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Very Large Telescope

Paranal Science Operations

GRAVITY Template Manual

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1 INTRODUCTION

1.1 Scope

This document describes the observing templates for the 2nd generation VLTI instrument GRAVITY. This document should be used for preparing GRAVITY observations starting with period P118.1. Like with other VLT instruments, observations with GRAVITY are carried out making use of **observation blocks** (OBs). The OBs must be created by the user during Phase 2 preparation either with the p2 web application or with the Phase 2 Application Programming Interface (API). An OB is a set of observing templates that describe and detail the target acquisition and the data recording. The user has to define the values of the template **keywords** (parameters).

The Template Manual requires the user to have some basic understanding of the GRAVITY instrument. If you are a first time user, we recommend to read the latest GRAVITY User Manual, which can be found on the GRAVITY Documentation website at:

`https://www.eso.org/sci/facilities/paranal/instruments/gravity/doc.html`

The OBs are prepared with the web application p2. The p2 web interface is available at:

`https://www.eso.org/p2`

Also, visiting observers at Paranal are asked to prepare their observations with this web-based application. OBs created or changed through p2 will be directly recorded in ESO's database and immediately become available at the telescope on Paranal.

The Phase 2 API allows to create, modify, or delete OBs in an automised way and is hence useful to programmatically produce or modify a large amount of OBs (e.g. for a Large Programme).

Finally, the VLTI User Manual needs to be consulted for a description of those parts of the interferometer which are not instrument specific (e.g. AT configurations, limiting magnitudes for field guiding, VLTI observation types etc.) that are required to prepare VLTI observations. The latest VLTI User Manual can be found on the GRAVITY Documentation website.

1.2 Contact information

In case of questions or suggestions related to the Phase 2 preparation should be addressed to USD via the contact form at ESO Operations Helpdesk.

1.3 Period of validity of this manual

This manual is valid for observations with GRAVITY starting with ESO Period 118.1 beginning on May 1st, 2027.

1.4 Glossary

- **Constraint Set (CS)**
  List of requirements for the conditions of the observation that is given inside an OB. OBs are only executed under this set of minimum conditions.
- **Observation Block (OB)**
  An Observation Block is the smallest schedulable entity for the VLT. It consists of a sequence of templates. Usually, a GRAVITY Observation Block includes one target acquisition and one exposure template. Especially for astrometric observations swapping the fringe-tracker and science targets, however, longer sequences are common.
- **Observation Description (OD)**
  A sequence of templates used to specify the observing sequences within one or more OBs.

- **Observation Toolkit (OT)**
  A tool used to create queues of OBs for scheduling and possible execution in service mode taking the constraint set (CS) into account.

- **Proposal Preparation and Submission (Phase 1)**
  The Phase 1 begins right after the Call for Proposals (CfP) and ends at the deadline for CfP. During this period the potential users are invited to prepare and submit scientific proposals. For more information, see:
  http://www.eso.org/sci/observing/phase1.html

- **Phase-2 Proposal Preparation (P2)**
  Once proposals have been approved by the ESO Observation Program Committee (OPC), users are notified and the Phase 2 begins. In this phase, users are requested to prepare their accepted proposals in the form of OBs using the p2 web application. See:
  http://www.eso.org/sci/observing/phase2.html

- **Service Mode (SM)**
  In service mode (in contrast to "Visitor-Mode"), the observations are carried out by the ESO Paranal Science-Operation staff (PSO) alone. Observations can be done at any time during the period, depending on the CS given by the user. OBs are put into a queue schedule in OT which later sends OBs to the instrument.

- **Template**
  A template is a sequence of operations to be executed by the instrument. The observation software of an instrument dispatches commands written in templates not only to instrument modules that control its motors and the detector, but also to the telescopes and VLTI subsystems.

- **Template signature file (TSF)**
  File which contains template input parameters.

- **Visitor Mode (VM)**
  The classic observation mode. The user is on-site to supervise his/her program execution, to directly analyse the data and to take real-time decisions if necessary.

1.5 Modifications for P118.1

For P118.1, the following template changes are implemented with respect to the templates from the previous period:

- Section 2.4 describes the best practices for efficient observations

2 GRAVITY TEMPLATES

The number of GRAVITY observing templates, is minimal and grouped according to the mode, i.e. either single-field (SF, on-axis fringe-tracking splitting the light from the science target to the fringe tracker and science combiner, or off-axis mode sending all the light to the fringe tracker), dual-field (DF, fringe-tracking using a reference star within the field-of-view), and dual-field wide (DW, fringe-tracking using a reference star picked by the Star Separator system). There are five templates for preset, acquisition and fringe search: single-field on-axis, single-field off-axis, dual-field on-axis, dual-field off-axis, and dual-field wide. There are two additional templates for the dual-field on-axis and off-axis modes: one template which allows to swap the fringe-tracking and science objects (swap template) as well as one template to acquire a source within the range of the Star Separator (STS)

systems without presetting the telescopes (dither template). Furthermore there are four templates for fringe observations: two for the single-field modes (science and calibrator) and two for the dual-field modes (again science and calibrator). Hence, there are 11 templates in total. The templates require user-provided input for a limited number of keywords.

2.1 Observing modes

A description of the GRAVITY observing modes can be found on the public GRAVITY web pages for the science users. In summary, the instrument consists of two independent interferometers, the so-called fringe-tracker (FT) and the science spectrometer (SC). The fringe-tracker stabilises the fringes on the science target (in single-field mode) or a nearby fringe-tracking reference star (in dual-field modes). This observing strategy allows longer exposures (significantly longer than the atmospheric coherence time) on the science spectrometer without losing significant fringe contrast. The observing wavelength is for both channels the K-band ($1.98 - 2.40\,\mu$m). The following setups of GRAVITY can be currently used:

- Five distinct modes: single-field (SF) on-axis and off-axis, dual-field (DF) on-axis and off-axis, and dual-field wide (DW). In single-field on-axis mode the light of a single science target is split 50%-50% between fringe-tracker and the science channel. In single-field off-axis, the science fiber is on the sky and all the light from the science target is sent to the fringe tracker. In dual-field mode, a nearby object (separation to the science target $d \leq 4''$ for the ATs and $d \leq 2''$ for the UTs) is used for fringe-tracking. In dual-field wide the VLTI Star Separators are used to allow fringe tracking from a source that is $d \leq 30''$ from the science target.

- Three spectral setups for the science spectrometer :

  1. Low Resolution $\mathcal{R} \sim 22$
  2. Medium Resolution $\mathcal{R} \sim 500$
  3. High Resolution $\mathcal{R} \sim 4000$

  Note, the resolution of the fringe-tracker is fixed at $\mathcal{R} \sim 22$ and its data are always delivered in the FITS files. Hence, low resolution for the SC spectrometer is normally only used in dual-field.

- Two polarisation modes for the fringe-tracker & science spectrometer:

  1. Split polarisation (only linear polarisation)
  2. Combined polarisation

  For the best visibility accuracy "split polarisation" is recommended. In case of faint objects and SNR limitations "combined polarisation" is recommended. The polarisation mode has to be the same for fringe-tracker and science spectrometer.

- Telescope configurations of four ATs or four UTs.

Table 3 in Sect. 2.3.2 gives guidelines for DIT values for the science spectrometer. Normally, the fringe-tracker DIT is set automatically based on the object's **correlated** K-band magnitude, as determined from the total K-band magnitude and visibility.

