10.2 Dark map

The dark map is computed from a set of images acquired with all shutters closed and with the same exposure time as the raw image and as close in time as possible. The dark is computed for FT, SC and MET.

The dark map is the median image of this set of images.

$$
\begin{equation*}
D_{i j}=\operatorname{median}_{f}\left(X_{f i j}\right) \tag{5}
\end{equation*}
$$

### 10.3 Spectrum extraction

The implemented spectrum extraction $Y_{f o j}$ from the 2D image $X_{f i j}$ is based on a profile image $p_{o i j}$.

## Profile definition

When computing the profile from the sequence of 4 FLAT files, the first step is to add the 4 median of the 4 files. Then for each output a Gaussian fit is perform for each column (spectral element) over the specified profile_width pixels.

Depending of the profile-mode option the used profile can be either the gausian fit (GAUSS), the mesured pixels intensity (PROFILE), or boxcar (BOX). AUTO is the default option value and means PROFILE for LOW and MED mode, and BOX for HIGH mode.

In LOW and MED spectral modes, the profile is identical to the one observed with the sequences of FLAT files. It resembles a Gaussian function with FWHM of 1.5 pixel. To ensure the overall flux is conserved in the

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extraction, we apply the following normalization which assumes the shape of the object spectrum is perfectly matched by the profile itself:

$$
\begin{equation*}
p_{o i j}=p_{o i j} \cdot \frac{\sum_{i} p_{o i j}}{\sum_{i} p_{o i j}^{2}} \tag{6}
\end{equation*}
$$

In HIGH mode, the profile is a boxcar of 6 pixels around the center of the best-fit Gaussian on the observed profile in the FLAT files. To ensure flux conservation, this boxcar is either 0 (outside) or 1 (inside).

## Bad pixels in profile

The bad pixels are forced to zero in the profile. Consequently, a profile with bad pixels will lead to a reduced amount of detected flux. This effect is calibrated by the P2VM algorithm because the P2VM coefficients and the data are affected by the same amout of flux losses. A worst, for some spectral channels, the spectra of one output (e.g A) can be forced zero if all the pixels are bad. The P2VM then relies on the remaining BCD outputs only.

## Extracted spectrum and variance for SC

$$
\begin{equation*}
Y_{f o j}=g \sum_{i}\left(X_{f i j}-S_{i j}\right) p_{o i j} \tag{7}
\end{equation*}
$$

where $S_{i, j}$ is the mean image measured on the SKY, and $g$ is the conversion gain from [ADU] to [e]. The sum $\sum$ is obviously performed in the compressed spatial direction.

Introducing the photon and detector noise, the variance of the extracted spectrum is:

$$
\begin{equation*}
\operatorname{var}(Y)_{f o j}=g \sum_{i}\left(X_{f i j}-D_{i j}\right) p_{o i j}^{2}+g^{2} \sum_{i} \sigma_{i j}^{2} p_{o i j}^{2} \tag{8}
\end{equation*}
$$

where $D_{i, j}$ is the mean level measured on the DARK, and $\sigma_{i j}^{2}$ is the variance measured on the DARK.
If no SKY is available, it is replaced by the DARK in Eq.7. Note that this can bias the result since the background estimate will miss the true sky brightness, which is significant for long DIT and at the end of the K-band. If no DARK is available, it is replaced by the SKY in Eq.8. Note however that the number of frames in the SKY may be insufficient to properly estimate the variance, especially for the long DIT. Therefore it is strongly recommended to always reduce SC science observation with both a DARK with high statistic, and a SKY taken close in time and observing condition.

## Extracted spectrum and variance for FT

$$
\begin{gather*}
Y_{f o j}=g \sum_{i}\left(X_{f i j}-S_{i j}\right) p_{o i j}  \tag{9}\\
\operatorname{var}(Y)_{f o j}=g \sum_{i}\left(X_{f i j}-S_{i j}\right) p_{o i j}^{2}+g^{2} \sum_{i} \sigma_{i j}^{2} p_{o i j}^{2} \tag{10}
\end{gather*}
$$

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Figure 10.1: Correction of $X=C-A$ and $Y=D-B$ with the fitted ellipse parameters
where $g$ is the conversion gain from [ADU] to [e], $S_{i, j}$ is the mean level measured on the SKY, and $\sigma_{i j}^{2}$ is the variance measured on the SKY.

If no SKY is available, it is replaced by the DARK in Eq. 9 and Eq.10. Using a DARK or SKY makes litle difference for the FT because the sky brightness is negligeable at the FT frame rate, and because there is always enough statistic. However, it is critical to use a DARK or SKY calibration taken close in time, and with exactly the same FT setup.

### 10.4 Wavelength calibration

### 10.4.1 Compute the phase from ABCD

To compute the phase from the $\mathrm{A}, \mathrm{B}, \mathrm{C}$ and D measurements without knowing the P 2 VM , the 2 quantities $X=C-A$ and $Y=D-B$ must be corrected to compensate for non-perpendicularities of $\mathrm{A}, \mathrm{B}, \mathrm{C}$ and D . An ellipse with equation 11 is fitted to the raw data.

$$
\begin{equation*}
\sqrt{(a X+b Y+c)^{2}+(d Y+e)^{2}}=1 \tag{11}
\end{equation*}
$$

Knowing the fitted parameters ( $\mathrm{a}, \mathrm{b}, \mathrm{c}, \mathrm{d}$ and e ), we compute the corrected $X^{\prime}=a X+b Y+c$ and $Y^{\prime}=d Y+e$. The corrected points are now on a centered and normalized circle (10.1).

The phases are now computed as :

$$
\begin{equation*}
\varphi=\arctan \left(\frac{X^{\prime}}{Y^{\prime}}\right) \tag{12}
\end{equation*}
$$

The phase values are between 0 and $2 \pi$, to reconstruct the continuous evolution of the phases one needs to unwrap the numbers.

### 10.4.2 Evaluation of the OPD

To do the wavelength calibration we have to compute the $O P D_{F T}$ and $O P D_{S C}$ from the FT and SC data and the metrology measurement. This is possible because the scanning of the FT and SC FDDL are at different time scale. The relation linking $O P D_{F T}=a \widetilde{\varphi}_{F T}, O P D_{S C}=b \widetilde{\varphi}_{S C}$ and the differential metrology is the following:

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$$
\begin{equation*}
a \widetilde{\varphi}_{F T}-b \widetilde{\varphi}_{S C}+c=d O P L_{M E T} \tag{13}
\end{equation*}
$$

We compute $\widetilde{\varphi}_{F T}\left(t_{F T}\right)$ from FT data as the mean phase. This is done by computing the phase of each spectral element with ellipse method, and then computing the mean of the phase for the whole wavelengths.

We compute $\widetilde{\varphi}_{S C}\left(t_{F T}\right)$ from SC data as the mean phase, by the same way, and scalled at the time of the FT data.

We compute $d O P D_{M E T}$ at the time scale of the FT data.

$$
\begin{aligned}
& d O P D_{M E T}=\varphi_{M E T} * \lambda_{M E T} / 2 \pi \\
& a \widetilde{\varphi}_{F T}-b \widetilde{\varphi}_{S C}+c=d O P D_{M E T}
\end{aligned}
$$

Find a and b by fitting eq 13 on the metrology data. This equation can be written with the following matrix:

$$
\binom{O P D_{M E T j}^{t}-O P D_{M E T i}^{t}}{\vdots}=\left(\begin{array}{ccc}
\widetilde{\varphi}_{F T i j}^{t} & -\widetilde{\varphi}_{S C i j}^{t} & 1 \\
\vdots & \vdots & \vdots
\end{array}\right)\left(\begin{array}{l}
a \\
b \\
c
\end{array}\right)
$$



$$
\left(\begin{array}{c}
a \\
b \\
c
\end{array}\right)=\left(\begin{array}{ccc}
\widetilde{\varphi}_{F T i j}^{t} & -\widetilde{\varphi}_{S C i j}^{t} & 1 \\
\vdots & \vdots & \vdots
\end{array}\right)^{-1}\binom{O P D_{M E T j}^{t}-O P D_{M E T i}^{t}}{\vdots}
$$

For each baseline we compute the following

$$
\begin{aligned}
O P D_{F T} & =a \widetilde{\varphi}_{F T} \\
O P D_{S C} & =b \widetilde{\varphi}_{S C}
\end{aligned}
$$

### 10.4.3 Spectral calibration

The wavelength of each spectral element is computed by comparing the measured phases of this spectral element with the realized OPD: OPD ${ }_{\text {FT }}$ or OPD ${ }_{\text {SC }}$.

The measured phases are computed from the $\mathrm{A}, \mathrm{B}, \mathrm{C}$ and D measurements with ellipse methode.
For each computed phase we know the expected OPD, OPD $_{\text {FT }}$ or OPD $_{\text {SC }}$ from the metrology The slope of the phase versus OPD gives us the wavelength of the spectral element.

This wavelength is the one of the ABCD set of spectral elements for a given position, which is the barycentre of these four spectral elements. When all spectral element wavelengths are computed we have two sets of calibrated points, one for each polarization. On each of these two sets, a model of lambda versus position on the detector is fitted. And from this the wavelength of each spectral element of each spectrum is computed and put in the wavelength map.

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### 10.5 Re-interpolation to a common wavelength

## Modified target wavelength for SC

For the output (region) $o$, let's call $j_{o l}$ the sample just below the target wavelength $\lambda_{l}$, and $j_{o l}+1$ the sample just above. Of course $j$ depends on the region because their wavelength tables are different.

For the SC, this target wavelength is slightly modified, in a different way, for each region:

$$
\begin{equation*}
\lambda_{o l}^{\prime}=\lambda_{o j_{l}}+\frac{\left(\lambda_{l}-\lambda_{o j_{l}}\right)\left(\lambda_{o j_{l}+1}-\lambda_{o j_{l}}\right)}{\left(\lambda_{l}-\lambda_{o j_{l}}\right)+\left(\lambda_{o j_{l}+1}-\lambda_{l}\right) \cdot \frac{F_{o j_{l}+1}}{F_{o, j_{l} l}}} \tag{14}
\end{equation*}
$$

where $F_{o j}$ is the flat measured on the internal light, extracted the same way as the data. This modification ensures that we later interpolate to a common effective wavelength for all regions. It also ensures that spectral channels whose interpolation includes a bad-pixel (forced to zero) are all set to zero.

## Modified target wavelength for FT

For the FT, we don't modify the target wavelength:

$$
\begin{equation*}
\lambda_{o l}^{\prime}=\lambda_{l} \tag{15}
\end{equation*}
$$

## Interpolation of flux and variance

The following coefficient $a_{o l}$

$$
\begin{equation*}
a_{o l}=\frac{\lambda_{o j+1}-\lambda_{o l}^{\prime}}{\lambda_{o j+1}-\lambda_{o j}} \tag{16}
\end{equation*}
$$

allows to linearly interpolate the fluxes:

$$
\begin{equation*}
Y_{f o l}=a_{o l} Y_{f o j_{l}}+\left(1-a_{o l}\right) Y_{f o j_{l}+1} \tag{17}
\end{equation*}
$$

and the variances:

$$
\begin{equation*}
\operatorname{var}(Y)_{f o l}=a_{o l}^{2} \operatorname{var}(Y)_{f o j_{l l}}+\left(1-a_{o l}\right)^{2} \operatorname{var}(Y)_{f o j_{l}+1} \tag{18}
\end{equation*}
$$

### 10.6 Computation of the P2VM

The P2VM theory is inspired by the amber data reduction (Tatulli et al. 2007), which is working fine. It has been adapted to the integrated optics specificities (Lacour et al. 2008).

