ESO Phase3 Data Release Description

Data Collection	GRAVITY
Data Provider	ESO, Science Data Quality Group
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Abstract

This is the release of calibrated dispersed visibilities (SCIENCE targets) and uncalibrated dispersed visibilities (SCIENCE and CALIBRATORS targets) for the GRAVITY instrument.
GRAVITY is part of the second generation VLTI instruments. It operates with 4 telescopes. More on the GRAVITY instrument can be found in the ESO instrument pages (https://www.eso.org/sci/facilities/paranal/instruments/gravity.html)
The instrument modes covered by this release include the GRAVITY modes offered at the beginning of the operations, these are listed in Table 1.
This release is an open stream. It contains data from start of operations in October 2016 and will grow regularly to include the more recent data.
In the first phase only uncalibrated visibilities (CALIBRATOR and SCIENCE targets) will be available. In the second phase, we will also release the science calibrated visibilities. After these 2 phases have been completed (which is expected to take a few months from the start of the release), the aim is to update the stream regularly with the newly acquired data.
Data from this release is processed with pipeline version 1.9 or higher. For the uncalibrated visibilities, detector and instrumental effects have been removed, while for the science calibrated visibilities, additional instrumental and atmospheric effects will also be removed using carefully chosen calibrator objects.
The products (including the uncalibrated visibilities) are OIFITS2 and ESO phase 3 compliant. The OIFITS2 format has been published: https://www.aanda.org/articles/aa/pdf/2017/01/aa26405-15.pdf.
The quality of the data (which will be described in the section "Data Quality") has been carefully studied with the help of the VLTI expertise centres (under OPTICON-RadioNet-Pilot, EC Contract 101004719).

Overview of Observations

The observations covered by this release have been taken with the GRAVITY modes available for the community at the start of operations (Table 1).
We do not consider for this release observations made using GRAVITY-WIDE (separation of the Fringe tracking and science targets from 2" up to 30") or GRAVITY+ which is the upgrade of the GRAVITY instrument and allows increased sensitivity, larger sky coverage and is more focused on scientific science goals.
Data processed for high precision astrometric observations are also included if taken in the modes described in Table 1, but the special analysis to recover the complete astrometry information is not included.
We do not make any difference for data taken with the 8.2m Unit Telescopes (UT), or with the 1.8-m Auxiliary Telescopes (ATs). The only requirement is that the observation is performed with 4 telescopes.

Field & Axis	Polarisation	Spectral Resolution
Single-field on-axis	Combine, split	Low ~22, Medium ~500, High ~4000
Dual-field on-axis	Combine, split	Low ~22, Medium ~500, High ~4000
Dual-field off-axis	Combine, split	Low ~22, Medium ~500, High ~4000

Table 1: GRAVITY modes included in this release.

Release Content

GRAVITY is a stream release providing the archive user with uncalibrated visibilities (SCIENCE and CALIBRATOR objects) as well as calibrated SCIENCE visibilities for the GRAVITY modes described in Table 1. The data stream starts with data taken from the start of operations (October 2016) and is growing regularly.
All the phase3 products are processed using calibrations reduced with the pipeline version 1.7 or higher.
The following files are available:

- OIFITS2 and Phase3 compliant uncalibrated visibilities for both nighttime calibrators and science data. The FITS files include the data for the Fringe Tracker (FT), the science detector (SC) and the acquisition camera (ACQ).
- OIFITS2 and phase3 compliant calibrated science data.
- Display plots to assess the quality of the data.

The data reduction has been done at the Observing Block (OB) level. For the uncalibrated visibilities (SCIENCE and CALIBRATOR targets), all the input files belonging to the same template result in one unique product. For the calibrated visibilities, the calibrator products (one or several) used belong to the same set-up or same observing run (OBS.PROG.ID). These calibrators are carefully assessed to check if they can be used to calibrate the science data.
For the uncalibrated visibilities on calibrator objects all available data have been processed, including data taken on the observatory dedicated calibrators. For the calibrated visibilities, science data belonging to observing programs 60.A* or 060.A* (header keyword OBS.PROG.ID) have been omitted as they are mostly observed for technical purposes.

Release Notes

Pipeline Description

A detailed description of the GRAVITY pipeline can be found in the pipeline user manual which is available on the ESO pipeline webpages (https://www.eso.org/sci/software/pipe_aem_main.html).
The pipeline version can be found in the products in the keyword "PROCSOFT".