It should be noted that the adaptive optics units GPAO, on the UTs (see Sect. 2.2.6), or NAOMI on the ATs (see Sect. 2.2.8) are a prerequisite for observations with GRAVITY. For proper adaptive optics (AO) operations, the Coudé guide star must be suitably bright for guiding and should be located close to the science target to ensure a good AO correction. See the VLTI user manual for details.

2.2 Acquisition templates

The first template in an OB must be an acquisition template, which points the telescope at a source and sets up the VLTI and instrument for observations. For GRAVITY, the name of this template is *GRAVITY_single_onaxis_acq*, *GRAVITY_single_offaxis_acq*, *GRAVITY_dual_onaxis_acq*, *GRAVITY_dual_offaxis_acq* or *GRAVITY_dual_wide_acq*. The sequence of these five templates is very similar. They start by a "preset": the target coordinates (α, δ) are sent to the telescopes and the delay lines, so they can slew to the position corresponding to the target coordinates at preset time. Once the VLTI is tracking and Coudé-guiding, the target(s) should be seen on the *Acquisition Camera* of GRAVITY. Internal actuators take care of the field rotation and ensure that the target(s) is/are injected into the fringe-tracker and science channel fibres. In dual-field mode, the internal differential delay lines are preset such that they compensate the differential optical path between the two objects. To ensure a correct compensation of the differential delay, it is advisable to use as accurate offsets from the fringe-tracker source to the science source as possible, at least using coordinates from the same catalogue (e.g. 2MASS). In dual-field wide mode, the internal differential delay lines are not used; instead, external differential delay lines compensate for the differential optical path between the two objects. The final step in the acquisition template is to search and track fringes. The search uses a saw tooth pattern around the nominal fringe position (i.e. zero OPD) with increasing amplitude. As soon as the fringes are found and the control loop is locked the acquisition template is finished and the science exposures defined in the observation template is executed.

In addition to the five standard acquisition templates mentioned above, there is a sixth acquisition template, the *GRAVITY_dual_acq_dither* template, which acts like reduced dual-field acquisition template. It allows offsetting the field within the stroke of the Star Separator (STS) actuator (8" in any direction; ~ 20" perpendicular to the roof) using the keywords `SEQ.DITHER.X` and `SEQ.DITHER.Y`. The purpose of this template is to allow fast observations of multiple targets within the given range, without sending a full preset to the telescopes. It can only be used if a previous preset has been sent to the telescopes, e.g. using the dual beam acquisition (*GRAVITY_dual_onaxis_acq* or *GRAVITY_dual_offaxis_acq*). Due to its complexity, the dither template is currently only offered in Visitor Mode.

What follows is a detailed description of some important definitions and parameters of the acquisition templates. The user is advised to read through these subsections in order to create the acquisition template correctly.

As GRAVITY observations may need up to three different objects (telescope Coudé guide star, instrument fringe-track object and instrument science object), the user can find in these three subsections details on how the different objects are defined in the three acquisition template.

2.2.1 Which star is which in single-field mode?

In GRAVITY SF on-axis mode, the science target and the FT object are the same object. In SF off-axis the science fiber is on sky and all the light from the science target is sent to the fringe tracker. Therefore, the SF acquisition templates only list the keywords related to the science object. For standard observations, one can either choose telescope on-axis or off-axis Coudé guiding for the telescope adaptive optics correction. In telescope on-axis guiding (option `COU.NGS.SOURCE = SCIENCE`), the observation uses only one object to perform the adaptive optics corrections, to track the fringes and to record the science data. If the science target is not bright enough for the adaptive optics system of the telescope, another, off-axis star can be chosen to guide the telescope (option `COU.NGS.SOURCE = SETUPFILE`). This is explained in detail in the VLTI user manual.

2.2.2 Which star is which in dual-field mode?

In order to make efficient use of the VLTI field of view of 4″ (ATs) and 2″ (UTs), in GRAVITY DF observations, both on-axis and off-axis, the telescope are preset to coordinates that correspond to a position in between the FT and SC source. The system does this automatically based on the coordinates and the separation provided in the acquisition template. **The coordinates in the target field are those of the FT object.** Here, Coudé guide star can be the fringe tracker object (option `COU.NGS.SOURCE = FT`), science target (option `SCIENCE`), or it can be a third star (option `SETUPFILE`). In most cases, the Coudé guide star is the same as the FT object as it is usually brighter than the science object both in the optical (for NAOMI and GPAO) and in the near-IR (for fringe-tracking and GPAO_IR). However the guide star can also be a third object (distance restrictions apply, see the VLTI user manual) when both the FT and SC objects are too faint for the adaptive optics of the telescope. It is also possible that the target of scientific interest is the Coudé guide star, e.g. when it is much bluer than the FT object and therefore the brighter object in the optical for adaptive optics correction.

2.2.3 Which star is which in dual-field wide mode?

For increasing the sky coverage of GRAVITY, in 2022 a new mode GRAVITY dual-field wide was implemented. This mode uses the Star Separators for picking a science target and a fringe tracker target that are at most separated by 30″. This dual-field wide mode works similarly to the normal dual-field mode, except that here **the coordinates in the target field are those of the SC object**. Also here, Coudé guide star can be the fringe tracker object (option `COU.NGS.SOURCE = FT`), science target (option `SCIENCE`), or it can be a third star (option `SETUPFILE`). In most cases, the Coudé guide star is the same as the FT object as it is usually brighter than the science object both in the optical (for NAOMI and GPAO) and in the near-IR (for fringe-tracking). However, the guide star can also be a third object (distance restrictions apply, see the VLTI user manual) when both the FT and SC objects are too faint for the adaptive optics of the telescope.

2.2.4 Proper motion and parallax

The knowledge of the current object coordinates (α, δ) determines the ability to predict the fringe position. For targets with a proper motion larger than 50 mas/year or a parallax greater than 100 mas it is important to provide both values in the acquisition template. If not provided, the fringe search can take significantly longer than normal. For an effective use of the allocated time we request that the known proper motions are incorporated into the OBs.

2.2.5 Mode for metrology laser

One noise source in GRAVITY is the back scattering of the metrology laser onto the science detector. Especially for faint targets this dominates over the other noise sources. Since P110 it has been possible to turn the metrology laser OFF, and in P112 new FAINT mode is introduced.
There are three metrology modes (`SEQ.MET.MODE`) that can be chosen:

- *ON*: In this mode metrology laser is on and operated normally.
- *OFF*: In this mode the metrology laser is turned off completely. This gives the best signal-to-noise ratio, but does not allow for phase referencing the SC and FT target. Therefore, it is only available in single-field observations, as well as for dual-field wide.
- *FAINT*: In this mode the SC and FT metrology lasers brightness is toggled with the observation. The brightness is reduces during the exposure and increased in between exposures. This

improves the signal-to-noise ratio, while still allowing for phase referencing between the SC and FT target. This mode slightly increases the overheads and is therefore recommended only for faint targets in dual-field on axis and off-axis observations.

OFF and FAINT modes are recommended for targets fainter than K=12 mag and K=9 mag for UTs and ATs, respectively (in MEDIUM spectral resolution). For brighter targets the metrology mode ON should be used. In the single-field off-axis mode, where the target is always faint and no phase referencing between the SC and FT target is needed, the metrology mode is by default OFF.

Note that at times the laser reflection in the acquisition camera affects the acquisition of the science target. In the case of single-field observations, where no phase referencing is needed, the metrology laser can be turned OFF to remove the reflection.