Figure 10.2 represents the generalized view of the transfer function of an integrated optics component. $E_{n}$ is the complex electric field entering the component via input $n$, and $S_{k}$ is the resulting field on output number $k$ . $T_{k, n}$ is a two dimensional complex matrix linking $S_{k}$ to $E_{n}$.

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Figure 10.2: Generalization of the transfer function of an integrated optics component

The flux q received by the detector from the output k at wavelength $\lambda$ and instant t is written as

$$
\begin{equation*}
q_{k}^{\lambda, t}=\left|S_{k}^{\lambda, t}\right|^{2}=\left|\sum_{n} T_{k, n}^{\lambda} E_{n}^{\lambda, t}\right|^{2} \tag{19}
\end{equation*}
$$

with the electric fields $E_{n}^{\lambda, t}$ and $S_{k}^{\lambda, t}$ as function of time and wavelength and of input $n$ and output $k$ respectively. $T_{k, n}^{\lambda}$ is the complex matrix function of wavelength linking $E_{n}^{\lambda, t}$ and $S_{k}^{\lambda, t}$.

With introduction of $V_{n, m}$ (coherence of the incoming electric field) and $C_{k, n, m}^{\lambda}$ (integrated optics conservation of light coherence) equation (7) can be developed as:

$$
\begin{equation*}
\left|S_{k}^{\lambda, t}\right|^{2}=R\left[\sum_{n}\left|T_{k, n}^{\lambda}\right|^{2}\left|E_{n}^{\lambda, t}\right|^{2}+\sum_{n} \sum_{m>n} 2 T_{k, n}^{\lambda} T_{k, m}^{\lambda *} C_{k, n, m}^{\lambda} E_{n}^{\lambda, t} E_{m}^{\lambda, t^{*}} V_{n, m}^{\lambda}\right] \tag{20}
\end{equation*}
$$

or

$$
\begin{gather*}
\left|S_{k}^{\lambda, t}\right|^{2}=\sum_{n}\left|T_{k, n}^{\lambda}\right|^{2}\left|E_{n}^{\lambda, t}\right|^{2}+\sum_{n} \sum_{m>n} \Re 2 T_{k, n}^{\lambda} T_{k, m}^{\lambda^{*}} C_{k, n, m}^{\lambda} \Re E_{n}^{\lambda, t} E_{m}^{\lambda, t^{*}} V_{n, m}^{\lambda} \\
-\sum_{n} \sum_{m>n} \Im 2 T_{k, n}^{\lambda} T_{k, m}^{\lambda *} C_{k, n, m}^{\lambda} \Im E_{n}^{\lambda, t} E_{m}^{\lambda, t^{*}} V_{n, m}^{\lambda} \tag{2}
\end{gather*}
$$

Using the matrix expression:

$$
\left(\begin{array}{c}
\left|S_{1}^{\lambda, t}\right|^{2}  \tag{22}\\
\vdots \\
\left|S_{K}^{\lambda, t}\right|^{2}
\end{array}\right)=R\left[V 2 P M_{C} \cdot\left(\begin{array}{c}
\left|E_{1}^{\lambda, t}\right|^{2} \\
\vdots \\
\left|E_{N}^{\lambda, t}\right|^{2} \\
E_{1}^{\lambda, t} E_{2}^{\lambda, t} V_{1,2} \\
\vdots \\
E_{N-1}^{\lambda, t} E_{N}^{\lambda, t} V_{N-1, N}
\end{array}\right)\right]=V 2 P M_{R} .\left(\begin{array}{c}
\left|E_{1}^{\lambda, t}\right|^{2} \\
\vdots \\
\left|E_{N}^{\lambda, t}\right|^{2} \\
R\left[E_{1}^{\lambda, t} E_{2}^{\lambda, t} V_{1,2}\right] \\
\vdots \\
R\left[E_{N-1}^{\lambda, t} E_{N}^{\lambda, t} V_{N-1, N}\right] \\
I\left[E_{1}^{\lambda, t} E_{2}^{\lambda, t} V_{1,2}\right] \\
\vdots \\
I\left[E_{N-1}^{\lambda, t} E_{N}^{\lambda, t} V_{N-1, N}\right]
\end{array}\right)
$$

with N entries and K output. The complex V2PM is defined as:

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$$
V_{2} P M_{C}=\left(\begin{array}{cccccc}
\left|T_{1,1}^{\lambda}\right|^{2} & \cdots & \left|T_{1, N}^{\lambda}\right|^{2} & 2 T_{1,1} T_{1,2} C_{1,1,2}^{\lambda} & \cdots & 2 T_{1, N-1} T_{1, N} C_{1, N-1, N}^{\lambda}  \tag{23}\\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\left|T_{K, 1}^{\lambda}\right|^{2} & \cdots & \left|T_{K, N}^{\lambda}\right|^{2} & 2 T_{K, 1} T_{K, 2} C_{K, 1,2}^{\lambda} & \cdots & 2 T_{K, N-1} T_{K, N} C_{K, N-1, N}^{\lambda}
\end{array}\right)
$$

Where the N first columns are the transmissions of the integrated optic, and the $\mathrm{N}(\mathrm{N}-1) / 2$ others are the coherences. The real V2PM matrix which can be used for visibility computing is:

$$
\begin{aligned}
& V 2 P M_{R}= \\
& \left(\begin{array}{cccccccc}
\left|T_{1,1}^{\lambda}\right|^{2} & \cdots & \left|T_{1, N}^{\lambda}\right|^{2} & R\left[2 T_{1,1} T_{1,2} C_{1,1,2}^{\lambda}\right] & \cdots & R\left[2 T_{1, N-1} T_{1, N} C_{1, N-1, N}^{\lambda}\right] & -I\left[2 T_{1,1} T_{1,2} C_{1,1,2}^{\lambda}\right] & \cdots \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots \\
\left|T_{K, 1}^{\lambda}\right|^{2} & \cdots & \left|T_{K, N}^{\lambda}\right|^{2} & R\left[2 T_{K, 1} T_{K, 2} C_{K, 1,2}^{\lambda}\right] & \cdots & R\left[2 T_{K, N-1} T_{K, N} C_{K, N-1, N}^{\lambda}\right] & -I\left[2 T_{K, 1} T_{K, 2} C_{K, 1,2}^{\lambda}\right] & \cdots
\end{array}\right.
\end{aligned}
$$

Compute the transmissions $\left|T_{k, n}^{\lambda}\right|^{2}$
This is done when only the shutter n is open. So we have $E_{m}^{\lambda, t}=0 \forall m \neq n$. Eq (3) becomes:

$$
\begin{equation*}
\left|S_{k}^{\lambda, t}\right|^{2}=\left|T_{k, n}^{\lambda}\right|^{2}\left|E_{n}^{\lambda, t}\right|^{2} \Leftrightarrow\left|T_{k, n}^{\lambda}\right|^{2}=\frac{\left|S_{k}^{\lambda, t}\right|^{2}}{\left|E_{n}^{\lambda, t}\right|^{2}} \tag{24}
\end{equation*}
$$

To avoid that $T_{k, n}^{\lambda}$ depends on the input flux, we assume that all incoming photons proceed to the exit of the optics, so:

$$
\begin{equation*}
\sum_{k}\left|S_{k}^{\lambda_{0}, t}\right|^{2} \times \widetilde{E}(\lambda)=\left|E_{n}^{\lambda, t}\right|^{2} \tag{25}
\end{equation*}
$$

Now $T_{k, n}^{\lambda}$ can be expressed as:

$$
\begin{equation*}
\left|T_{k, n}^{\lambda}\right|^{2}=\frac{\left.\left.\langle | S_{k}^{\lambda, t}\right|^{2}\right\rangle_{t}}{\left.\left.\left\langle\sum_{k}\right| S_{k}^{\lambda_{0}, t}\right|^{2}\right\rangle_{t} \times \widetilde{E}(\lambda)} \tag{26}
\end{equation*}
$$

Compute the coherences $2 T_{k, n}^{\lambda} T_{k, m}^{\lambda *} C_{k, n, m}^{\lambda}$
This is done when the shutter n and m are open and others closed. So we have $E_{i}^{\lambda, t}=0 \forall i \neq m, n$.
A calibration source is used with $V_{n, m}^{\lambda}=1$, so from eq (8) we have:

$$
\begin{equation*}
\left|S_{k}^{\lambda, t}\right|^{2}=\left|T_{k, n}^{\lambda}\right|^{2}\left|E_{n}^{\lambda, t}\right|^{2}+\left|T_{k, m}^{\lambda}\right|^{2}\left|E_{m}^{\lambda, t}\right|^{2}+R\left[2 T_{k, n}^{\lambda} T_{k, m}^{\lambda^{*}} C_{k, n, m}^{\lambda} E_{n}^{\lambda, t} E_{m}^{\lambda, t^{*}}\right] \tag{27}
\end{equation*}
$$

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This can be developed with $E_{n}^{\lambda, t}=\sqrt{I_{n}^{\lambda, t}} e^{-2 i \pi \frac{O P D_{n}^{t}}{\lambda}}$ as:

$$
\begin{equation*}
\left|S_{k}^{\lambda, t}\right|^{2}=\left|T_{k, n}^{\lambda}\right|^{2} I_{n}^{\lambda, t}+\left|T_{k, m}^{\lambda}\right|^{2} I_{m}^{\lambda, t}+2\left|T_{k, n}^{\lambda} T_{k, m}^{\lambda^{*}} C_{k, n, m}^{\lambda}\right| \sqrt{I_{n}^{\lambda, t} I_{m}^{\lambda, t}} \cos 2 \pi \frac{O P D_{m, n}^{t}}{\lambda}+\varphi_{k, n, m}^{\lambda} \tag{28}
\end{equation*}
$$

With $O P D_{m, n}^{t}=O P D_{m}^{t}-O P D_{n}^{t}$ and $\varphi_{k, n, m}^{\lambda}$ is the phase of $T_{k, n}^{\lambda} T_{k, m}^{\lambda *} C_{k, n, m}^{\lambda}$.
This equation can be fitted by a sinusoid with 3 free parameters ( $\mathrm{a}, \mathrm{b}$ and c )

$$
\begin{equation*}
\left|S_{k}^{\lambda, t}\right|^{2}=a_{k, m, n}^{\lambda} \cos \frac{O P D_{m, n}^{t}}{\lambda} 2 \pi+b_{k, m, n}^{\lambda} \sin \frac{O P D_{m, n}^{t}}{\lambda} 2 \pi+c_{k, m, n}^{\lambda} \tag{29}
\end{equation*}
$$

With:

$$
\begin{gather*}
c_{k, m, n}^{\lambda}=\left|T_{k, n}^{\lambda}\right|^{2} I_{n}^{\lambda, t}+\left|T_{k, m}^{\lambda}\right|^{2} I_{m}^{\lambda, t}  \tag{30}\\
\varphi_{k, n, m}^{\lambda}=\arctan [\mathrm{E} 09 \mathrm{E} \text { ? }] \frac{b_{k, m, n}}{a_{k, m, n}} \text { [E09F?] }  \tag{3}\\
2\left|T_{k, n}^{\lambda} T_{k, m}^{\lambda^{*}} C_{k, n, m}^{\lambda}\right| \sqrt{I_{n}^{\lambda, t} I_{m}^{\lambda, t}}=\sqrt{a_{k, m, n}^{\lambda}{ }^{2}+b_{k, m, n}^{\lambda}{ }^{2}} \tag{3}
\end{gather*}
$$

The coherences ( $2 T_{k, n}^{\lambda} T_{k, m}^{\lambda *} C_{k, n, m}^{\lambda}$ ) can be expressed by their phases and amplitudes. The phase is given by eq. (13) and the amplitude is given by eq. (14). But the amplitude depends on the $I_{n}^{\lambda, t}$ which can be evaluated with eq. (12).