Data Reduction and Calibration

The calibration cascade to obtain the two different types of phase3 products is shown in Fig1.

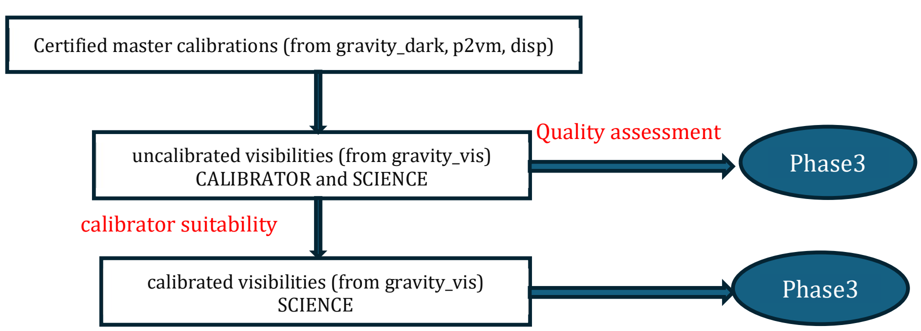


Fig. 1: Calibration cascade

Uncalibrated visibilities:

- The raw data is corrected to remove the detector features and the instrumental effects. A summary of the different calibration steps is given in Table 2.

HIERARCH ESO PRO CATG	recipe	Measurement
DARK	gravity_dark	Dark for the 3 detectors
BAD	gravity_p2vm	Bad pixel map for the 3 detectors
FLAT	gravity_p2vm	Flat for the 3 detectors
WAVE	gravity_p2vm	Spectral dispersion of the beam combiner
P2VM	gravity_p2vm	Instrumental Transmission, coherence and phase

Table 2: Calibrations used to obtain uncalibrated visibilities

Calibrated visibilities:

- The uncalibrated visibilities from science data are associated with suitable uncalibrated visibilities of one or several calibrators with a known diameter to provide the calibrated science visibilities.
- The assessment of the suitability of a calibrator is done using a set of QC parameters calculated by the pipeline based on the closure phases and their associated errors.
- The Transfer function to be applied to the science data is calculated using the diameter and the associated error provided by the JSDC catalog (https://www.jmmc.fr/english/tools/data-bases/jsdc-72/). We do not use any calibrator which does not have any entry in the JSDC catalog.

Data products format

Both uncalibrated and calibrated visibilities products are FITS files and follow the FITS standard for Optical Interferometry (OIFITS2[1]) and the ESO science data product standard.
The instrument setup is coded in the keywords HIERARCH ESO PRO CATG and INSMODE (see Table 3)
The value of the keyword INSMODE is a combination of

- the field: SINGLE or DUAL
- the spectral dispersion: LOW, MEDIUM or HIGH
- the polarisation: SPLIT or COMBINED

The value of the keyword PRO.CATG is a combination of

- the field: SINGLE or DUAL
- the category of the observation: CAL (calibrator object) or SCI (science target)
- the level of calibration: VIS (uncalibrated visibility) or VIS_CALIBRATED (calibrated visibility)

	PRO.CATG	INSMODE	observation
Uncalibrated	SINGLE_CAL_VIS	SINGLE,LOW/MEDIUM/HIGH,SPLIT/COMBINED	Calibrator in single field mode
Uncalibrated	SINGLE_SCI_VIS	SINGLE,LOW/MEDIUM/HIGH,SPLIT/COMBINED	Science target in single field mode
Uncalibrated	DUAL_CAL_VIS	DUAL,LOW/MEDIUM/HIGH,SPLIT/COMBINED	Calibrator in dual field mode

[1] OIFITS2 standard: https://www.aanda.org/articles/aa/pdf/2017/01/aa26405-15.pdf

Uncalibrated	DUAL_SCI_VIS	DUAL,LOW/MEDIUM/HIGH,SPLIT/COMBINED	Science target in dual field mode
Calibrated	SINGLE_SCI_VIS_CALIBRATED	SINGLE,LOW/MEDIUM/HIGH,SPLIT/COMBINED	Science target in single field mode
Calibrated	DUAL_SCI_VIS_CALIBRATED	DUAL,LOW/MEDIUM/HIGH,SPLIT/COMBINED	Science target in dual field mode

Table 3: PRO.CATG for the uncalibrated and calibrated visibilities for the different modes.