2.2.6 GPAO guiding with the UTs

On the Unit Telescopes, adaptive optics correction is currently provided by GPAO. GPAO offers two modes with a natural guide star (NGS) from a visible wavefront sensor (GPAO_NGS_VIS) or IR wavefront sensor (GPAO_NGS_IR). From P117, GPAO offers two modes with Laser Guide Star (LGS) from a visible wavefront sensor (GPAO_LGS_VIS) or IR wavefront sensor (GPAO_LGS_IR).

The IR wavefront system is the former CIAO, now under the GPAO architecture, and remains largely the same. Note that for the dual-field wide mode GPAO_NGS_IR and GPAO_LGS_IR are not available. Details on GPAO can be found in the VLTI User Manual, which also includes information on which system to choose for a certain observational setup. Here we list only the main properties of these systems.

GPAO (GRAVITY+ Adaptive Optics) has the following requirements:

- The guide star must be within a radius of 57.5 arcsec from a point 10 arcsec to the East of the science target.
- The GPAO_VIS wavefront sensor is sensitive in the G_{rp} filter, the red GAIA filter. Where possible, this magnitude should be provided rather than the broader GAIA G band.
- The guide star (NGS) must be fainter than $G_{rp} = -3^m$ and brighter than $G_{rp} = 12.5^m$. Note that this limit is brighter than the old MACAO system.
- In LGS mode a guide star is still required for tip-tilt correction.
  - For LGS_VIS, a visible tip-tilt guide star is required. The guide star must be fainter than $G_{rp} = 10.0^m$ and brighter than $G_{rp} = 17.0^m$.
  - For LGS_IR, an infrared tip-tilt guide star is required. The guide star must be brighter than $K = 10.0^m$.
- The faintest (if variable) G or K magnitude of the Coudé guide star should be given in the keyword `COU.GS.MAG`.

GPAO_IR is an infrared Shack-Hartmann type adaptive optics system and has the following requirements:

- The guide star must be brighter than $K = 10^m$ in off-axis mode in both GPAO_NGS_IR and GPAO_LGS_IR.
- The separation of the guide star from the science target must be between 4 and 60 arcsec for off-axis Coudé guiding with both GPAO_NGS_IR and GPAO_LGS_IR.

- Seeing ≤ 1.1 arcsec and coherence time > 1.5 ms, both at 500 nm.
- GPAO_NGS_IR and GPAO_LGS_IR cannot be used in the GRAVITY dual-field wide mode.

The respective AO system is selected using the keyword `COU.AO.TYPE` in the acquisition template. By default (`COU.AO.TYPE` = *NGS_VIS*) GPAO will be used for the UTs. For GPAO_NGS_IR off-axis guiding, `COU.AO.TYPE` must be set to *NGS_IR*, with no impact on the sensitivity of GRAVITY. See also Sect. 3.1.

To ensure a good AO correction, a distance of < 15″ between the Coudé guide star and the science target is recommended, as otherwise anisoplanatic effects deteriorate the correction. To efficiently inject light into GRAVITY, AO correction must be used. It is not possible under any weather conditions to perform GRAVITY observations without AO correction.

From P118, GPAO offers a new mode for objects that appear extended at optical wavelengths when using GPAO_LGS_VIS. An extended object is defined as having a core which is ¿0.4 arcsec (i.e. resolved by the low-order wavefront sensor sub-apertures) or having an extended background flux around the core (¿10%). In all other cases, the user is advised to leave COU.NGS.PROFILE.NAME to the default POINT. More information can be found in the VLTI user manual.

2.2.7 LGS positioning

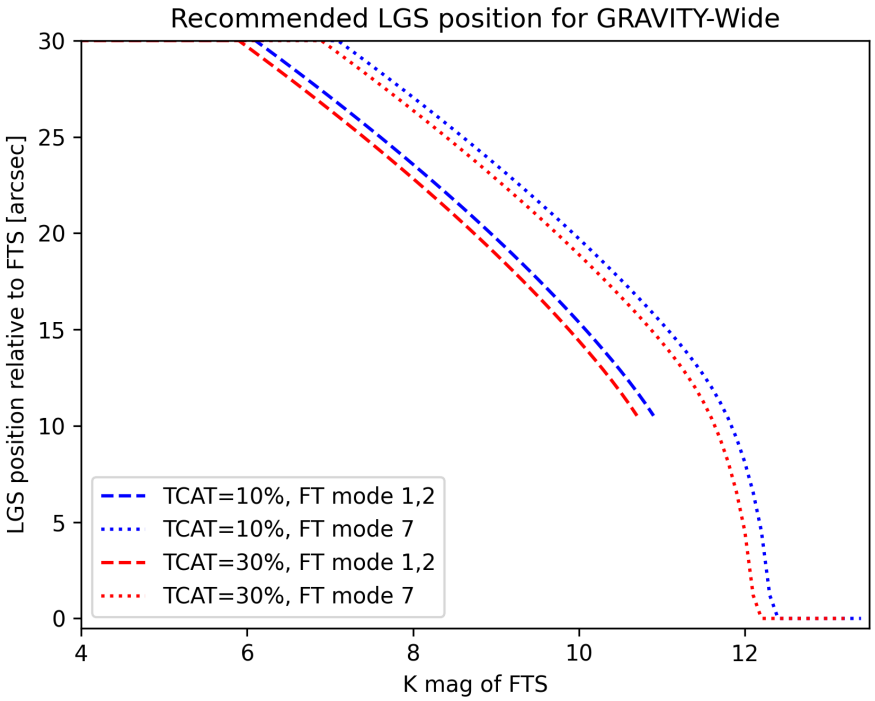

Figure 1: LGS recommend positioning for GRAVITY-wide observations as a function of **correlated** K magntitude. The LGS should be moved along the axis between the FTS and SC. The aim should be to have the LGS positioned as close to the SC target as possible. Only Turbulence categories (TCAT) 10% and 30% are shown, as GRAVITY-wide is not offered in poorer conditions. FT mode 1 and 2 are only valid down to $K_{corr} = 11.0$.

The LGS position can be specified within the acquisition template. The available options are:

- FTS: The position of the fringe tracker star.

- SC: The position of the science target.
- SETUPFILE: User-defined coordinates for the LGS position

In GRAVITY single-field and dual-field observations, in both on-axis and off-axis observations, the LGS position should be either FTS or SC, as the distance between the two targets is never enough for a degradation in the PSF of either target.

The exception to this rule is concatenations where the SCI and CAL are very different G_{rp} mag. As described in the VLTI User Manual, if the tip-tilt star is too bright, it can contaminate the WFS laser, causing significant PSF degradation. One solution is to manually move the laser to a safe distance from the tip-tilt star using SETUPFILE. This requires a minimum separation of 10 arcsec between the LGS and the tip-tilt star. An alternative solution is to switch between LGS and NGS mode for the different CAL and SCI; this has been demonstrated to ensure good calibration also.

For **GRAVITY-Wide**, the large separations make the laser's position critical for successful observations. A careful balance must be made between sufficient flux on the FT star for fringe tracking while maximising the Strehl of the faint science object. In order to calculate the best position of the laser for a given configuration, use Figure 1.