Eq.(12)can be expressed as a matrix equation where the $\left|T_{k, n}^{\lambda}\right|^{2}$ matrix is already:

$$
\left(\begin{array}{c}
c_{1, m, n}^{\lambda}  \tag{3}\\
\vdots \\
c_{K, m, n}^{\lambda}
\end{array}\right)=\left(\begin{array}{ccc}
\left|T_{1,1}^{\lambda}\right|^{2} & \cdots & \left|T_{1, N}^{\lambda}\right|^{2} \\
\vdots & \ddots & \vdots \\
\left|T_{K, 1}^{\lambda}\right|^{2} & \cdots & \left|T_{K, N}^{\lambda}\right|^{2}
\end{array}\right) \cdot\left(\begin{array}{c}
I_{1}^{\lambda, t} \\
\vdots \\
I_{N}^{\lambda, t}
\end{array}\right)
$$

This over determined system can be solved by inverting the matrix $\left|T_{k, n}^{\lambda}\right|^{2}$ with a singular value decomposition method. And knowing $I_{n}^{\lambda, t}$, we can compute the coherences amplitudes:

$$
\begin{equation*}
2\left|T_{k, n}^{\lambda} T_{k, m}^{\lambda^{*}} C_{k, n, m}^{\lambda}\right|=\frac{\sqrt{a_{k, m, n}^{\lambda}{ }^{2}+b_{k, m, n}^{\lambda}{ }^{2}}}{\sqrt{I_{n}^{\lambda, t} I_{m}^{\lambda, t}}} \tag{34}
\end{equation*}
$$

This should be done for each base $(\mathrm{n}, \mathrm{m}>\mathrm{n}$ couple).

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## Phases calibrations

The phases $\varphi_{k, n, m}^{\lambda}$ of the integrated optics coherences $C_{k, n, m}^{\lambda}$ can be divided into two components: the modulation phases (ABCD-like modulation) $\psi_{k, n, m}^{\lambda}$ and the baseline phases $\varphi_{n, m}^{\lambda}$ :

$$
\begin{equation*}
\varphi_{k, n, m}^{\lambda}=\psi_{k, n, m}^{\lambda}+\varphi_{n, m}^{\lambda} \tag{35}
\end{equation*}
$$

Modulation phases The modulation phases $\psi_{k, n, m}^{\lambda}$ are defined as the instrumental phases introduced by the beam combiner between the two interfering beams n and m . For each baseline defined by the couple of beams $(\mathrm{n}, \mathrm{m})$, the corresponding modulations phases are defined relatively to one of the beams at the output $k=A_{(n, m)}$ acting as a reference, such that:

$$
\begin{equation*}
\psi_{k, n, m}^{\lambda}=\psi_{k, n, m}^{\lambda}-\psi_{A_{(n, m)}, n, m}^{\lambda} \tag{3}
\end{equation*}
$$

Absolute baseline phases The baseline phases $\varphi_{n, m}^{\lambda}$ are defined as the absolute instrumental phases introduced by the beam combiner on each baseline. They induce instrumental closure phases different from zero, and then bias the source closure phases.

However, the absolute values of the baseline phases cannot be measured, due to different reference phases and piston disturbances. The closure phases they induce do not depend on these biases, however. The baseline phases can be calibrated and included in the V2PM, in a way not to bias the closure phases of the source.
Thus, instead of measuring the absolute baseline phases $\varphi_{n, m}^{\lambda}$, relative baseline phases $\widetilde{\varphi}_{n, m}^{\lambda}$ can be determined, inducing the same closure phases as the absolute instrumental phases.

Closure phases and relative baseline phases Let $\Phi_{n, m}^{\lambda}$ and $\widetilde{\Phi}_{n, m}^{\lambda}$ be the vectors of respectively the 6 absolute and the 6 relative baseline phases, $\varphi_{n, m}^{\lambda}$ and $\widetilde{\varphi}_{n, m}^{\lambda}$, for the apertures $(n, m) \in[301 \mathrm{~A} ?] 0,3[301 \mathrm{~B} \text { ? }]^{2}$ :

$$
\begin{align*}
& \Phi_{n, m}^{\lambda}=\left(\varphi_{0,1}^{\lambda} \varphi_{0,2}^{\lambda} \varphi_{0,3}^{\lambda} \varphi_{1,2}^{\lambda} \varphi_{1,2}^{\lambda} \varphi_{2,3}^{\lambda}\right)^{T}  \tag{37}\\
& \widetilde{\Phi}_{n, m}^{\lambda}=\left(\widetilde{\varphi}_{0,1}^{\lambda} \widetilde{\varphi}_{0,2}^{\lambda} \widetilde{\varphi}_{0,3}^{\lambda} \widetilde{\varphi}_{1,2}^{\lambda} \widetilde{\varphi}_{1,2}^{\lambda} \widetilde{\varphi}_{2,3}^{\lambda}\right)^{T} \tag{38}
\end{align*}
$$

Let $\Xi_{n, m, l}^{\lambda}$ be the vector of the 4 resulting closure phases $\xi_{n, m, l}^{\lambda}$ between the 3 apertures $(n, m, l) \in[301 \mathrm{~A}$ ? $] 0,3[301 \mathrm{~B} \text { ? }]^{3}$ :

$$
\begin{equation*}
\Xi_{l, n, m}^{\lambda}=\left(\xi_{0,1,2}^{\lambda} \xi_{0,1,3}^{\lambda} \xi_{0,2,3}^{\lambda} \xi_{1,2,3}^{\lambda}\right)^{T} \tag{39}
\end{equation*}
$$

such that:

$$
\begin{equation*}
\xi_{n, m, l}^{\lambda}=\varphi_{n, m}^{\lambda}+\varphi_{m, l}^{\lambda}-\varphi_{n, l}^{\lambda} \tag{40}
\end{equation*}
$$

Three of these closure phases are independent, and the fourth is related to the other by:

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$$
\begin{equation*}
\xi_{0,1,2}^{\lambda}+\xi_{0,2,3}^{\lambda}=\xi_{0,1,3}^{\lambda}+\xi_{1,2,3}^{\lambda} \tag{41}
\end{equation*}
$$

Generalizing relation (22) to the vectors of closure phases and baseline phases leads to equation (24):

$$
\begin{equation*}
\Xi_{n, m}^{\lambda}=M \Phi_{n, m}^{\lambda} \tag{42}
\end{equation*}
$$

with the matrix M :

$$
M=\left(\begin{array}{cccccc}
1 & -1 & 0 & 1 & 0 & 0  \tag{43}\\
1 & 0 & -1 & 0 & 1 & 0 \\
0 & 1 & -1 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & -1 & 1
\end{array}\right)
$$

The relative baseline phases $\widetilde{\varphi}_{n, m}^{\lambda}$ must result from a linear operation of the known closure phases, and lead to the same closure phases $\xi_{n, m, l}^{\lambda}$. Therefore the vector $\widetilde{\Phi}_{n, m}^{\lambda}$ must be linked to the closure phases $\Xi_{n, m, l}^{\lambda}$ by a matrix N such that:

$$
\begin{equation*}
\widetilde{\Phi}_{n, m}^{\lambda}=N \Xi_{n, m}^{\lambda} \tag{44}
\end{equation*}
$$

and verify the same equation as(24):

$$
\begin{equation*}
\Xi_{n, m}^{\lambda}=M \widetilde{\Phi}_{n, m}^{\lambda} \tag{45}
\end{equation*}
$$

Thus, combining equations (26) and (27), the relative baseline phases are defined by the matrix N such that:

$$
\begin{equation*}
\Xi_{n, m}^{\lambda}=M N \Xi_{n, m}^{\lambda} \tag{46}
\end{equation*}
$$

N is not unique and we suggest to use the N matrix such that:

$$
N=\frac{1}{4} M^{T}=\frac{1}{4}\left(\begin{array}{cccc}
1 & 1 & 0 & 0  \tag{47}\\
-1 & 0 & 1 & 0 \\
0 & -1 & -1 & 0 \\
1 & 0 & 0 & 1 \\
0 & 1 & 0 & -1 \\
0 & 0 & 1 & 1
\end{array}\right)
$$

Equation (26) easily leads to the vector of relative baselines phases:

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$$
\widetilde{\Phi}_{n, m}^{\lambda}=\frac{1}{4}\left(\begin{array}{c}
\xi_{0,1,2}^{\lambda}+\xi_{0,1,3}^{\lambda}  \tag{48}\\
-\xi_{0,1,2}^{\lambda}+\xi_{0,2,3}^{\lambda} \\
-\xi_{0,1,3}^{\lambda}+\xi_{0,2,3}^{\lambda} \\
\xi_{0,1,2}^{\lambda}+\xi_{1,2,3}^{\lambda} \\
\xi_{0,1,3}^{\lambda}-\xi_{1,2,3}^{\lambda} \\
\xi_{0,2,3}^{\lambda}+\xi_{1,2,3}^{\lambda}
\end{array}\right)
$$

Compute the closure phases This is done when all the shutters are open together, with a calibration source with $V_{n, m}^{\lambda}=1$. Using an intermediate V2PM with null instrumental closure phases and baseline phases, from the intensities $q_{k}^{\lambda, t}$ we can compute the vector (eq. (4)):

$$
\left(\begin{array}{c}
\left|E_{1}^{\lambda, t}\right|^{2}  \tag{49}\\
\vdots \\
\left|E_{N}^{\lambda, t}\right|^{2} \\
R\left[E_{1}^{\lambda, t} E_{2}^{\lambda, t} \exp \left(i \varphi_{1,2}^{\lambda}\right)\right] \\
\vdots \\
R\left[E_{N-1}^{\lambda, t} E_{N}^{\lambda, t} \exp \left(i \varphi_{N-1, N}^{\lambda}\right)\right] \\
I\left[E_{1}^{\lambda, t} E_{2}^{\lambda, t} \exp \left(i \varphi_{1,2}^{\lambda}\right)\right] \\
\vdots \\
I\left[E_{N-1}^{\lambda, t} E_{N}^{\lambda, t} \exp \left(i \varphi_{N-1, N}^{\lambda}\right)\right]
\end{array}\right)
$$

The phases $\varphi_{n, m}^{\lambda}$ can be expressed by the equation:

$$
\begin{equation*}
\varphi_{n}^{\lambda, t}+\varphi_{m}^{\lambda, t}+\varphi_{n, m}^{\lambda}=\arctan \left(\frac{I\left[E_{n}^{\lambda, t} E_{m}^{\lambda, t} \exp \left(i \varphi_{n, m}^{\lambda}\right)\right]}{R\left[E_{n}^{\lambda, t} E_{m}^{\lambda, t} \exp \left(i \varphi_{n, m}^{\lambda}\right)\right]}\right) \tag{50}
\end{equation*}
$$

With $\varphi_{n}^{\lambda, t}$ the phase of the electric field $E_{n}^{\lambda, t}$. Equation (24) therefore leads to the instrumental closure phases, free of the electric fields phases $\varphi_{n}^{\lambda, t}$. The relative baseline phases $\widetilde{\varphi}_{n, m}^{\lambda}$ can then be deduced from equation (30).