For each mode, the product is OIFITS2 compliant and contains the mandatory extensions as well as an additional one: OI_FLUX.
The extensions OI_VIS, OI_VIS2, OI_T3, OI_FLUX are given both for the fringe tracker and the science detector. To differentiate these, the user needs to check the header of the extension and identify the INSNAME which could be GRAVITY_FT (fringe tracker) or GRAVITY _SC (science detector) for a COMBINED observation (Fig. 2).

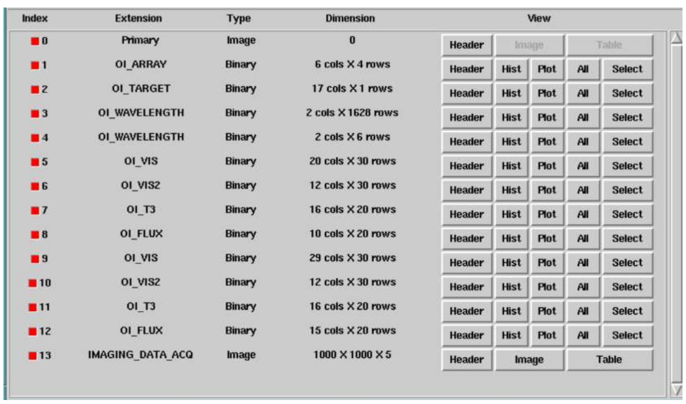


Fig. 2: Different extensions in the product, this is an example of a COMBINED observation.

In the case of SPLIT (so 2 polarisations), there will be 4 tables with each name (OI_VIS, OI_VIS2, OI_T3 and OI_FLUX). Like for the COMBINED mode, the extensions are differentiated with the INSNAME keyword: GRAVITY_SC_P1 and GRAVITY_SC_P2 for the 2 polarisations of the science detector and GRAVITY_FT_P1 and GRAVITY_FT_P2 for the 2 polarisations of the FT (Fig. 3).

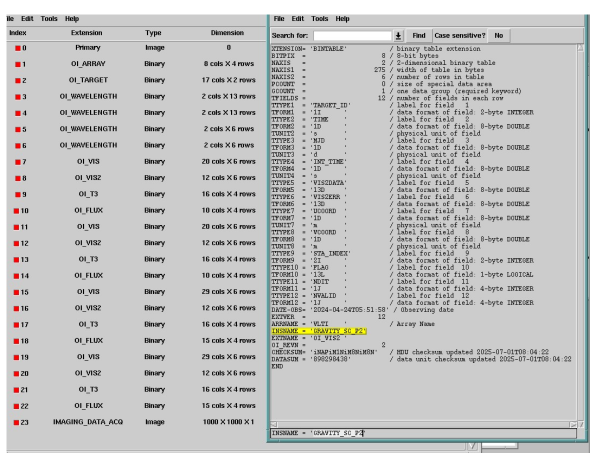


Fig. 3: Different extensions in the product, this is an example of a SPLIT observation.

Data Quality

Master Calibrations:

The master calibrations since start of operations have been processed (or reprocessed if needed) with a pipeline version 1.7 or higher. They have been quality-reviewed and certified and are available in the ESO archive when requesting science data.

Quality assessment of the uncalibrated visibilities:

The GRAVITY pipeline produces for each product a large number of quality control parameters which record the state of the system, the atmospheric condition and the quality of the data.
To be able to assess in a semi-automatic way the quality of the data, we needed to identify a small set of quality control parameters.
An extended study of a large number of products in the different modes has been conducted between ESO and the VLTI expertise centre community[2] (led by the Portuguese VLTI expertise centre). For the different instrument modes, a thorough analysis of all the control parameters and the different correlations between them have been performed mostly by the expertise centers. From this analysis, it was found e.g. that no clear correlation was seen between the ambient conditions and the image quality of the acquisition camera. When a correlation existed, we carefully looked at a large number of files to further select a reasonable number of quality parameters to assess the data quality.
The further complication was to make sure that the defined quality parameters were valid for all the instrument modes.
After identifying the set of quality control parameters to look at, we needed to define ranges. We decided to implement 3 different thresholds for bad quality, warning and good quality (Table 4). The number of "bad" and "warning" flags is given in the product header as "HIERARCH ESO QC NFLAG BAD" and "HIERARCH ESO QC NFLAG WARN".