In order to manually calculate the best LGS position for a given GRAVITY-wide setup, you can use the equations below.

$$\text{FT_SNR} = \frac{\sqrt{A \cdot 10^{-0.4 \cdot K}}}{(1 + 10^{2(K-B)})^{0.2}} \tag{1}$$

The constants A and B are provided below in Table 1. K is the correlated K-band magnitude of the fringe tracker star.

$$\frac{SNR(x)}{SNR(0)} = e^{-(\frac{x}{16})^{1.6}} \tag{2}$$

Here, x is the separation (in arcseconds) / isoplanatic angle of the FT and LGS position.

Table 1: Constants for calculating the fringe tracker SNR using the above equation. The constants are provided assuming a turbulence category of 10%. For worse turbulence categories, the K band magnitude should be scaled by -0.2^{mag}.

	FT MODE = 1,2		FT MODE = 7	
Turbulence Category	A	B	A	B
10%	8e5	11.5	2e6	12.0

The following procedure can be used to calculate the optimal LGS position.

1. Calculate the on-axis FT SNR using equation (1).
2. Adjust the FT SNR using equation 2 until reaching a FT SNR = 3-4 for the maximum separation possible. The ideal configuration is the LGS directly on the SC target if possible.
3. Experiment with both FT MODE = 2 and 7. If FT MODE = 2 does not allow for the LGS to be placed directly on the SC, then FT MODE=7 should be used.

2.2.8 NAOMI guiding with the ATs

Since P102, the Auxiliary Telescopes guide by means of the New Adaptive Optics Module for Interferometry (NAOMI). NAOMI is a low-order Shack-Hartman system operating in the visible which

replaced the previous STRAP tip-tilt guiding. Even for the best atmospheric conditions, it is not possible to perform GRAVITY observations without that the telescopes are properly guiding. The requirements for successful NAOMI guiding are the same as previously for STRAP guiding:

- The guide star must be brighter than $R = 15^m$. Note however that the tip-tilt correction drops significantly in K for a guide star fainter than 11th magnitude. E.g. when Coudé guiding on a star of $R = 13^m$, the K-band limit for fringe-tracking drops by about 1 magnitude.
- The guide star should be within a radius of $< 15''$ from the science target in order to guarantee a good AO correction: the effective adaptive optics correction drops with distance from the science target, so it is recommended that the user chooses a guide star as close as possible. A rule of thumb is that the magnitude limit of GRAVITY is brighter by 1 magnitude for every $15''$ from the science object.
- It is requested that the faintest (if variable) R magnitude of the guide star is given in the keyword `COU.NGS.MAG`.

The NAOMI units are used by default when observing with the ATs (`COU.AO.TYPE` = *NGS_VIS*).

2.2.9 Science and fringe-tracking K magnitudes

In dual-field on-axis, dual-field off-axis, and dual-field wide modes, the `SEQ.FT.ROBJ.MAG` keyword must be used to specify the **total** K-band magnitude, $K_{\rm tot}$, of the fringe-tracking object. From this the correlated magnitude $K_{\rm cor} = K_{\rm tot} - 2.5 \times \log_{10}(V)$ is calculated using the expected visibility V on the longest baseline of an "open telescope triplet" (or non-closed triangle for example AT1-AT2, AT2-AT3 and AT3-AT4). This baseline does not have to be the longest baseline of the quadruplet as fringe-tracking will make use of so-called bootstrapping: if one knows the zero-OPD on two of the baselines of a closed triangle then the remaining one can be deduced (e.g. if ZOPD on baseline 12 and 23 are known then the ZOPD on 13 can be deduced). The correlated magnitude $K_{\rm cor}$ is used to set up the fringe-tracker (see Sect. 2.2.13). The total K magnitude of the science target should be independently provided using the keyword `SEQ.INS.SOBJ.MAG.K`.

In single-field mode the **total** K-band fringe-tracking magnitude is equivalent to the science target K-band magnitude. Hence only the keyword `TEL.TARG.MAG.K` is available in the templates *GRAVITY_single_onaxis_acq* and *GRAVITY_single_offaxis_acq*.

2.2.10 Field guiding H-band magnitude

The `TEL.TARG.MAG.H` keyword should be used to specify the uncorrelated H-band magnitude of the science source (in single-field). In dual-field mode both `TEL.TARG.MAG.H` and `SEQ.INS.SOBJ.MAG.H` are required for the two objects (FT and SC respectively). The *Acquisition Camera* uses the H-band light for the object acquisition and slow field guiding.

In dual-field wide mode the flux injection to the science fiber is stabilised by measuring the position of the science target on the acquisition camera field image. Therefore, for this mode both H-band magnitudes, SC and FT, have to be defined. The H-band magnitude of the science object is defined by using the keyword `SEQ.INS.SOBJ.MAG.H`. In dual-field wide mode the H-band magnitude of the SC target has to be brighter than $H = 14.0^m$ and $H = 19.5^m$ for ATs and UTs, respectively.

2.2.11 Selecting the polarisation mode

Observations can be done in polarisation split or combined mode. In split mode a Wollaston prism is introduced in the beam. It splits the two linear polarisations on the detector. This increases the visibility accuracy as polarisation phase shifts originating from the optical train are separated.

The disadvantage however is that the light is spread over twice as many pixels, i.e. the read noise is increased. In case of bright targets (where read noise can be neglected) the split mode is to be preferred. The combined mode should be used in case of faint objects, where read noise dominates the signal to noise. Currently FT and SC have to be in the same polarisation mode. Polarisation split mode can be chosen by setting the keywords `INS.FT.POL` and `INS.SPEC.POL` to *IN*: Wollaston prism inserted. The combined mode is chosen with *OUT*: Wollaston prism out.

2.2.12 Selecting the science combiner resolution

In SF two spectral resolutions are offered (medium and high), whereas in DF and DW all three can be chosen. The spectral mode can be selected by setting the keyword `INS.SPEC.RES` to *LOW*, *MED* or *HIGH*. The choice of the spectral resolution depends on whether the observations are in SF or DF, on the target brightness, on the science goals, on the desired visibility accuracy (SNR) and on the available observing time. As a "rule-of-thumb", the user should consider high resolution (and combined polarisation) only for targets brighter than $K < 8^m$ on the ATs or $K < 12^m$ with the UTs. Otherwise the necessary on-source integration time exceeds 1 h for any reasonable SNR. Fainter targets should be observed in medium or low resolution. The reason why low resolution is offered in DF only is that the FT resolution is the same as SC and those SC low resolution in SF would imply duplication of data (as the same polarisation is imposed). From P113, the dual-field wide mode is offered in all three modes: *LOW*, *MED* and *HIGH*. It is strongly recommended that's users have excellent precision for target coordinates when using *LOW* spectral resolution in GRAVITY-wide. *LOW* spectral resolution also has an inherent closure phase error limit of $\sim 3-4^\circ$ in GRAVITY-wide mode.

2.2.13 Fringe-tracker

GRAVITY always operates with the internal fringe-tracker. It is not possible to use GRAVITY without this system. Normally, the DIT of the fringe-tracker is automatically selected based on the correlated K-band magnitude, $K_{\rm cor}$, calculated from both the total K-band magnitude, $K_{\rm tot}$, and expected visibility V specified by the user according to: $K_{\rm cor} = K_{\rm tot} - 2.5 \times \log_{10}(V)$.