### 10.7 Extraction of the coherent fluxes and telescope fluxes via P2VM

The fluxes of each telescope $F_{f t l}$ and the complex coherent flux of each base $R_{f b l}+i I_{f b l}$ are extracted from a matricial analysis of the profiles, based on the P2VM calibration

$$
\begin{equation*}
\left(F_{f t l}, R_{f b l}, I_{f b l}\right)=P 2 V M_{b / t l}^{o} \times Y_{f o l} \tag{51}
\end{equation*}
$$

The variances are propagated assuming no correlation between the input $Y_{f o l}$.

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$$
\begin{equation*}
\left(\operatorname{var}(F)_{f t l}, \operatorname{var}(R)_{f b l}, \operatorname{var}(I)_{f b l}\right)=\left(P 2 V M_{b / t l}^{o}\right)^{2} \times \operatorname{var}(Y)_{f o l} \tag{52}
\end{equation*}
$$

The $P 2 V M$ is a well conditioned matrix thanks to the design of the integrated beam combiner. To demonstra the underlying reasoning, let's consider a perfect $P 2 V M$. The four regions related to baseline $b$ (say $0,1,2,3$, also called ABCD regions of baseline $b$ ) can be combined together to build the following quantities:

- $R_{f b l}=Y_{f 0 l}-Y_{f 2 l}$,
- $I_{f b l}=Y_{f 1 l}-Y_{f 3 l}$ and
- $F_{f t_{1} l}+F_{f t_{2} l}=Y_{f 0 l}+Y_{f 1 l}+Y_{f 2 l}+Y_{f 3 l}$.

The two first are directly the complex coherent flux of baseline $b$, while the latter, combined with the constraints of the 5 other baselines, easily solve for the flux $F_{f t l}$ of individual beams. In practice, the actual $P 2 V M$ matrix takes into account the exact interferometric phase-shift between the four ABCD regions, and the relative photometric throughputs. It is a global fit of the 24 outputs into $6 \times 2$ coherent fluxes $\left(R_{f b l}, I_{f b l}\right)$ and 4 photometric fluxes $\left(R_{f t l}\right)$, for each frame, each wavelength channel, and each polarisation.

### 10.8 Computation of reduced chi2

Once the fluxes quantities ( $R_{f b l}, I_{f b l}$ and $R_{f t l}$ ) have been estimated via propagation through the $P 2 V M$, it is possible to recompute the corresponding expected output values:

$$
\begin{equation*}
Z_{f o l}=V 2 P M_{o}^{b / t l} \times\left(F_{f t l}, R_{f b l}, I_{f b l}\right) \tag{53}
\end{equation*}
$$

From these, we can compute a reduced chi 2 with respect to the measurements:

$$
\begin{equation*}
C H I 2_{f l}=\sum_{o} \frac{\left(Y_{f o l}-Z_{f o l}\right)^{2}}{\operatorname{var}(Y)_{f o l}} \frac{1}{24-16} \tag{54}
\end{equation*}
$$

### 10.9 Computation of SNR

## Individual SNR

The Signal to Noise Ratio (SNR) of each baseline and each frame of the the FT is computed using a running mean of the complex coherent flux over 10 consecutive samples. The complex coherent flux of the two polarisations, if any, are also averaged together after having recentered them to a common mean phase.

$$
\begin{equation*}
S N R_{f b}=\frac{\left(\sum_{f_{r} l} R_{f_{r} b l}\right)^{2}+\left(\sum_{f_{r} l} I_{f_{r} b l}\right)^{2}}{\sum_{f_{r} l} \operatorname{var}(R)_{f_{r} b l}+\sum_{f_{r} l} \operatorname{var}(I)_{f_{r} b l}} \tag{55}
\end{equation*}
$$

where $f_{r}$ is the $f$ index running in the interval $\in\{f-5, f+5\}$ in order to implement the smoothing over 10 samples.

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## Bootstrapped SNR

If fringes are detected on two consecutive baselines, then, by nature of light, fringes are detected on the closing baseline. The purpose of bootstrapping is to increase the confidence on the signal for the baselines with lowest SNR (whose SNR may well be null for astrophysical reason), by looking at these closing baseline.

A "bootstraped" SNR is computed for each baseline and each frame, as the maximum between the SNR of this baseline and all closing triangles. For instance for the baseline $b=b_{i j}$ among the beams $i, j, k, l$ :

$$
\begin{equation*}
S N R B_{f b_{i j}}=\max \left\{S N R_{f b_{i j}}, \min \left\{S N R_{f b_{i_{i}}}, S N R_{f b_{k j}}\right\}, \min \left\{S N R_{f b_{i l}}, S N R_{f b_{l j}}\right\}\right\} \tag{56}
\end{equation*}
$$

The quantities SNR and SNRB are also computed for the SC, although they are not used in the processing.

### 10.10 Computing the vFactor

The purpose of the vFactor is to estimate the visibility loss of each individual SC frame due the phase jittering, from an analysis of the FT real-time data. This visibility loss is derived as the ratio between the coherent integration (squared norm of complex sum over DITs) and the incoherent integration (sum over DITs of complex squared norm) of the complex coherent flux of FT, across each SC DIT.

A white-light vFactor is first computed for each SC frame $f$ with the FT data:
where the sum over $l$ is over the 6 spectral channels of the FT and the sum over $f_{F T}$ is over the FT frames acquired during the corresponding SC frame. This white-light vFactor at $\lambda_{0}$ (the central wavelength of the FT) is then extrapolated to the SC channels with:

$$
\begin{equation*}
\widetilde{v}_{f b l}=\exp \left(-\ln \left(v_{f b}\right) \frac{\lambda_{0}^{2}}{\lambda_{l}^{2}}\right) \tag{58}
\end{equation*}
$$

This vFactor correction is proved to be very efficient as long as the FT astrophysical visibility remain larger than 0.1 . For fully resolved baselines, the vFactor results into a indefinit $0 / 0$ ratio. In such a sitation, and if on-axis, one could simply rescale the SC visibilities to the one of the FT (see options of the recipes). In off-axis case with a fully resolved object on the FT, there is not much to be done however.

### 10.11 Computing the pFactor

The purpose of the pFactor is to estimate the visibility loss of each individual SC frame due to flux flickering, from an analysis of the FT real-time flux data. This visibility loss is derived as the ratio between the sum over DITs of the geometry mean, and the geometric mean of the sum over DITs of the photometric flux of FT, across each SC DIT.

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We compute a white-light pFactor with the following formula:

$$
\begin{equation*}
p_{b f}=\frac{\left[\sum_{f_{r}} \sqrt{\left(\sum_{l} \text { flux }_{f_{r} t_{1} l}\right)\left(\sum_{l} \text { flux }_{f_{r} t_{2} l}\right)}\right]^{2}}{\left(\sum_{f_{r l} l} \text { fux }_{f_{r \pi} t_{1} l}\right)\left(\sum_{f_{r l} l} \text { fux }_{f_{r} t_{2} l} l\right)} \tag{59}
\end{equation*}
$$

This pFactor is computed in the P2VMRED product but not used so far

### 10.12 Frame rejection

A FT frame is rejected if any of the conditions are met:

- its bootstrapped $S N R B$ is below the threshold.
- the OPDC state of this baseline is below the threshold. The OPDC states are: $1=$ IDEL, $2=$ GD_TRACKING, $3=$ PHASE_TRACKING, $4=$ SEARCHING, $5+=$ internal calibrations.

A SC frame is rejected if any of the conditions are met:

- the fraction of accepted FT frame during this SC frame is below the threshold.
- its computed vFactor is below the treshold.

The frame selection is done on a per-baseline basis. That is the baselines have a different selection map, and thus will have a different effective time after the averaging process.

### 10.13 Phase referencing

## Self-referencing the FT phase

The phase reference of a FT frames is the runnning mean phase of the FT itself over few samples:

$$
\begin{equation*}
\mathrm{P}_{-} \mathrm{REF}_{f b l}=\arctan \left(\sum_{f_{r}} I_{f_{r} b l}, \sum_{f_{r}} R_{f_{r} b l}\right) \tag{60}
\end{equation*}
$$

where $f_{r}$ is in the interval $\in\{f-3, r+3\}$, exluding $f_{r}=f$ to avoid biases. Note that this phase is not unwrapped neither temporally nor spectrally (SNR too low, and FT supposed to be near constant phase all the time thanks to real-time tracking).

## Referencing the SC phases in single case

The phase reference of a SC frame is the mean phase of the FT during this SC frame:

$$
\begin{equation*}
\mathrm{P}_{-} \mathrm{REF}_{f b l}=\arctan \left(\sum_{f_{r r}} I_{f_{f r r} b l}, \sum_{f_{r_{r}}} R_{f_{r r} b l}\right) \tag{61}
\end{equation*}
$$

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where the sum over $f_{F T}$ is over the FT frames acquired during the corresponding SC frame.
This P_REF, which have 6 spectral channels only, is interpolated/extrapolated into the wavelengths of the SC with a polynomial fit of order 2 (after properly unwrapping the phase along the spectral direction).

## Referencing the SC phases in dual case

In case of dual-field observation, the previous reference phase is modified to account for the sideral motion of the binary separation $(\mathrm{dE}, \mathrm{dN})$ and the metrology measurements:

$$
\begin{equation*}
\mathrm{P}_{-} \mathrm{REF}_{-} \mathrm{IMG}_{f b l}=\mathrm{P}_{-} \mathrm{REF}_{f b l}+\frac{2 \pi}{\lambda_{l}}\left(\mathrm{UCOORD}_{f b} \mathrm{dE}+\mathrm{VCOORD}_{f b} \mathrm{dN}-\text { OPD_DISP }_{f b l}\right) \tag{62}
\end{equation*}
$$

### 10.14 Geometric flux

The geometric flux of a baseline is the product of the photometric fluxes of the two beams of this baseline. It is needed to then normalise the complex coherent fluxes into complex visibilities.

## For the FT

The FT real-time photometry is affected by large photometric fluctuations, which make it going near zero (flux loss event) or even going to negative values because of noise. Since the geometric flux will enter the visibility normalisation in the denominator, we have to avoid as much as possible these near-zero events.