Each of the following keywords is given for each of the 6 baselines, which gives at the end a total of 36 values to assess the quality. If a QC parameter (except sc.snrb.avg) has the 6 values in the "bad" category, the product is considered as of inadequate quality. If a user is looking for very high quality or accuracy data, the QC.NFLAG.WARN value should be taken into account for further analysis.

Header keyword starts with HIERARCH ESO QC	Description	Bad quality	Warning flag	Good quality
FT TRACKING RATIO (in %)	Fringe tracker tracking ratio	< 80	[80,90]	>90
FT PHASE RMS	Fringe tracker root mean square of the phase	>0.6	[0.5,0.6]	<0.5
VFACTOR	Ratio of frames non affected from the visibility loss due to flux flickering	<0.45 and >1.1	[0.45,0.8]	>0.8
PFACTOR	Ratio of frames not affected by the visibility loss due to phase jittering	<0.6 and >1.1	[0.6,0.85]	>0.85
FT SNRB AVG	SNR for the fringe tracker channel	<10	[10,30]	>30
SC SNRB AVG	SNR for the science channel	<50	[50,150]	>150

Table 4: QC parameters to assess the quality of the data

[2] https://european-interferometry.eu/vlti-expertise-centers/

Preview image and plots:

The preview image (Fig. 4) is a representation of the raw input files.

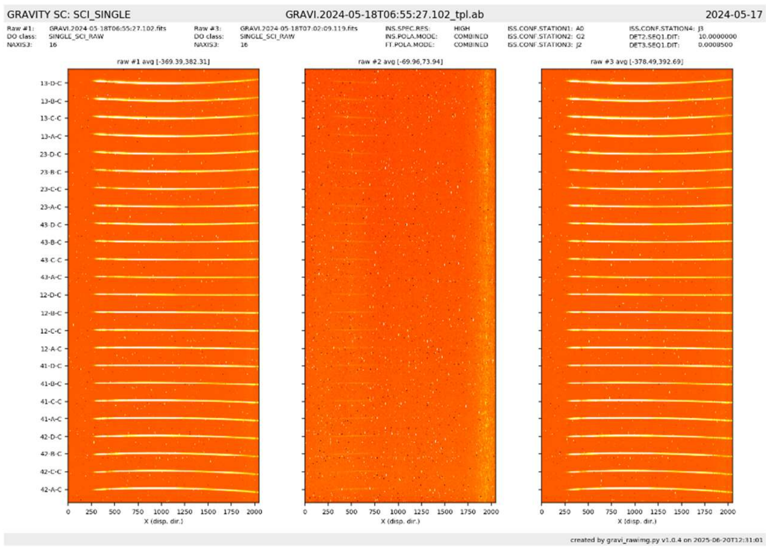


Fig. 4: Preview image of the input raw data. In this example the raw files #1 (left) and #3 (right) are on the object, #2 (middle) is a sky frame.

Preview plots for quality checks:

The quick look plots show mostly the same information for both uncalibrated (Fig. 5 and 6) and calibrated visibilities (Fig. 7).

The different sections of the preview plots are described below (see colored boxes and tags on Fig. 5):

1 (blue) The information on the top shows the value of some of the header keywords such as category of the product, how many files were used as input, pipeline version as well as the characteristics of the Fringe tracking and science target, the instrument setup and the atmospheric conditions. It also resumes the number of QC parameters which have been rejected (HIERARCH ESO QC TOT NFLAG BAD).

2 (red) The table shows the different QC parameters that have been defined to assess the quality of the data. The cell is colored in bright red if the value is considered as bad, and in light red if the value is a warning. In the example shown in Fig. 5, the data set shows only 2 warning flags (light red) and passed the data quality, while for Fig. 6, the data did not pass the quality assessment.

3 (green) The four images (4 telescopes) show part of the acquisition camera where the science target and the fringe tracker object are located. This position is sometimes wrongly calculated by the pipeline (see known issues). In this case the object will be outside the circle.

4 (purple) The plots show:

4a. VIS2DATA: the squared visibilities for the 6 baselines, both for the fringe tracker and the science target. The visibilities are expected to be between 0 and 1.

4b. VISPHI The phases for the 6 baselines (in deg).

For these 2 plots, the Fringe tracking data measurements are represented as squares

4c left FT FLUXDATA: the fringe tracker flux for the 4 telescopes,

4c right SC FLUXDATA: the object flux for the 4 telescopes

The fluxes on the 4 telescopes are expected to be within the same range.