Currently, fringe-tracking is feasible under the following conditions:

- Seeing below $1.4''$ and τ_0 above 1.6 ms (that is turbulence $T \leq 85\%$).
- Transparency THN or better.
- Altitude above 30 degrees.
- All AO loops closed and resulting in a Strehl ratio at least 10%.
- Fringe-tracker object fulfilling the limiting correlated magnitude constraints on at least three baselines that do not form a triangle (e.g. 13/23/24, or 12/13/14). These are listed on the GRAVITY instrument website. Then it is possible to boot-strap other baselines with lower visibilities.

In practice, the fringe-tracker mode is normally set up according to the expected correlated magnitude of the fringe-tracking object: FT mode = floor($K_{\rm cor} - K_{\rm AT/UT}$), where the magnitude is modified by $K_{\rm AT/UT}$ which takes the value $K_{\rm AT/UT} = 0^m$ when observing with the ATs and $K_{\rm AT/UT} = 4^m$ when observing with the UTs, i.e. a certain fringe-tracker mode is activated for 4^m fainter magnitudes on the UTs than for the ATs. The currently available modes of the fringe-tracker and their magnitude ranges are listed in Table 2. This corresponds to the default procedure when `FT.MODE` = *AUTO*.

The fringe-tracker can also be forced into a certain mode by setting the keyword `FT.MODE` to one of the available fringe-tracker modes. This may be necessary under certain circumstances, for example

Table 2: Currently defined fringe-tracker modes. Magnitude ranges are given for the ATs; for the UTs, the same modes apply but for 4^m fainter magnitudes. FOR FT modes 2,7& 9, the **correlated** magnitude is required to ensure sufficient SNR for fringe tracking. For FT mode 1, the **uncorrelated** magnitude is used to ensure the detector does not saturate.

FT mode	magnitude range (ATs)	gain	DIT [ms]	Kalman mode
1	$K_{\rm tot} < 2^m$	low	0.85	2
2	$2^m \leq K_{\rm cor} < 7^m$	high	0.85	2
7	$7^m \leq K_{\rm cor} < 9^m$	high	3	2
9	$9^m \leq K_{\rm cor}$	high	10	2

because both science target and calibrator should have the same fringe-tracking setup. If the magnitudes are such that the science target and calibrator would lead to different fringe-tracker modes, the calibrator can be forced into the same mode by explicitly setting the mode with the keyword `FT.MODE`. For example for observations with the UTs of a science target in DF with a correlated magnitude of the fringe-tracking object of $K_{\rm cor}^{\rm FT} = 10.2^m$ the corresponding FT mode is 7. An associated calibrator in SF with a correlated magnitude of $K_{\rm cor}^{\rm cal} = 9.3^m$ would imply FT mode 2. To ensure that both the science and calibrator use the same fringe-tracker setup, `FT.MODE = 7` should be set for the calibrator. Note that the fringe-tracker modes are the same for ATs and UTs, but their respective magnitude ranges are shifted by 4^m.

2.2.14 Single-field mode

Starting Period 112 the single-field mode has two separate acquisition templates: on-axis and off-axis. The *GRAVITY_single_onaxis_acq* template has the same behaviour as the old single-field template *GRAVITY_single_acq*.

The new *GRAVITY_single_offaxis_acq* can be used when the user wants to observe a faint target and is only interested in using the fringe tracker to record data. In this case the science fiber is just placed on the sky and the target is observed only with the fringe tracker. In addition, this template is used for GRA4MAT acquisition.

2.2.15 Dual-field mode

Starting in Period P112, there are two acquisition templates in dual-field mode depending on the distance of the FT and SC objects and whether the UTs or ATs are used:

- *Dual-field on-axis*: If the separation is less than $0.6''$ for the UTs and $2.7''$ for the ATs, the dual-field mode can be used in the "on-axis" set-up. Here, the source is placed on the beam splitter as for the single-field mode and the light from the science and the fringe-tracking targets are picked up by moving the fibres accordingly. With this set-up, arbitrary low separations between the FT and SC objects can be achieved; for a separation of $0''$ (e.g. for calibration purposes) the set-up is identical to the single-field mode. In this set-up, less than 50% of the light of each object are injected into the fibres only, i.e. the throughput is reduced by about a factor of 2. This loss has to be taken into account for the limiting magnitudes. Dual-field on-axis templates also support the use of Dark Hole Mode, as described in Section 2.3.5.

- *Dual-field off-axis*: For separations larger than $0.27''$ for the UTs and $1.17''$ for the ATs, the dual-field mode can be used in the "off-axis" set-up, where the source is placed on a roof-top mirror which separates the light from the science target and the fringe-tracking target and

injects ~ 100% of the light of each source into the respective fibres. The limiting separation for this mode is set by the VLTI field-of-view, i.e., 2″ for the UTs and 4″ for the ATs.

In dual-field on-axis and off-axis modes, the offset in right ascension and declination in milliarcseconds of the science target relative to the fringe-tracking object has to be provided with the keywords `SEQ.INS.SOBJ.X` and `SEQ.INS.SOBJ.Y`, i.e. the coordinates of the FT source are the reference. As a result, the FT coordinates need to be filled out in the "target" tab of the OB (i.e. the `TEL.TARG` keywords). The binary separation should be as accurate as possible, at least accurate to within 100 mas. If the separation is poorly known the differential delay lines will not preset correctly and the fringes in the science channel will not necessarily be close to 0 OPD. Also, the time to fringe search might increase significantly, i.e. the observing efficiency could be reduced. See also Sect. 2.2.2 for the definition of the FT, SC and Coudé guide objects.

The requirements for the dual-field mode in general are:

- The separation between fringe-tracker source and science target must be < 2.0″ for the UTs and < 4.0″ for the ATs in order to prevent vignetting of the sources.

2.2.16 Dual-field wide mode

In dual-field wide mode the science targets coordinates are given in the "target" tab of the OB. The fringe tracker target parameters on the other hand are defined in the acquisition template GRAVITY_dual_wide_acq itself. It is very important to include accurate information on the coordinates and proper motions for both targets.
The requirements for the dual-field wide mode are:

- The fringe tracker target correlated K-band magnitude must be < 13.0 mag and < 9.5 mag for UTs and ATs, respectively.
- The limiting magnitude for the science target depends on the turbulence category and the separation between the science target and fringe tracker target. More information can be found from: GRAVITY Instrument Description website.
- The separation between fringe-tracker source and science target must be < 30.0″ for both the UTs and ATs. This is due to atmosphere anisoplanatism which induces coherence loss with increased separation.
- The science target has to have magnitude H< 14 mag on the ATs and H< 19.5 mag on the UTs.

Due to the need of good atmospheric conditions (turbulence class 30% and better), observations in service mode are strongly encouraged to optimise the scientific return. Note also that the dual-field wide mode only provides relative measures (differential visibilities and phases), no absolute visibilities, due to atmospheric effects when separation increases. Calibrations of the interferometric transfer function are thus not needed and not offered for this mode.