The photometric fluctuations are highly corrected in the spectral direction. On the other side, the important property of the fluctuations to be extracted are the temporal correlations. Therefore we first compute a broadband sum of the real-time flux of each beam, that we is temporally smooth:

$$
\begin{equation*}
F_{f t}^{\prime}=\frac{\sum_{f_{r} l} F_{f_{r} t l}}{11} \tag{63}
\end{equation*}
$$

where $f_{r}$ is in the interval $\in\{f-5, f+5\}$ (time smoothing). We also compute a normalized time-averaged spectrum for each beam:

$$
\begin{equation*}
F_{l t}^{\prime \prime}=\frac{\sum_{f} F_{f t l}}{\sum_{f l} F_{f t l}} \tag{64}
\end{equation*}
$$

Only then the geometric mean is computed from these two quantities:

$$
\begin{equation*}
F F_{f b l}=F_{f t_{1}}^{\prime} F_{f t_{1} l}^{\prime \prime} \times F_{f t_{2}}^{\prime} F_{f t_{2} l}^{\prime \prime} \tag{65}
\end{equation*}
$$

## For the SC

For the science, the geometric flux is simply computed as:

$$
\begin{equation*}
F F_{f b l}=F_{f t_{1} l} \times F_{f t_{2} l} \tag{66}
\end{equation*}
$$

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### 10.15 Averaged flux estimator

The previous sections describe how the real-time quantities are extracted from every single FT and SC frame. We here describe the process of averaging these real-time quantities into final product. For the flux, all frames are simply co-added. There is no frame selection at all.

$$
\begin{equation*}
\widetilde{\operatorname{fux}}_{t l}=\sum_{f} F_{f t l} \tag{67}
\end{equation*}
$$

Hence the final flux $\widetilde{f l u x}_{t l}$ is the sum of all electron-events collected during the entire exposure and across all regions, for the beam $t$ at channel $l$.

### 10.16 Averaged complex visibility estimator

For a given baseline, the averaged is computed only with accepted frames of this baseline.
The complex coherent flux vector is first rotated with the computed reference phase P_REF (or with P_REF_IMG in the case of dual-observations):

$$
\begin{gather*}
R_{f b l}^{\prime}=\cos \left({\left.\mathrm{P} \_\mathrm{REF}_{f b l}\right)} R_{f b l}-\sin \left({\left.\mathrm{P} \_\mathrm{REF}_{f b l}\right)} I_{f b l}\right.\right.  \tag{68}\\
I_{f b l}^{\prime}=\sin \left({\left.\mathrm{P} \_\mathrm{REF}_{f b l}\right)} R_{f b l}+\sin \left({\left.\mathrm{P} \_\mathrm{REF}_{f b l}\right)} I_{f b l}\right.\right. \tag{69}
\end{gather*}
$$

The visibilities of each frame are averaged together accounting for the visibility loss expected from the vFactor (only for SC, that is $v_{f b l}=1.0$ for FT). Note that the coherent flux and the photometric flux are actually averaged first, before normalisation. The noise property is better than simply averaging the real-time normalised visibilities (Cauchy statistic).

## Visibility amplitude

$$
\begin{equation*}
\text { visAmp }_{b l}=\frac{\sqrt{\left(\sum_{f} R_{f b l}^{\prime}\right)^{2}+\left(\sum_{f} I_{f b l}^{\prime}\right)^{2}}}{\sum_{f} \sqrt{F F_{f b l} v_{f b l}}} \tag{70}
\end{equation*}
$$

## Visibility phase

$$
\begin{equation*}
\widetilde{\operatorname{visPhi}}_{b l}=\arctan \left(\sum_{f} I_{f b l}^{\prime}, \sum_{f} R_{f b l}^{\prime}\right) \tag{71}
\end{equation*}
$$

The mean spectral slope (stored in the GDELAY quantity) and mean spectral value (stored in the PHASE quantity) are removed from the VISPHI quantity.

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### 10.17 Average squared visibility estimator

The square visibilities of each frame are averaged together accounting for the visibility loss expected from the vFactor (only for SC, that is $v_{f b l}=1.0$ for FT).

For a given baseline, the averaging is performed only with accepted frames of this baseline.

$$
\begin{equation*}
\widetilde{\operatorname{vis}}_{b l}=\frac{\sum_{f} R_{f b l}^{2}+\sum_{f} I_{f b l}^{2}-\sum_{f} \operatorname{var}(R)_{f b l}-\sum_{f} \operatorname{var}(I)_{f b l}}{\sum_{f}\left(F F_{f b l} v_{f b l}\right)} \tag{72}
\end{equation*}
$$

### 10.18 Average closure-phase estimator

The averaged bispectrum of triplet $b_{i j k}$ is computed as the coherent integration of the bispectrum of each frame:

$$
\begin{equation*}
\widetilde{B}_{b_{i j k} l}=\sum_{f}\left(R_{f b_{i j} l}+i I_{f b_{i j} l}\right) \cdot\left(R_{f b_{j k} l}+i I_{f b_{j k} l}\right) \cdot\left(R_{f b_{i k} l}-i I_{f b_{i k} l}\right) \tag{73}
\end{equation*}
$$

For a given triplet, the integration is performed only with frames for which all three baselines forming the triangles are accepted.

## Bispectrum phase

The closure phase is computed:

$$
\begin{equation*}
\mathrm{t}_{3 \mathrm{Ph}}^{\mathrm{B}_{i j k l} l}=\arctan \left(\widetilde{B}_{b_{i j k}} l\right) \tag{74}
\end{equation*}
$$

## Bispectrum amplitude

The bispectrum amplitude is also computed. However this quantity has not been verified yet.

$$
\begin{equation*}
\mathrm{t} \widetilde{\mathrm{Am}}_{b l}=\frac{\widetilde{B}_{b_{i j k} l}}{\sum_{f}\left(F_{f t_{i} l} F_{f t_{j} l} F_{f t_{k} l} \sqrt{v_{f b_{i j} l} v_{f b_{i k} l} v_{f b_{j k} l}}\right)} \tag{75}
\end{equation*}
$$

### 10.19 Uncertainty on average quantities

The uncertainty on average quantities is computed by bootstrapping over the accepted frames. Basic fundamentals about this technic can be in the numerical recipes book, section 15.6.
See also: https://en.wikipedia.org/wiki/Bootstrapping_(statistics)
The implementation of the bootstraping method makes use of segmentation when the number of frame is larger than 100, or of Monte-Carlo when the number of frame is smaller than 5 .

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## Segmentation (mostly for FT)

When the number of frames is larger than 100, the dataset is first split into a smaller number of segments (typically 20 to 100). First integration is done inside the segments. The final variance is estimated by bootstrapping over the segments. The number of segments does change the temporal sampling of the bootstrap, and thus the estimation of the uncertainties. We choose the number of segment so that each is about 1 s length.

Note that this is mostly relevant for the FT, since the SC has often less than 100 frames (so each frame is a segment).

## Monte-Carlo (mostly for very long DIT on SC)

When the number of frames is smaller than 5 , the bootstrap method provides unrealistically small uncertainties. Hence the dataset is complemented with few fake frames (up to 5), on which a random realisation of the theoretical noise is added, using the theoretical variance.

This noise is added on the correlated flux quantity only, not on the photometric fluxes, vFactor, reference phase... Moreover it is clear that Monte-Carlo propagates the fundamental uncertainties only (photon and detector noise), but not the atmospheric noises (effect of injection fluctuation, tracking quality fluctuation).

As a matter of fact, the final uncertainty when the number of frames is very low can still be under-estimated.

### 10.20 Calibration with the TF

## From CAL to TF estimations

For every observation $c$ of an calibration star (VIS_CAL), the visibilities are converted into VIS_TF by dividing the VISAMP quantities by the expected visibility, accounting for the provided diameter. The uncertainty on the diameter is not propagated to the VIS_TF.

$$
\begin{align*}
& \widetilde{\mathrm{tfmp}}_{b l c}=\frac{\widetilde{\mathrm{visAmp}}_{b l c}}{J 1\left(\pi B_{b} / \lambda_{l}\right) /\left(\pi B_{b} / \lambda_{l}\right)}  \tag{76}\\
& \widetilde{\mathrm{tfPhi}_{b l}}=\widetilde{\mathrm{visPh}}_{b l c} \tag{77}
\end{align*}
$$

## Interpolation of TF at the time of SCI

The TF are then averaged to obtain an estimation at the time of the SCI measurement:

$$
\begin{equation*}
\operatorname{tfAmp}_{b l}=\frac{\sum_{c} W_{b c} \widetilde{v i s A m p}_{b l c}}{\sum_{c} W_{b c}} \tag{78}
\end{equation*}
$$

where the weight is a combination of the distance in time $\left(T-T_{c}\right)$, and of the precision of the individual measurements:

$$
\begin{equation*}
W_{b c}=\frac{\exp \left(-2\left(T-T_{c}\right)^{2} / \Delta^{2}\right)}{\operatorname{median}_{l}\left(\sigma_{b l c}^{2}\right)} \tag{79}
\end{equation*}
$$

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The free parameter $\Delta$ corresponds to the expected stability of the instrumental + atmosphere responses. Calibrations recorded within this time interval are mostly averaged, calibrations separated by about this time interval are mostly interpolated, and calibrations far away from this time interval will be discarded (closed one becomes dominent).

A similar approach is used for the phases:

$$
\begin{equation*}
\widetilde{\mathrm{tfPh}}_{b l}=\arg \left(\sum_{c} W_{b c} \exp \left(i \widetilde{\operatorname{visPh}}_{b l c}\right)\right) \tag{80}
\end{equation*}
$$

## Calibration

$$
\begin{align*}
& \text { visAmp } \widetilde{b l}_{b l}=\frac{\text { visAmp }_{b l}}{\mathrm{tfAmp}_{b l}}  \tag{81}\\
& \widetilde{\operatorname{visPh}_{b l}}=\arg \left(\exp \left(i\left(\widetilde{\operatorname{visPh}_{b l}}-\widetilde{\mathrm{fPh}}_{b l}\right)\right)\right) \tag{82}
\end{align*}
$$

### 10.21 Processing of ACQ

## Pre-processing

The pre-processing re-interpolates the bad-pixels. For the pupil images, the background is computed from the median of the images and subtracted.

## Analysis of pupil images

The pupil scale, rotation and position is computed for each frame by adjusting a spot model ( 16 spot on the expected grid) to the image. the degree of freedom are: rotation angle of pupil (same for the four sub-appertures), scaling of pupil (same for the four sub-appertures), mean x and y of each sub-apperture, FWHM (same for all diodes), and flux (one per diode).

The mean displacement of the pupil is computed (mean of the four sub-apperture) as PUPIL_X and PUPIL_Y. Then the expected opd introduced by the mean pupil displacement is computed by:

$$
\begin{equation*}
\text { OPD_PUPIL = PUPIL_S . SEP . }(\text { PUPIL_X } \cos \Psi+\text { PUPIL_Y } \sin \Psi) \tag{8}
\end{equation*}
$$

where $\Psi$ is the angle of the binary separation in the ACQ camera frame, PUPIL_S is the pupil scale ( $\mathrm{mm} / \mathrm{pix}$ ) in the ACQ images (read from header, DROTOFF position), and SEP is the binary separation in [rad] (read from header).