4d. T3PHI: the closure phases for the baseline triangle (deg). As above, the Fringe Tracking points are shown as squares

4e. The (u,v) coverage which shows the position of the telescopes at the time of the observation.

The Fringe tracker (FT) data are shown as squares, while the observed object is shown as a continuous line.
When the observation is performed in SPLIT mode, the blue represents the polarisation 1, the red the pol 2 (Fig. 5).

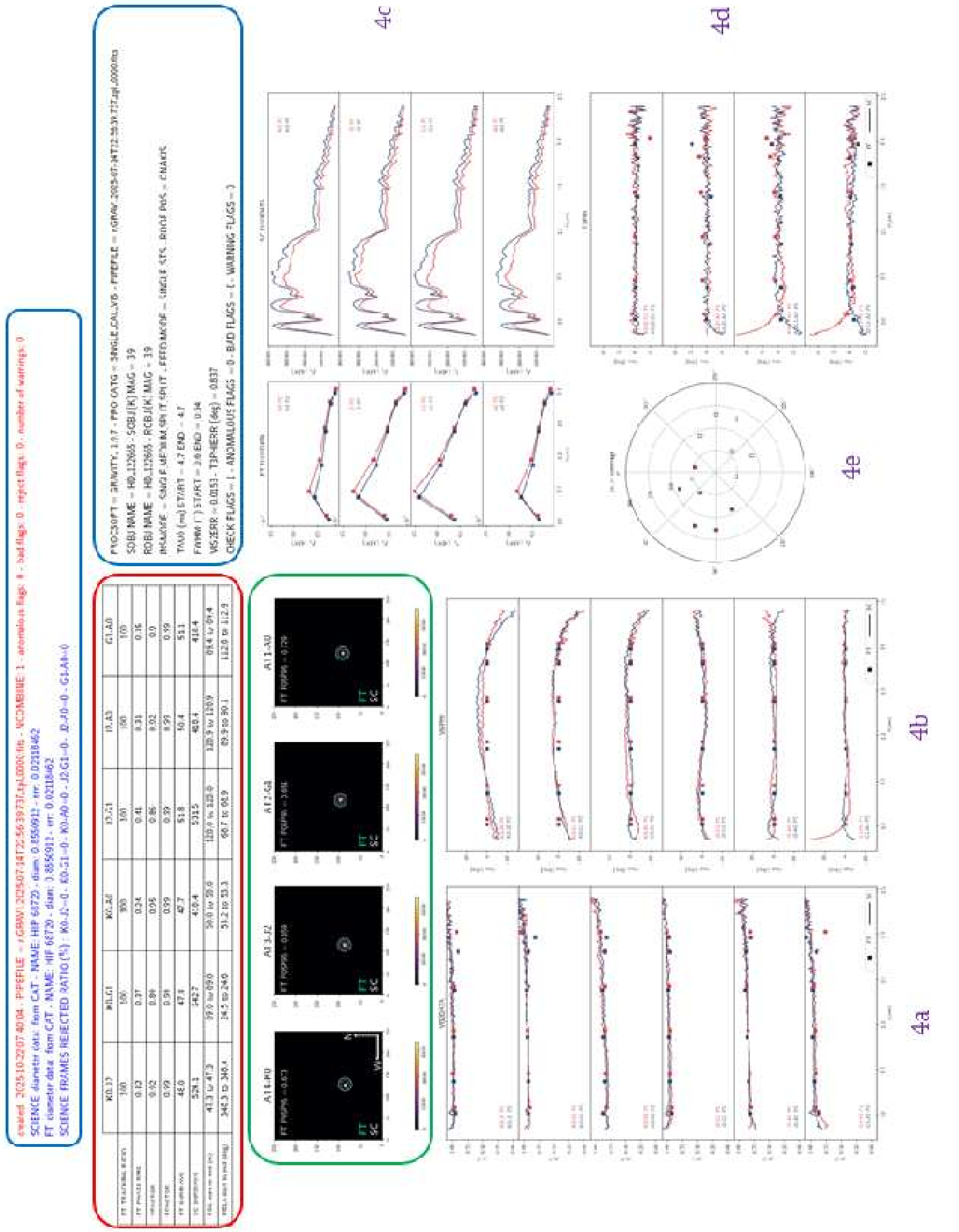


Fig. 5: Preview plot for a data set which passed the quality control. The description of the different plots can be found above. As explained in Table 4, the assessment is done on a set of QC parameters calculated by the pipeline. These parameters are scored. In this ex. none of the parameters have been flagged. This data set is considered good quality. The colors red and blue represent both polarisations.