2.2.17 Which dual-field acquisition template to use?

The illustration of the possible separations for the different dual-field modes is given in Fig. 2.
The lower separation limit for the dual-field off-axis mode is set by the sharpness of the roof prism and the largest possible separation for the dual-field on-axis mode is set by the tip-tilt piston stroke. The largest possible separation for the dual-field off-axis mode is set by the VLTI field-of-view.
The lower separation limit for the dual-field wide mode (4″/2″ on ATs/UTs) is not absolute and from the technical point of view smaller separations can also be used. However, as dual-field wide does

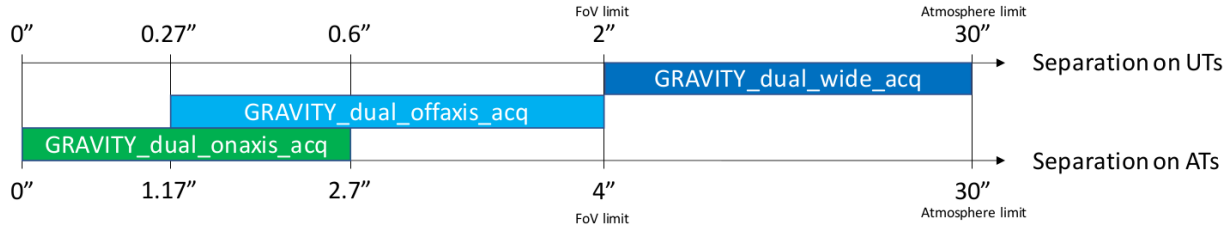

Figure 2: Possible target separations for the different dual-field acquisition templates: on-axis, off-axis and wide.

not provide absolute calibrations, it is recommended to use dual-field off-axis when possible. In any case, with a waiver it is possible to use dual-field wide with smaller separations.

2.3 Observing templates

Following the acquisition template, the user has to chose an observation template. This template is the second and the last one in a normal GRAVITY OB. It is used to record the fringe and sky data. There are currently only four observation templates:

1. single-field science target, *GRAVITY_single_obs_exp*
2. single-field calibrator, *GRAVITY_single_obs_calibrator*
3. dual-field science target, *GRAVITY_dual_obs_exp*
4. dual-field calibrator, *GRAVITY_dual_obs_calibrator*

The templates use almost identical keywords. The appropriate template should be chosen according to the mode (single/dual) and the target (science/calibrator). Dual-field wide uses the same observing template as the normal dual-field observation (GRAVITY_dual_obs_exp), no calibrator observations are offered in this mode.

Each template allows a sequence of exposures. The sequence consists of science target exposures (OBJECT) and off-source exposures (SKY). The observing sequence can be defined by the user with the keyword `SEQ.OBSSEQ`. The sequence can contain any combination of object (O) and sky (S) exposures. For high contrast dual-field observations, a Dark Hole (D) exposure can also be used, see Section 2.3.5. The `SEQ.SKY.X` and `SEQ.SKY.Y` are used to select the offset of the sky exposure. These offsets will move the GRAVITY internal actuators in the directions given. It is suggested to use offsets of at least 2000 mas to avoid any star light entering the fibres, depending on the atmospheric conditions. The total sky offset ($sqrt(X^2 + Y^2)$) cannot be more than 8000 mas. Also, make sure that in dual-field the sky offset will not position the SC star on the FT fibre or vice versa. The safest is to offset perpendicular to the binary separation vector.

2.3.1 Integration time

The exposure time for the science spectrometer should be chosen according to the mode and **uncorrelated** K-band magnitude of the science target. It is specified by the keyword `DET2.DIT`. Table 3 lists the suggested ranges of K-band magnitudes that can be observed with the different DIT values when using that ATs in on-axis mode (light split 50%-50% between the SC and FT channels). Figure 3 shows the same information in graphical form. For the given magnitude ranges the data will be photon noise limited. For magnitudes brighter / lower than indicated, the detector will become non-linear and ultimately saturate. For magnitudes significantly fainter / higher, the data will start to become read noise limited. With combined polarisation 0.5^m fainter targets can be observed than

Table 3: Suggested ranges of the uncorrelated K-band magnitude, K, of the science object for the various offered DITs of the science combiner when observing with the ATs and UTs. Values are given for single-field or dual-field on-axis mode with Combined polarisations, where the light is split 50%-50% between the SC and FT channels. In Split polarisation mode, the limits are offset by $\Delta K = 0.5^m$ to brighter magnitudes. In dual-field off-axis and in dual-field wide, 100% of the object light reaches the science combiner; hence, the suggested magnitude ranges are offset by $\Delta K = 0.7^m$ to fainter magnitudes. If the object falls between two DITS, it is recommended to choose the longer DIT. We do not set a maximum K-band magnitude for the 100s and 300s DITs, as observations quickly become background-limited. The limit magnitudes are reached by stacking multiple exposures. Note that DIT > 30 s for low spectral resolution is only possible with `MET.MOD=OFF` (see text).

		Spectral Resolution (`INS.SPEC.RES`):		
DIT [s]	Array	*LOW*	*MED*	*HIGH*
0.3	ATs	$4.0 < K < 6.5$	$0.5 < K < 3.0$	$-2.5 < K < 0.0$
1	ATs	$5.0 < K < 7.5$	$1.5 < K < 4.0$	$-1.5 < K < 1.0$
3	ATs	$6.5 < K < 9.0$	$3.0 < K < 5.5$	$0.0 < K < 2.5$
10	ATs	$7.5 < K < 10.0$	$4.0 < K < 6.5$	$1.0 < K < 3.5$
30	ATs	$8.5 < K < 11.0$	$5.0 < K < 7.5$	$2.0 < K < 4.5$
100	ATs	$10.0 < K <$ -	$6.5 < K <$ -	$3.5 < K < 7.0$
300[1]	ATs	$11.0 < K <$ -	$7.5 < K <$ -	$4.5 < K < 7.0$
0.3	UTs	$8.0 < K < 10.5$	$4.5 < K < 7.0$	$1.5 < K < 4.0$
1	UTs	$9.0 < K < 11.5$	$5.5 < K < 8.0$	$2.5 < K < 5.0$
3	UTs	$10.5 < K < 13.0$	$7.0 < K < 9.5$	$4.0 < K < 6.5$
10	UTs	$11.5 < K < 14.0$	$8.0 < K < 10.5$	$5.0 < K < 7.5$
30	UTs	$12.5 < K < 15.0$	$9.0 < K < 11.5$	$6.0 < K < 8.5$
100	UTs	$14.0 < K <$ -	$10.5 < K <$ -	$7.5 < K < 11.0$
300[1]	UTs	$15.0 < K <$ -	$11.5 < K <$ -	$8.5 < K < 11.0$

[1] DIT = 300 s only offered in Visitor Mode and quickly becomes background limited