## Analysis of field images

The positions on the acquisition camera detector of the SC and FT targets are measured by fitting a gaussian profile, after an initial guess based on the separation SOBJ. $[\mathrm{X} \mid \mathrm{Y}]$, given in the main header, between the FT and

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Figure 10.3: Geometry of the Acquisition Camera field image. The nominal positions of the $F T$ and $S C$ targets (red dots) are given in the acquisition camera field coordinates $(x, y)$. The orientation of the FT/SC pair matches the orientation of the roof prism $\theta_{\text {Roof }}$ given by the keywords ESO.INS.DROTOFF $n$. The direction of North $\theta_{\text {North }}$ on the acquisition camera field is related to the position angle of the pair $\theta_{\mathrm{PA}}$, calculated from the offset keywords ESO.INS.SOBJ. $[\mathrm{X} \mid \mathrm{Y}]$, and to the roof angle $\theta_{\text {Roof }}$.

SC targets. The results of the fitting process is available in table OI_VIS_ACQ, columns FIELD_SC_[X|Y] and FIELD_FT_[X|Y], with associated errors FIELD_SC_[X|Y]ERR and FIELD_FT_[X|Y]ERR.

In true dual-field mode, and when the separation SOBJ. $[\mathrm{X} \mid \mathrm{Y}]$ is not zero, the plate scale of the acquisition camera is measured for each frame as the ratio between the separation and the distance between the two detected objects:

$$
\begin{equation*}
\text { FIELD_SCALE }=\frac{\| \text { SOBJ. }[\mathrm{X} \mid \mathrm{Y}] \|}{\| \text { FIELD_SC_[X } \mid \mathrm{Y}]- \text { FIELD_FT_[X } \mid \mathrm{Y}] \|}, \tag{8}
\end{equation*}
$$

and associated error FIELD_SCALEERR.
In addition, an error signal FIELD_FIBER_D $[\mathrm{X} \mid \mathrm{Y}]$ is generated between the detected SC/FT target relative positions and the $\mathrm{SC} / \mathrm{FT}$ fibre relative positions, taking into account any dithering offset SOBJ.OFF $[\mathrm{X} \mid \mathrm{Y}]$.

$$
\begin{align*}
\text { FIELD_D }[\mathrm{X} \mid \mathrm{Y}]= & (\text { FIELD_SC }[\mathrm{X} \mid \mathrm{Y}]-\text { FIELD_FT }[\mathrm{X} \mid \mathrm{Y}]) \\
& \quad+\text { SOBJ.OFF }[\mathrm{X} \mid \mathrm{Y}] / \text { FIELD_SCALE } \\
& -(\text { ACQ.FIBER.SC }[\mathrm{X} \mid \mathrm{Y}]-\text { ACQ.FIBER.FT }[\mathrm{X} \mid \mathrm{Y}]) \tag{85}
\end{align*}
$$

This quantity is later used to unwrap the telescope metrology diode signals.
Finally, a Strehl ratio is estimated from each frame and stored in the FIELD_STREHL column.

### 10.22 Processing of MET and FDDL

## From Volts to real time SC-FT phases

The signals of all diodes are analysed independently, without prior correction of the voltage, and converted into a real-time SC-FT phase for each diode. This real-time SC-FT phase is unwrapped and forced to match the

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OCS.MET reference. Both the unwrapping and the absolute reference are done with fringe-integer corrections only. These quantities are labeled OPD_TEL and OPD_FC in the OI_VIS_MET table.

## Averaging SC-FT phase inside SC DIT

The phase of a diode is averaged inside each SC DIT, as a scalar quantity (not phasor). This averaged signal is stored for each beam in OI_FLUX table and each base in OI_VIS table. These quantities are labeled OPD_MET_TEL and OPD_MET_FC.

## Average the FDDL inside SC DIT

The mean SC and FT FDDLs strain gauge voltage during each frame of the SC, and per beam, is stored in the OI_FLUX table. Columns are labelled SC_POS and FT_POS.

### 10.23 Applying dispersion correction to MET

## Correction of FFDL non linearity

The DISP_MODEL provides, for each beam $t$ :

- $\operatorname{linSC}_{t m}$ : the non-linearity coefficients of order $m$ of the SC FDDL.
- $\operatorname{linFT}_{t m}:$ the non-linearity coefficients of order $m$ of the FT FDDL.

SC_POS and FT_POS are first corrected from non-linearity of the strain gauge, and then averaged to get the mean position of the two fibers:

$$
\begin{equation*}
\left.\mathrm{FDDL}_{t f}=\frac{\sum_{m}\left(\operatorname{linSC}_{t m} \mathrm{SC}_{-} \mathrm{POS}_{t f}^{m}\right)+\sum_{m}(\operatorname{linFT}}{t m} \mathrm{FT}_{-} \mathrm{POS}_{t f}^{m}\right)(2 \tag{86}
\end{equation*}
$$

## Dispersion-included metrology signal

The DISP_MODEL allows to compute the mean refractive index of SC and FT FDDL at wavelength $l$ for each beam $t$, normalized to the one at the metrology wavelength (hereafter called nmean ${ }_{t l}$ ); and the differential refractive index between SC and FT FDDL wavelength $l$ for each beam $t$, normalized to the one at the metrology wavelength (hereafter called ndiff $t l$ ).

In practice, these two quantities are stored as a polynomial model versus wavenumber, centered in the middle of the K-band $\left(\lambda_{0}=2.2 \mu \mathrm{~m}\right)$ :

$$
\begin{equation*}
\operatorname{nmean}_{t l}=\sum_{m}\left(\operatorname{nmean}_{t m}\left(\frac{\lambda_{0}}{\lambda_{l}}-1\right)^{m}\right) \tag{87}
\end{equation*}
$$

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$$
\begin{equation*}
\operatorname{ndiff}_{t l}=\sum_{m}\left(\operatorname{ndiff}_{t m}\left(\frac{\lambda_{0}}{\lambda_{l}}-1\right)^{m}\right) \tag{88}
\end{equation*}
$$

where nmean $_{t m}$ and ndiff ${ }_{t m}$ are the polynomial coefficients of order $m$ of beam $t$, read from the DISP_MODEL.
From the dispersion and the metrology signal, we can compute the amount of delay introduced by the differential delay-line, for each spectral channel and each baseline. This quantity is called OPD_DISP ${ }_{b f l}$ :

$$
\begin{align*}
\mathrm{OPD}_{2} \mathrm{DISP}_{b f l}= & \operatorname{nmean}_{t_{1} l} \mathrm{OPD}_{1} \mathrm{MET}^{2} \mathrm{FC}_{t_{1} f}-\mathrm{nmean}_{t_{2} l} \mathrm{OPD} \mathrm{\_MET} \mathrm{\_FC}_{t_{2}} f+ \\
& \operatorname{ndiff}_{t_{1} l} \mathrm{FDDL}_{t_{1} f}-\operatorname{ndiff}_{t_{2} l} \mathrm{FDDL}_{t_{2} f} \tag{89}
\end{align*}
$$

## Dispersive group-delay and remaining phase

The signal OPD_DISP ${ }_{b f l}$ contains a fraction of group-delay coded as a spectral slope. This shall be properly taken into account when attempting to compute astrometric/absolutes phases out of the dataset.

Therefore the pipeline also provide an additional representation of the same quantity, but decomposed into the total group-delay in the middle of the K-band (GDELAY_DISP ${ }_{b f}$ in unit of distance, thus [m]), and the remaining phase (PHASE_DISP ${ }_{l b f}$, in [rad]).

The total group-delay introduced by FDDL in the middle of the band is:

$$
\begin{equation*}
\mathrm{GDELAY}_{-} \mathrm{DISP}_{b f}=\frac{\lambda_{l_{1}}^{-1} \mathrm{OPD}_{-} \mathrm{DISP}_{l_{1} b f}-\lambda_{2}^{-1} \mathrm{OPD}_{-} \mathrm{DISP}_{l_{2} b f}}{\lambda_{l_{1}}^{-1}-\lambda_{l_{2}}^{-1}} \tag{90}
\end{equation*}
$$

where $l_{1}$ and $l_{2}$ are two consecutive wavelength channel in the middle of the band. The remaining phase is:

$$
\begin{equation*}
\text { PHASE_DISP }_{l b f}=\arctan \left(\exp \left(\frac{2 i \pi}{\lambda_{f}}\left(\mathrm{OPD}_{-} \mathrm{DISP}_{l b f}-\text { GDELAY_DISP }_{b f}\right)\right)\right) \tag{91}
\end{equation*}
$$

The GDELAY_DISP ${ }_{b f}$ quantities are defined to within a constant: the so-called dispersed metrology zeros $\mathrm{Z}_{-} \mathrm{DISP}_{t}$ (one per beam). When combined with the group-delays from SC and FT, the GDELAY_DISP ${ }_{b f}$ can be used to construct a group-delay astrometry, e.g:

$$
\begin{align*}
\overrightarrow{B_{b_{i j}}} \cdot \vec{\delta}+\left(\mathrm{Z}_{-} \mathrm{DISP}_{i}-\mathrm{Z}_{-} \mathrm{DISP}_{j}\right)= & \text { GDELAY_DISP }_{b_{i j} f} \\
& -\left(\mathrm{GDELAY}_{-} \mathrm{SC}_{b_{i j} f}-\text { GDELAY_FT }_{b_{i j} f}\right) \tag{92}
\end{align*}
$$

In order to use the telescope metrologies, additional corrections need to be added to the astrometric equation above:

$$
\begin{align*}
\overrightarrow{B_{b_{i j}}} \cdot \vec{\delta}+\left(\mathrm{Z}_{-} \mathrm{DISP}_{i}-\mathrm{Z}_{-} \mathrm{DISP}_{j}\right)= & \text { GDELAY_DISP }_{b_{i j} f} \\
& +(\text { TELFC_MCORR }+ \text { FC_CORR }) \\
& -\left(\text { GDELAY_SC }_{b_{i j} f}-\text { GDELAY_FT }_{b_{i j} f}\right) \tag{93}
\end{align*}
$$

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### 10.24 Astrometric transformations and projected baseline

Due to its astrometric requirements, the pipeline uses the ERFA astrometric library (derived from SOFA) to transform coordinates between the Celestial and Observed reference frames. The SOFA documentation gives a good description of the transformations between the two reference frames; the present manual only describes its use.