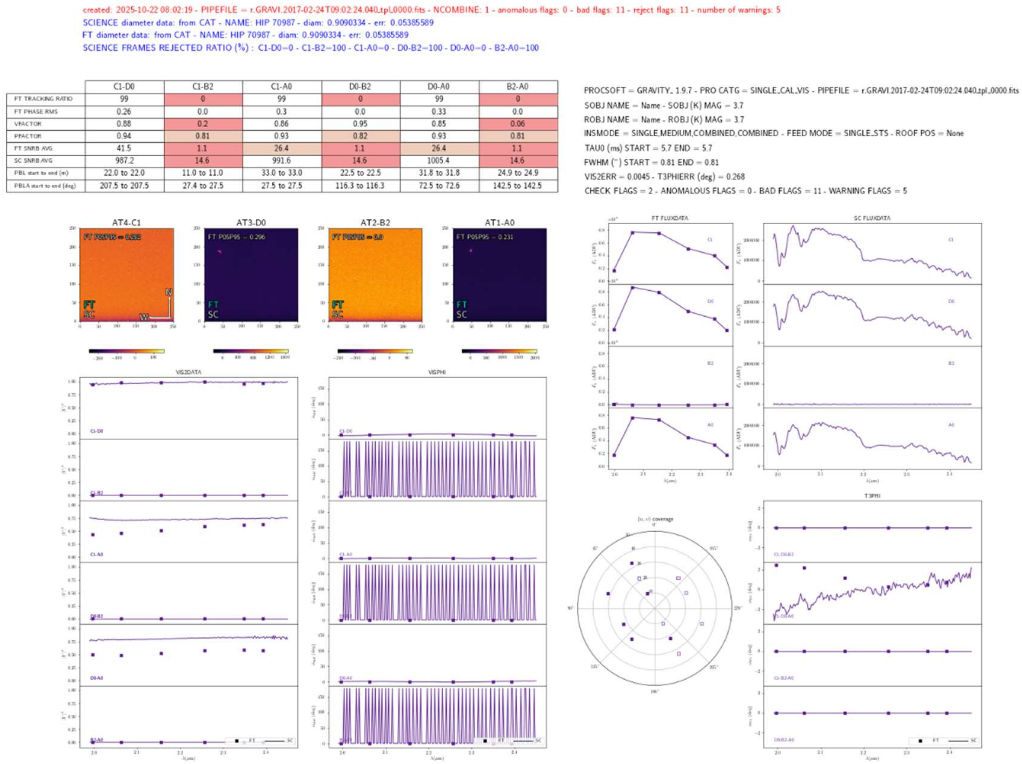


Fig. 6: Preview plot for a data set with 11 "bad" flags. The bright red cells in the table identify the non-optimal "bad" parameters. The lighter pink cells identify the parameters which fall in the "warning" category. In this example, there are many red flags but none of the QC parameters accumulate 6 red flags. A visual inspection of the plots shows that one telescope was not tracking. These data are not rejected; they still could be useful on the remaining 3 baselines.

Review of the suitability of the calibrator uncalibrated visibility to calibrate the science data.

To be able to calibrate the science data and obtain the science calibrated visibility, suitable calibrators must be used.
A calibrator data set is defined by the value of the PRO.CATG of the product, it contains "CAL" as opposite to SCI for the science data. We calibrate the science data only with calibrators which are of good quality and have a diameter listed in the JSDC catalogue (https://apps.jmmc.fr/~sclcat/JSDC/) . The matching is performed using the RA and DEC coordinates.
In some cases, an observer will choose a calibrator which is not present in the JSDC catalogue. These calibrators are considered as "non suitable" to further calibrate.
In some instances, we found that the data set, even flagged as calibrator by the observer could not be used to further calibrate the science. We used the version 2025-05-25 of the JSDC catalogue (https://apps.jmmc.fr/~sclcat/JSDC/) and the columns CalFlag and BADCAL (see [3]) to identify "non suitable" calibrators. The most common "non-suitable" calibrator observed is a multiple object.