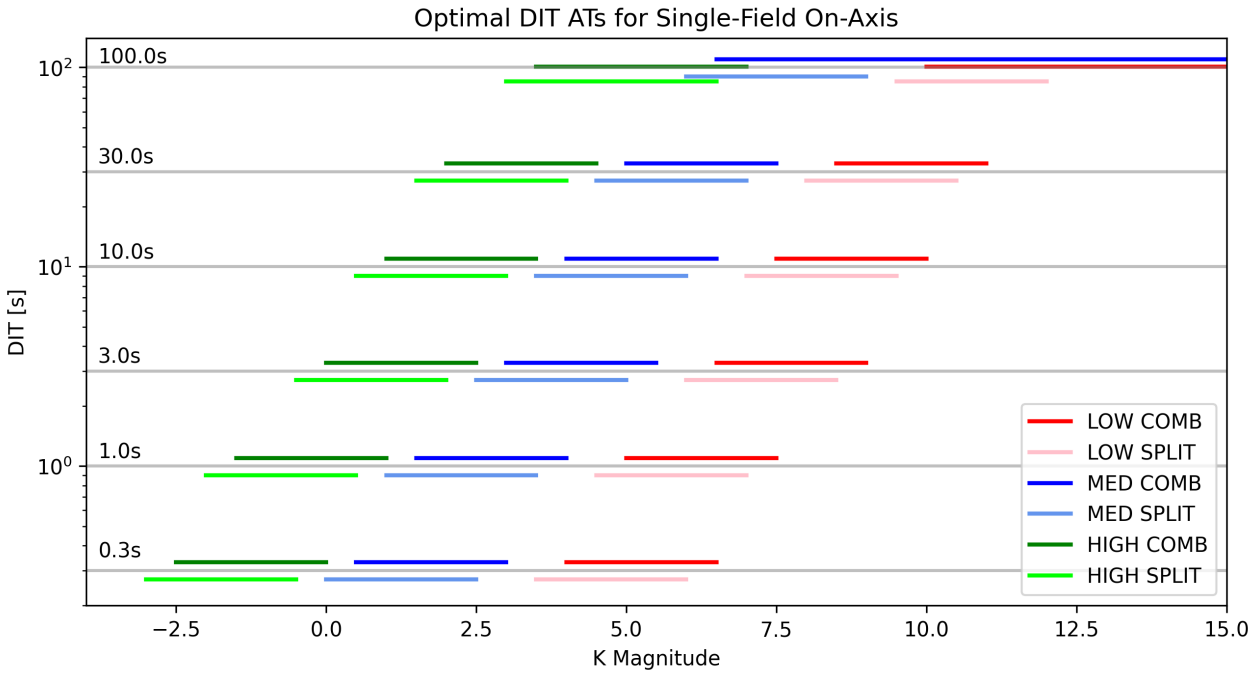

Figure 3: Suggested DIT values for the science combiner, `DET2.DIT`, for the **ATs** as a function of the instrument mode and of the **uncorrelated** K-band magnitude of the science object. The shaded areas show the suggested range of DITs as a function of K-band magnitude, the horizontal lines the actually available DIT values. Values are given for single-field or dual-field on-axis mode, where the light is split 50%-50% between the SC and FT channels. The limiting magnitude of the ATs ($K = 16.5^m$) has been demonstrated in both LOW and MEDIUM resolutions, requiring only a different number of exposures to achieve. For example for a target with $K = 2.5^m$, observations can be carried in both high resolution split mode for `DET2.DIT` = 10.0 s or 30.0 s (intersections with dark green lines) as well as medium resolution split mode with `DET2.DIT` = 0.3 s or 1.0 s (blue line), c.f. table 3. For the UTs, see Fig. 4.

with split polarisation as the light is spread over less pixels. In off-axis dual-field and dual-field wide modes 100% light of the science target reaches the science detector, hence the suggested magnitude ranges are offset by $\Delta K = 0.7^m$ to fainter magnitudes: $K_{\rm DF} \triangleq K_{\rm SF} + 0.7^m$, where $K_{\rm SF}$ are the values listed in table 3. Because of the higher photon collecting power of the UTs, the magnitudes given in table 3 are shifted by $\Delta K = 3^m$ to fainter magnitudes for on-axis observations and by $\Delta K = 3.7^m$ for off-axis dual-field observations. That is $K_{\rm UTs} \triangleq K_{\rm ATs} + 3^m$. Figure 4 shows the suggested magnitude ranges for the UTs, for the on-axis case.

DITs larger than 30 s saturate the detector in low spectral resolution due to the backscatter of the metrology laser alone. Note that already for `INS.SPEC.RES` = *LOW*, `INS.SPEC.POL` = *COMB* and DIT = 30 s count rates of ~ 20 000 ADU are reached from this laser contamination alone. Therefore, `MET.MOD=OFF` should be used for low spectral resolution observations of most faint targets.

Note that the science detector DIT does not need to be the same in the science target and calibrator observations; the vfactor calculation removes different visibility losses due to different DIT. Still, it is recommended to use the same science detector DIT for both the calibrator and science target observations. Note also that the viscal workflow in the GRAVITY pipeline checks for the same setup, including the same science detector DIT, if needed this can be turned off by setting force_calib to TRUE.

The number of frames (NDIT) per exposure can be specified with `DET2.NDIT.OBJECT` for the science exposure and `DET2.NDIT.SKY` for the sky exposure. See Table 4 for recommended NDIT values as a function of the DIT and number of exposures. The following requirements apply:

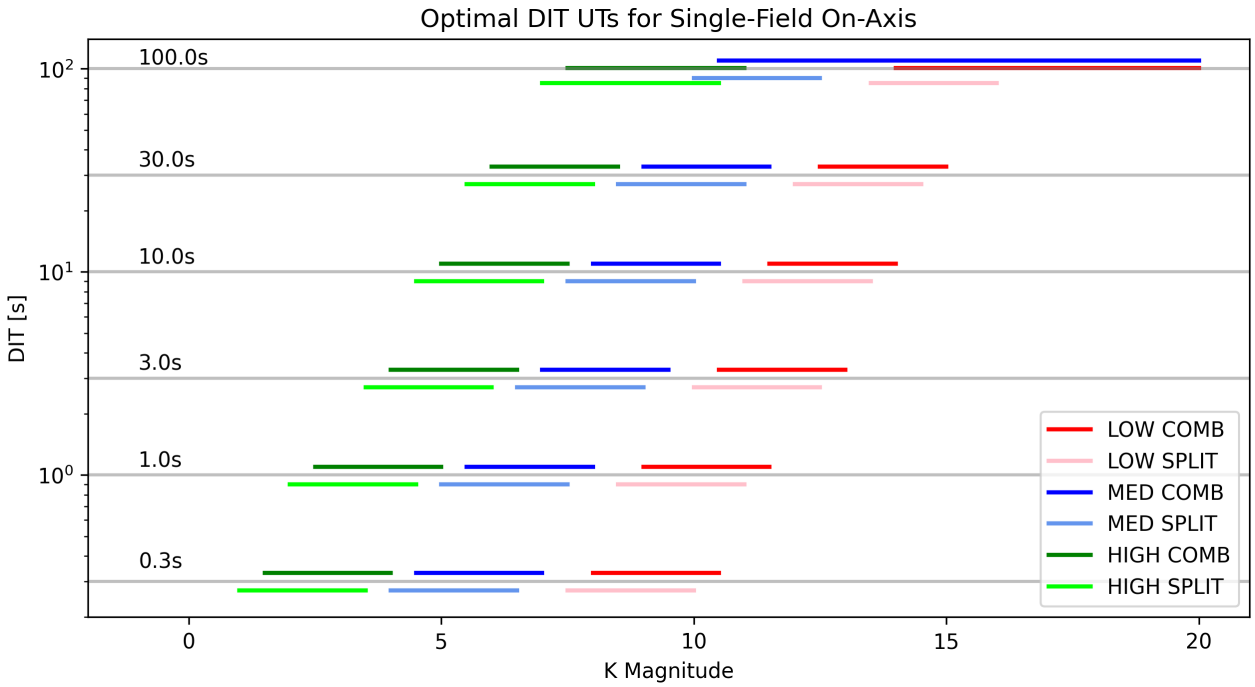

Figure 4: Suggested DIT values for the science combiner, `DET2.DIT`, for the **UTs** as a function of the instrument mode and of the **uncorrelated** K-band magnitude of the science object. Values shown for on-axis observations, for off-axis the magnitudes are shifted by $\Delta K = 0.7^m$ towards fainter magnitudes. The limiting magnitude of the ATs ($K = 20.0^m$) has been demonstrated at both LOW and MEDIUM resolutions, requiring only a different number of exposures to achieve it.