For each observation, the mid-point $\left(\alpha_{c}, \delta_{c}\right)$ between the FT and SC targets in celestial (ICRS) is first converted into barycentric (BCRS) by applying space motion (proper motion, parallax, and radial velocity).

$$
\begin{equation*}
\left(\alpha_{c}, \delta_{c}\right) \Rightarrow\left(\alpha_{b}, \delta_{b}\right) \equiv \vec{e}_{W b} \tag{94}
\end{equation*}
$$

The equatorial directions $\left(\vec{e}_{U b}, \vec{e}_{V b}\right)$ are then computed from the pointing direction $\vec{e}_{W b}$ and the direction of the pole $\vec{e}_{Z b}$ as follows:

$$
\begin{gather*}
\vec{e}_{U b}=\frac{\vec{e}_{Z b} \times \vec{e}_{W b}}{\left\|\vec{e}_{Z b} \times \vec{e}_{W b}\right\|}  \tag{95}\\
\vec{e}_{V b}=\vec{e}_{W b} \times \vec{e}_{U b} \tag{96}
\end{gather*}
$$

The unit vectors $\vec{e}_{U b}$ and $\vec{e}_{V b}$ point in the direction of increasing right ascension and declination respectively.
Since ERFA is only capable of transforming coordinates, a set of four coordinates at a small $\epsilon= \pm 10 \mathrm{arcsec}$ angle in right ascension and declination is used instead: the cardinal asterism. They are created by rotating the pointing direction $\vec{e}_{W b}$ around the right ascension and declination directions ( $\vec{e}_{U b}, \vec{e}_{V b}$ ) by this small $\epsilon$ angle.

$$
\begin{align*}
& \left(\alpha_{b}+\epsilon, \delta_{b}\right) \equiv \vec{e}_{W+U b}=\mathcal{R}_{-\epsilon \vec{\epsilon}_{V b}}\left(\vec{e}_{W b}\right)  \tag{97}\\
& \left(\alpha_{b}-\epsilon, \delta_{b}\right) \equiv \vec{e}_{W-U b}=\mathcal{R}_{+\epsilon \vec{\epsilon}_{V b}}\left(\vec{e}_{W b}\right)  \tag{98}\\
& \left(\alpha_{b}, \delta_{b}+\epsilon\right) \equiv \vec{e}_{W+V b}=\mathcal{R}_{+\epsilon \vec{\epsilon}_{U b}}\left(\vec{e}_{W b}\right)  \tag{99}\\
& \left(\alpha_{b}, \delta_{b}-\epsilon\right) \equiv \vec{e}_{W-V b}=\mathcal{R}_{-\epsilon \vec{\epsilon}_{U b}}\left(\vec{e}_{W b}\right) \tag{100}
\end{align*}
$$

ERFA is then used to transform the pointing origin and cardinal asterism coordinates from barycentric to observed reference frame. This transformation uses the Earth Orientation Parameters (UT1-UTC and polar motion) published by the IERS.

$$
\begin{gather*}
\left(\alpha_{b}, \delta_{b}\right) \Rightarrow\left(\alpha_{o}, \delta_{o}\right) \equiv \vec{e}_{W o}  \tag{101}\\
\left(\alpha_{b}+\epsilon, \delta_{b}\right) \Rightarrow\left(\alpha_{o}+\epsilon, \delta_{o}\right) \equiv \vec{e}_{W+U o} \tag{102}
\end{gather*}
$$

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$$
\begin{align*}
& \left(\alpha_{b}-\epsilon, \delta_{b}\right) \Rightarrow\left(\alpha_{o}-\epsilon, \delta_{o}\right) \equiv \vec{e}_{W-U o}  \tag{103}\\
& \left(\alpha_{b}, \delta_{b}+\epsilon\right) \Rightarrow\left(\alpha_{o}, \delta_{o}+\epsilon\right) \equiv \vec{e}_{W+V o}  \tag{104}\\
& \left(\alpha_{b}, \delta_{b}-\epsilon\right) \Rightarrow\left(\alpha_{o}, \delta_{o}-\epsilon\right) \equiv \vec{e}_{W-V o} \tag{105}
\end{align*}
$$

Then the pointing directions to the cardinal asterism are combined to generate the equatorial directions ( $\vec{e}_{U o}, \vec{e}_{V o}$ ) in the observed reference frame.

$$
\begin{align*}
& \vec{e}_{U o}=\frac{1}{2 \epsilon} \vec{e}_{W o} \times\left(\vec{e}_{W+U o} \times \vec{e}_{W-U o}\right)  \tag{106}\\
& \vec{e}_{V o}=\frac{1}{2 \epsilon} \vec{e}_{W o} \times\left(\vec{e}_{W+V o} \times \vec{e}_{W-V o}\right) \tag{107}
\end{align*}
$$

Even though $\left(\vec{e}_{U b}, \vec{e}_{V b}, \vec{e}_{W b}\right)$ is an orthonormal basis in the barycentric reference frame, $\left(\vec{e}_{U o}, \vec{e}_{V o}, \vec{e}_{W o}\right)$ is not orthonormal in the observed reference frame. The pointing vector $\vec{e}_{W_{o}}$ is a unit vector, but the right ascension and declination vectors ( $\vec{e}_{V o}, \vec{e}_{W o}$ ) are not: they carry a scaling factor associated to the effect of astronomical aberration.

The azimuth and zenith distance directions $\left(\vec{e}_{A Z o}, \vec{e}_{Z D o}\right)$ are also calculated from the observed pointing direction $\vec{e}_{W o}$ and the zenith direction $\vec{e}_{Z o}$.

$$
\begin{gather*}
\vec{e}_{A Z o}=\frac{\vec{e}_{W o} \times \vec{e}_{Z o}}{\left\|\vec{e}_{W o} \times \vec{e}_{Z o}\right\|}  \tag{108}\\
\vec{e}_{Z D o}=\vec{e}_{W o} \times \vec{e}_{A z o} \tag{109}
\end{gather*}
$$

The vectors $\vec{e}_{U o}, \vec{e}_{V o}, \vec{e}_{W o}, \vec{e}_{A Z o}, \vec{e}_{Z D o}$ populate the columns $\mathbf{E} \_\mathbf{U}, \mathbf{E} \_\mathbf{V}, \mathbf{E} \_\mathbf{W}, \mathbf{E} \_\mathbf{A Z}, \mathbf{E} \_\mathbf{Z D}$ of the pipeline products.
Finally, the projected baseline is calculated as the scalar product between the physical baseline $\vec{B}_{o}$ in the observed reference frame and the equatorial directions $\left(\vec{e}_{U o}, \vec{e}_{V o}\right)$ also in the observed reference frame.

$$
\begin{align*}
& B_{U b}=\vec{B}_{o} \cdot \vec{e}_{U o}  \tag{110}\\
& B_{V b}=\vec{B}_{o} \cdot \vec{e}_{V o} \tag{111}
\end{align*}
$$

The projections $B_{U b}, B_{V b}$ populate the columns UCOORD, VCOORD of the pipeline products.
Last element of importance, the baseline vector $\vec{B}_{o}$ in the observed reference frame is supposed to be the physical or vacuum vector. However, the telescope positions reported in the fits headers correspond to OPD models that

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Figure 10.4: Geometry in the pupil, looking toward the target. It shows the azimuth and zenith distance directions $\left(\vec{e}_{A Z}, \vec{e}_{Z D}\right)$, the right ascension and declination directions $\left(\vec{e}_{U}, \vec{e}_{V}\right)$, and the parallactic angle $q$.
are scaled by the refractive index of air $(n=1.0002028)$ at the atmospheric pressure of Paranal and at the wavelength of the Helium Neon laser of the VLTI delay lines. The pipeline takes care of compensating this refractive index scaling when computing the observed baseline from the headers.

$$
\begin{equation*}
\vec{B}_{o}=1 / n \vec{B}_{\text {header }} \tag{112}
\end{equation*}
$$

### 10.25 The metrology data flow for phase astrometry

The metrology computations starts with the Volts values in the raw fits files. They are used to compute at 2 kHz the PHASE_FC (1 value per telescope) and PHASE_TEL (4 values per telescope). To convert voltages to phases, two algorithms are implemented in the pipeline: the one from the RTC (which only look at the past), and the new algorithm from the DRS (which is doing zero lag temporal smoothing). The default algorithm is the one from the DRS, but that can be changed by the gravity_vis parameter "-use-met-rtc" (default = false).

These phases are converted into OPD using the mean wavelength from the METROLOGY table (the value is stored in the QC "MET LAMBDA MEAN" inside the header). They are used to produced 2 quantities, which are necessary to calculate the astrometry: OPD_DISP and PHASE_MET_TELFC.

The first quantity is OPD_DISP. This quantity is obtained from PHASE_FC, which is converted to OPD_FC in the OI_MET table. OPD_FC us then averaged to the SC DIT frequency and stored into the OI_FLUX table under the name OPD_MET_FC. Last, it is combined with the position of the FDDL sensor gauge, and using a model of the fiber dispersion, it is converted into a wavelength dependent OPD_DISP (in meters). To be noted, it is possible to add a constant value to this OPD_DISP calculation thanks to the -use-met-zero parameter. It is recommanded not to use this parameter because the keyword values in the files header are not always consistent between exposures.

The PHASE_MET_TELFC actually corresponds to the difference between the phase at the telescope center and the phase measured on the fiber coupler (OPD_FC). The issue at stake is to account from the fact that the metrology at the telescope level is not properly unwrapped, and $2 \pi$ offsets can exist. To do so, several intermediary product are computed:

- OPD_FC_CORR, to project the diode at the fiber coupler to the center of the telescope

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Figure 10.5: The data flow of the metrology, starting from the phase extracted from the metrology voltage, to the final products OPD_DISP and PHAS_MET_TEFC

- OPD_TEL_CORR, to project the phase at the center of the telescope to the position of the diode sensors. This calculation includes a model of astigmatism, and an approximation of the separation of the FC/SC fibers.
- OPD_TEFC_CORR_XY, to account for residual astigmatism and the tip-tilt between the two fibers.
- OPD_TEFC_CORR, are the phase residuals, which will have to be included in the astrometry (hopefully, they are smaller than $2 \pi$ to be properly averaged.

The last part is to use the OPD_FC_CORR and OPD_TEFC_CORR value and add them together. The sum is then averaged as a wavelength dependant phasor over an SC DIT. The phase of the phasor is therefore of length Nwave (233 in MED resolution, as shown in Fig. 10.5). It is stored in the OI_VIS table.

The OPD_DISP and PHASE_MET_TELFC values, both stored in the astrored files, can then be used to perform astrometry as described in section 10.26.

### 10.26 Phase referencing the science visibilities for astrometry

### 10.26.1 Phasing the VISDATA

Astrometry is typically done with the *_ASTROREDUCED products. These products are intermediary fits that can be obtained using the "-astro-file=TRUE" option with esorex gravity_vis recipe (they are not produced by

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default). The advantage of this data product is that the Science DITs are not co-added. This is how astronomers have all latitude to co-add the complex visibilities coherently at any position in space. Alternatively, astronomers can use directly VISPHI in the dualvis files, but the coadding will be done for the X and Y positions which are in the header.

Of importance is the OI_VIS table in the *_ASTROREDUCED data product. Inside are stored the complex coherent amplitude (VISDATA), the differential fibered delay lines optical delay (OPD_DIS), the differential phase between Fiber Coupler and telescope diodes (PHASE_MET_TELFC), and the phase of the fringe tracker (PHASE_REF). All theses values, in this table, are sampled at the frequency rate of the SC detector. They are also re-sampled to the spectral resolution of the science detector. It is by adding all these variable that one can phase the science VISDATA, and perform astrometry.