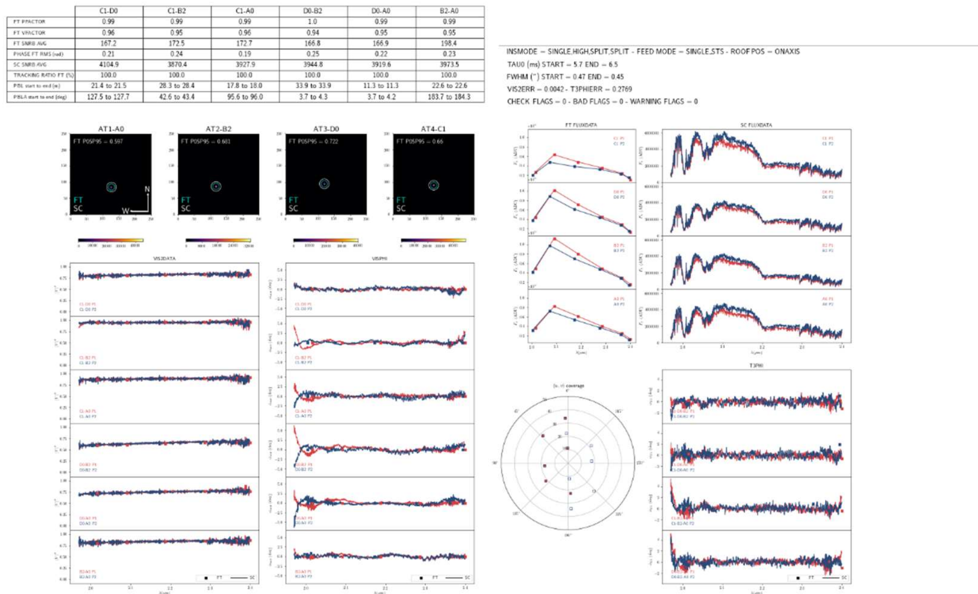
[3]Column CalFlag: Calibrator Flag (bit field): bit 0 is set if LDD_CHI2 is above 5 or the spectral type is missing or not precise (BRIGHT); bit 1 is set if the star is a known double in WDS (Cat. B/wds/wds) with separation inferior to 1 arcsec; bit 2 is set if the star is, according to Simbad's OTYPEs, one of the codes which signals a possible binarity or pulsating stars; bit 3 is set if the star has neighbors within 3 arcsec (ASCC / GAIA / 2MASS).
Column BADCAL: JMMC badcal identifier (https://www.jmmc.fr/badcal/)

Review of the quality of the science calibrated visibilities:

Science calibrated Visibilities will only be available in a second phase.

The review of the data quality of the calibrated visibilities is expected to be identical to the review of the uncalibrated visibilities. We will assess the quality on the same 36 quality parameters.

We will also provide a quick look plot which will be similar to the quick plot for the uncalibrated visibilities (Fig. 7)



	C1-D0	C1-B2	C1-A0	D0-B2	D0-A0	B2-A0
FT PFACTOR	0.99	0.99	0.99	1.0	0.99	0.99
FT VFACTOR	0.96	0.95	0.96	0.94	0.95	0.95
FT SNRB AVG	167.2	172.5	172.7	166.8	166.9	198.4
PHASE FT RMS (rad)	0.21	0.24	0.19	0.25	0.22	0.23
SC SNRB AVG	4104.9	3870.4	3927.9	3944.8	3919.6	3973.5
TRACKING RATIO FT (%)	100.0	100.0	100.0	100.0	100.0	100.0
PBL start to end (m)	21.4 to 21.5	28.3 to 28.4	17.8 to 18.0	33.9 to 33.9	11.3 to 11.3	22.6 to 22.6
PBLA start to end (deg)	127.5 to 127.7	42.6 to 43.4	95.6 to 96.0	3.7 to 4.3	3.7 to 4.2	183.7 to 184.3

Fig. 7: Quick plot for the calibrated visibility product.

Known issues

The already known processing problems are described in the user manual (https://www.eso.org/sci/software/pipe_aem_main.html).

- The accuracy in the wavelength calibration can generate biases in the closure phase of a maximum of 3deg.
- When there is a low number of valid frames (< 5) the final uncertainties are not reliable. The number of valid frames can be found in the OI_VIS2 extension table (INSNAME = GRAVITY_SC) under the column NVALID.

During the initial work to prepare the initial release, some additional issues which do not affect the quality of the final science products have been found. These issues have been found with v 1.9.3 and 1.9.7.

- The position of the science and Fringe Tracker object is sometimes not picked at the right position by the pipeline. This does not affect the quality of the data but the image in the preview plot could show the object at the wrong position (Fig. 8)

Fig. 8: the position of the science and fringe tracking object has been wrongly picked up

- The QC parameter values reflect the quality of the input raw data and not the quality of the output science data.
  For ex. concerning the VFACTOR: any single frame below VFACTOR=0.1 (default value for the pipeline) is removed from the final integration. It is not, however, removed from the calculated QC parameter shown in the header of the final product: HIERARCH QC VFACTORij_Pk (ij: baseline, k Polarisation).
  The consequence in some cases is that the VFACTOR value could be outside of the good quality thresholds but the final data product quality will be acceptable, this is the case when in the input raw data some frames are good and a few frames are terrible, the VFACTOR will reflect these input data (including the bad frames) while the final QC and the final data quality could be fine.
  A user could judge the reliability of the values of the VFACTOR and PFACTOR QC parameters by checking the header keywords "HIERARCH ESO QC REJECTED RATIO SCij" which represent the frame rejection ratio of the science frames.

File identification

Both uncalibrated and calibrated visibilities products contain the mandatory extension tables for the OIFITS2 as well as OI_FLUX which is an additional table.
The different products can be classified using the header keyword PRO.CATG which is listed below in Table 5 and Table 6.
To distinguish between uncalibrated and calibrated visibilities, an additional header keyword VISCAL is also written in the product, which value can be either UNCALIBRATED or CALIBRATED.
The file naming convention is:
GR_<type>_OBS.ID_ARCFILE_<array>_<field_mode>_<resolution>_<polarisation_mode> where:

- GR: GRAVITY instrument
- <type> is described in Table 5 and Table 6
- OBS.ID: keyword header
- ARCFILE: truncated name of the first input raw file
- <array> could be A1234 if the observation was done on the Auxiliary Telescopes (AT) and U1234 if the data were acquired with the Unit Telescopes (UT)
- <field_mode>: SINGLE or DUAL
- <resolution>: LO (Low), ME (Medium), HI (High)
- <polarisation_mode>: COM (COMBINED), SPL (SPLIT)

Type	Product category (PRO.CATG)	Format	Description	VISCALIB
SCVS	SINGLE _CAL_VIS	OIFITS2	CALIBRATOR, single mode	UNCALIBRATED
SSVS	SINGLE _SCI_VIS	OIFITS2	SCIENCE, single mode	UNCALIBRATED
SCVD	DUAL_CAL_VIS	OIFITS2	CALIBRATOR, dual mode	UNCALIBRATED
SSVD	DUAL_SCI_VIS	OIFITS2	SCIENCE, dual mode	UNCALIBRATED

Table 5: Uncalibrated visibilities files, no ancillary FITS files are provided.

Type	Product category	Format	Primary or ancillary	Description	VISCALIB
SVCS	SINGLE_SCI_VIS_CALIBRATED	OIFITS2	primary	single mode	CALIBRATED
ACTS	SINGLE_CAL_TF	FITS	ancillary	Transfer Function (TF) estimated on calibrators, single mode	

ASTS	SINGLE_SCI_TF	FITS	ancillary	TF interpolated at the time of science, Single mode	
SVCD	DUAL_SCI_VIS_CALI-BRATED	OIFITS2	Primary	dual mode	CALIBRATED
ACTD	DUAL_CAL_TF	FITS	ancillary	Transfer Function estimated on calibrators, dual mode	
ASTD	DUAL_SCI_TF	FITS	ancillary	TF interpolated at the time of science, dual mode	

Table 6: Primary and ancillary FITS files products for SCIENCE calibrated visibilities.

Acknowledgements

VLTI expertise centers (https://european-interferometry.eu/vlti-expertise-centers/) have been contributing in setting up the automatic quality control of the products released to the community. They also defined the content of the plots which allow a user to check quickly if the data fulfills what is expected for the science goal.
This study was done under an Opticon RadioNet Pilot contract (EC contract 101004719 26-UPORTO: GRAVITY curated data).

According to the Data Access Policy for ESO data held in the ESO Science Archive Facility, all users are required to acknowledge the source of the data with appropriate citation in their publications.

Since processed data downloaded from the ESO Archive are assigned Digital Object Identifiers (DOIs), the following statement must be included in all publications making use of them:

- *Based on data obtained from the ESO Science Archive Facility with DOI: https://doi.org/10.18727/archive/101*