To be more explicit, the goal, to be able to do astrometry, is to reference the phase of the science complex visibility with respect to the phase of the object observed on the fringe tracker. This is done as follows:

$$
\begin{equation*}
V I S D A T A_{\mathrm{phasedFT}}=V I S D A T A \times \exp \left(i\left[P H A S E \_R E F-P H A S E \_M E T_{-} T E L F C-\frac{2 \pi}{\lambda} O P D \_D I S P\right]\right) \tag{113}
\end{equation*}
$$

It is important to realise at this point that $V I S D A T A_{\text {phasedFT }}$ is a highly wrapped quantity. It does not convey the notion of interferometric field. It is therefore often useful to reference the VISDATA to an arbitrary position in the field of the interferometer. To do so, one can add a specific phase offset, as follows:

$$
\begin{equation*}
V I S D A T A_{\mathrm{phasedXY}}=V I S D A T A_{\mathrm{phasedFT}} \times \exp \left(i \frac{2 \pi}{\lambda}(U C O O R D \times X+V C O O R D \times Y)\right) \tag{114}
\end{equation*}
$$

using the UCOORD and VCOORD columns in the OI_VIS table. These values are the projected baseline coordinates, also described in the previous section by Eqs. (110) and (111). X and Y are the position coordinates, in radians, from the position of the fringe tracker star.

Because a few lines of python code are worth a thousands words, here is the code to reference the VISDATA to the fringe tracker object position.

```
extension = 10 # for COMBINED observations
wave=fits.getdata(f,'OI_WAVELENGTH', extension).field('EFF_WAVE')
opdDisp = fits.getdata(f,'OI_VIS',extension).field('OPD_DISP')
phaseTelFc = fits.getdata(f,'OI_VIS',extension).field('PHASE_MET_TELFC')
phaseRef = fits.getdata(f,'OI_VIS',extension).field('PHASE_REF')
phaseFt = phaseRef - 2*pi/wave*opdDisp - phaseTelFc
visData = fits.getdata(f,'OI_VIS',extension).field('VISDATA')
visData_phasedFT = visData * exp(1j*phaseFt)
```

with " $f$ " the astroreduced file. If the user wants to reference the phase to the GRAVITY pointing position (value in the header), it can be done as follows:

```
X=fits.getheader(f)["HIERARCH ESO INS SOBJ X"]
Y=fits.getheader(f)["HIERARCH ESO INS SOBJ Y"]
X/=1000/(180/pi*3600)
Y/=1000/(180/pi*3600)
```

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```
ucoord=fits.getdata(f,'OI_VIS',extension).field('UCOORD')
vcoord=fits.getdata(f,'OI_VIS',extension).field('VCOORD')
phaseXY=2*pi*( ucoord*X + vcoord*Y)[:,None]/wave
visData_phasedXY = visData_phasedFT * exp(1j*phaseXY)
```

$V I S D A T A_{\text {phasedXY }}$ is now phased with respect to an arbitrary position: XY. To do astrometry between

### 10.26.2 "Zeroing" the phase constant from the metrology

We now have two quantities, VISDAT $A_{\text {phasedFT }}$ and $V I S D A T A_{\text {phasedXY. }}$. To perform the final astrometry, it is now important to "zero" the astrometry. To "zero" the astrometry, we need 2 distinct observations. To start with a general case, we can assume that we have 2 distinct observations, of 2 different binary systems. The physical separation between the 2 objects are respectively ( $X_{1}, Y_{1}$ ) and ( $X_{2}, Y_{2}$ ). The 2 arguments of the VISDATA are therefore:

$$
\begin{align*}
& \arg \left(V I S D A T A_{\text {phasedFT1 }}\right)=\frac{2 \pi}{\lambda}\left(U C O O R D_{1} \times X_{1}+V C O O R D_{1} \times Y_{1}\right)+\phi_{\lambda}  \tag{115}\\
& \arg \left(V I S D A T A_{\text {phasedFT2 }}\right)=\frac{2 \pi}{\lambda}\left(U C O O R D_{2} \times X_{2}+V C O O R D_{2} \times Y_{2}\right)+\phi_{\lambda} \tag{116}
\end{align*}
$$

where $\phi_{\lambda}$ is the constant, internal, phase offset. The key, to do phase astrometry, is to determine this offset (we call that "zeroing" the metrology).

To do so, there are 2 options, depending if the observations are done on-axis or off-axis:

1. On-axis mode: the second observation is obtained on the FT target. In that case, $X_{2}=0$ and $Y_{2}=0$. If we have the possibility to get such an observation (it requires using the $50 / 50$ beam splitter), the metrology phase offset can be obtained directly from the on-star observation:

$$
\begin{equation*}
\phi_{\lambda}=\arg \left(V I S D A T A_{\text {phasedFT2 } 2}\right) \tag{117}
\end{equation*}
$$

2. Swap in off-axis mode: in this mode, we rotate the K-mirror to swap the fringe tracker source with the science combiner source: $X_{2}=-X_{1}$ and $Y_{2}=-Y_{1}$. In that situation:

$$
\begin{align*}
\phi_{\lambda} & =\arg \left(V I S D A T A_{\mathrm{phasedFT} 1} V I S D A T A_{\mathrm{phasedFT} 2}^{*}\right) / 2 \\
& -\frac{2 \pi}{\lambda}\left[\frac{U C O O R D_{1}-U C O O R D_{2}}{2} \times X_{1}+\frac{V C O O R D_{1}-U C O O R D_{2}}{2} \times Y_{1}\right] . \tag{118}
\end{align*}
$$

If the swap is done fast enough, $U C O O R D_{1} \approx U C O O R D_{2}$ and $V C O O R D_{1} \approx V C O O R D_{2}$, and to first order, the values of $X_{1}$ and $Y_{1}$ do not matter. For serious astrometry, astronomers should fit simultaneously $\phi_{\lambda}, X_{1}$ and $Y_{1}$.

Once $\phi_{\lambda}$ is known, $X_{1}$ and $Y_{2}$ (or $X_{2}$ and $Y_{2}$ ) values can be obtained by fitting the Eq. (115) or (116) to the $\operatorname{VISDAT} A_{\text {phasedFT }}$ measurement. The only remaining difficulty is that the fit is not convex because of the $2 \pi$ wrapping. So it is important to start with a good initialisation of the $X_{1}$ and $Y_{2}$ values to avoid falling into a local minimums.

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## A Installation

One is advised to read the installation instructions delivered with the GRAVITY pipeline distribution kit. These release-specific instructions can be found in the file README located in the top-level directory of the unpacked GRAVITY pipeline source tree. The supported platforms are listed in Section A.1. It is recommended reading through Section A. 2.2 before starting the installation.

A bundled version of the GRAVITY pipeline with all the required tools and an installer script is available from http://www.eso.org/pipelines/, for users who are not familiar with the installation of software packages.

## A. 1 Supported platforms

The utilisation of the GNU build tools should allow to build and install the GRAVITY pipeline on a variety of UNIX platforms, but it has only been verified on the VLT target platforms:

- Linux (glibc 2.1 or later),
- Sun Solaris 2.8 or later,
using the GNU C compiler (version 3.2 or newer).


## A. 2 Building the GRAVITY pipeline

This section shows how to obtain, build and install the GRAVITY pipeline from the official source distribution.

## A.2.1 Requirements

To compile and install the GRAVITY pipeline one needs:

- the GNU C compiler (version 3.2 or later),
- the GNU gzip data compression program,
- a version of the tar file-archiving program, and,
- the GNU make utility.

An installation of the Common Pipeline library (CPL) must also be available on the system. Currently the CPL version 2.1.1 or newer is required. The CPL distribution can be obtained from [3].

Please note that CPL itself depends on an existing qfits installation. The qfits sources are available from the CPL download page or directly from the qfits homepage at http://www.eso.org/projects/aot/qfits. In conjunction with CPL 2.1.1 qfits 5.3.1 must be used.

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In order to run the GRAVITY pipeline recipes a front-end application is also required. Currently there are two such applications available, a command-line tool called EsoRex and the Java based data file organizer, Gasgano, which provides an intuitive graphical user interface (see Section 5.2, page 17). At least one of them must be installed. The EsoRex and Gasgano packages are available at http://www.eso.org/cpl/esorex.html and http://www.eso.org/gasgano respectively.

For installation instructions of any of the additional packages mentioned before please refer to the documentation of these packages.

## A.2.2 Compiling and installing the GRAVITY pipeline

The GRAVITY pipeline distribution kit 1.0 contains:
gravity-manual-1.0.pdf
install_pipeline
cpl-7.2.2.tar.gz
esorex-3.13.3.tar.gz
gasgano-2.4.8.tar.gz
gravity-1.6.6.tar.gz
gravity-calib-1.6.6.tar.gz

The GRAVITY pipeline manual
Install script
CPL 7.2.2
esorex 3.13.3
GASGANO 2.4.8for Linux
GRAVITY 1.6.6
GRAVITY calibration files 1.6.6

Here is a description of the installation procedure:

1. Change directory to where you want to retrieve the GRAVITY pipeline recipes 1.6 .6 package. It can be any directory of your choice but not:
```
$HOME/gasgano
$HOME/.esorex
```

2. Download from the ESO ftp server, http://www.eso.org/pipelines/, the latest release of the GRAVITY pipeline distribution.
3. Verify the checksum value of the tar file with the cksum command.
4. Unpack using the following command:
```
tar -xvf \pipename-kit-\pipelinevers.tar
```

Note that the size of the installed software (including Gasgano) together with the static calibration data is about 1.3 Gb , mainly du to the test data.
5. Install: after moving to the top installation directory,

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it is possible to perform a simple installation using the available installer script (recommended):
./install_pipeline
(beware: the execution may take a few minutes on Linux and several minutes on SunOS).
Note that this release still needs to link to the eclipse library. At the end of the installation the user in addition to follow what reported by the installation script, needs to source an file (\$HOME/..eclipse_bash.rc or \$HOME/..eclipse_bash.rc, depending from the user shell) to set a few environment variables used by a few low level eclipse library based modules.

By default the script will install the GRAVITY recipes, Gasgano, EsoRex, all the necessary libraries, and the static calibration tables, into a directory tree rooted at $\$$ HOME. A different path may be specified as soon as the script is run.

The only exception to all this is the Gasgano tool, that will always be installed under the directory \$HOME/gasgano. Note that the installer will move an existing \$HOME/gasgano directory to \$HOME/gasgano.old before the new Gasgano version is installed.

Important: the installation script would ensure that any existing Gasgano and EsoRex setup would be inherited into the newly installed configuration files (avoiding in this way any conflict with other installed instrument pipelines).

Alternatively, it is possible to perform a manual installation (experienced users only): the README file located in the top installation directory contains more detailed information about a step-by-step installation.

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## B Abbreviations and acronyms

| ANSI | American National Standards Institute |
| :--- | :--- |
| ASCII | American Standard Code for Information Interchange |
| CalibDB | Calibration Database |
| CPL | Common Pipeline Library |
| DFO | Data Flow Operations department |
| DFS | Data Flow System department |
| DHS | Data Handling Server |
| DO | Data Organizer |
| DMD | Data Management and Operations Division |
| DRS | Data Reduction System |
| ESO | European Southern Observatory |
| ESOREX | ESO-Recipe Execution tool |
| FDDL | Fibered Differential Delay Lines |
| FITS | Flexible Image Transport System |
| FOV | Field Of View |
| FT | Fringe-Tracker |
| SC | Science-Combiner |
| GUI | Graphical User Interface |
| OB | Observation Block |
| OIFITS | OIFITS format, see [4] |
| PSO | Paranal Science Operations |
| QC | Quality Control |
| RON | Read Out Noise |
| SOF | Set Of Frames |
| UT | Unit Telescope |
| AT | Auxiliary Telescope |
| VLTI | Very Large Telescope Interferometer |