1. The total exposure time (DIT × NDIT) must not exceed 420 s, i.e. 7 min.
2. The number of science frames (NDIT) should be more than 4 and at most 320.

To efficiently remove any incoherent flux and any possible bias of the measurements, the GRAVITY internal piezos are modulated for each exposure of the science detector with a repetitive pattern of 4 or 16 exposures (for details, see Lacour et al. 2019, A&A 624, A99). It is therefore recommended to always use a multiple of 4 in the NDIT, or even better a multiple of 16 for sufficiently short DITs.

2.3.2 Execution time

A conservative estimate of a CAL/SCI sequence is one hour. Each acquisition takes roughly 10 min (it can take longer on faint targets). About 20 min have to be spent for object and sky exposures. As the calibrator normally is observed with the same configuration, the total execution time for one calibrated visibility spectrum is 60 minutes (SCI – CAL).

The following model for the calculation of the execution time is applied for SF observations:

$$\text{exectime} = 600\,\text{s} + \text{DIT} \times \text{NDIT} \times \text{NEXP} + 40\,\text{s} \times \text{NEXP} \tag{3}$$

and for DF observations:

$$\text{exectime} = 800\ \text{s} + \text{DIT} \times \text{NDIT} \times \text{NEXP} + 40\,\text{s} \times \text{NEXP}, \tag{4}$$

where NEXP is the number of exposure entered in the observing template keyword `SEQ.OBSSEQ`. For background limited data, the default is to use the same number of NDIT for S(ky) and O(bject).

A typical example on how to fill the 30 minutes would be the following:

Table 4: Overview of DIT and recommended NDIT values for different number of exposures for SF and DF mode as well as the resulting total execution time of the OB (including the acquisition). The value DIT × NDIT should be less than 420 seconds and the number of science frames (NDIT) must not exceed 320, while the total execution time of the OB should ideally stay below 1800 seconds. NDIT should be a multiple of 4 or better of 16.

DIT [s]	NEXP (O S ..)	NDIT SF	Exec. time SF [s]	NDIT DF	Exec. time DF [s]
0.3	5	320	1280	320	1480
	6	320	1416	320	1616
	7	320	1552	320	1752
	8	320	1688	272	1773
	9	304	1781	224	1765
1.0	2	320	1320	320	1520
	3	320	1680	288	1784
	4	256	1784	208	1792
	5	192	1760	160	1800
	6	160	1800	112	1712
3.0	2	128	1448	128	1648
	3	112	1728	96	1784
	4	80	1720	64	1728
	5	64	1760	48	1720
	6	48	1704	32	1616
10.0	2	32	1320	32	1520
	3	32	1680	16	1400
	4	16	1400	16	1600
	5	16	1600	16	1800
	6	16	1800	12	1760
30.0	2	12	1400	12	1600
	3	12	1800	8	1640
	4	8	1720	4	1440
	5	6	1400	4	1600
100.0	2	4	1480	4	1680
	3	4	1920	4	2120

One could try to observe an OS sequence in single-field mode; so we have to subtract 600 s for the acquisition as well as 2×40 s for the merging of the FITS file and offset to / from the sky position. This leaves 1120 s for the integration, or 560 s seconds for each exposure, which is too long for Service Mode. Instead, aiming at an exposure time of roughly 5 minutes, we better use an OSOO sequence, leaving 1040 s, or 260 s per exposure. So, for a target with $K = 3^m$ and observations in medium spectral resolution using the ATs, this would typically mean choosing DIT = 1 s and NDIT = 256, the latter being a multiple of 16 in order to reduce the bias from incoherent flux (see previous section). If on the other hand, observations in high spectral resolution are needed, this would imply DIT = 10 s, and a sequence of OOOSOO with NDIT = 16 would optimally fill out the 30 minutes. It has been

demonstrated that no more than one S exposure is needed per 40 minutes of observing.

2.3.3 Acquisition camera frames

The internal *Acquisition Camera* is used for the object acquisition as well as slow pupil and tilt guiding. By default, each science exposure contains a continuous sequence of acquisition frames (`DET1.NDIT` = 0) with an integration time DIT = 0.7 s. This means the user obtains H-band images of the science target with roughly 2″ (on the UTs) / 4″ (on the ATs) field-of-view during the entire integration time. In certain cases, the acquisition frames may be scientifically interesting to the user.

2.3.4 The swapping template

The swapping template, *GRAVITY_dual_obs_swap*, can only be used for dual-field on-axis and off-axis observations. It swaps the fringe-tracking and science objects by rotating the field by 180° using the derotator of GRAVITY. This template can be used for normal science observations, if the user wishes to observe both dual-field objects with spectral resolution (e.g. binary stars, YSOs etc). In this case, the template avoids using a full acquisition and saves observing time. This template is also required for astrometry to obtain an independent metrology zero point. However note that the astrometric mode of GRAVITY is currently still under development. Although the use of the template is supported by ESO, the extraction of astrometric quantities is not.

This is a stand-alone template which do not require parameters provided by the user. Similar to an acquisition template, no data is taken during the execution of the swapping template.

A normal observing sequence using the swapping template would hence consist of 4 templates:

- Acquisition (*GRAVITY_dual_onaxis_acq*) or (*GRAVITY_dual_offaxis_acq*)
- Science exposure (*GRAVITY_dual_obs_exp*)
- Swap of objects (*GRAVITY_dual_obs_swap*)
- Science exposure (*GRAVITY_dual_obs_exp*; fringe-tracker and science object swapped)

2.3.5 Dark Hole Exposures

As described in the GRAVITY User Manual, the Dark Hole Mode requires specific exposures in order to measure the Dark Hole and the modulation that needs to be applied to the DM in order to null excess stellar flux at the position of the science object. These exposures must take place in additional science exposure template (*GRAVITY_dual_obs_exp*) and require a single 'D' rather than the standard 'O' in the observing sequence. The 'D' must be immediately proceeded by a Sky 'S' exposure with the same DIT (but can be a different NDIT).

The Dark Hole 'D' exposure in this template **MUST** use the following setup:

- DIT = 1 or 3 seconds (to match the DIT used on the host star exposure)
- NDIT = 84

The science exposure template to measure the Dark Hole must be re-applied every 15 minutes of observing time, as atmospheric conditions cause the efficiency of the null to decrease with time. The recommended observing sequence for high contrast science using Dark Hole is:

- Dual-field on-axis acquisition template (*GRAVITY_dual_onaxis_acq*).
- Science template with 'O' exposure(s), ending with an 'S' exposure. The science fibre should be positioned on the host-star (*GRAVITY_dual_obs_exp*).

- Science template with a 'D' exposure with the science fibre at the position of the companion (*GRAVITY_dual_obs_exp*).
- Science template with 'O' exposure(s) including an 'S' exposure, with the science fibre at the position of the companion (*GRAVITY_dual_obs_exp*).
- The Dark Hole measurement/optimisation must be repeated every 15 minutes to ensure a good correction.
- The host star exposure is recommended to be repeated every 30 minutes.

2.4 Best practices for efficient observations

The following recommendations are made to ensure efficient use of observing time and to maximise on-source integration.

- In general, only one S(ky) is needed per 40 minutes of observing, with a minimum of once per OB (i.e. once per CAL, once per SCI). Only for OBs exceeding 40 minutes in total length should additional S(ky) exposures be considered.
- The NDIT for O(bject) and S(ky) exposures should be the same. To increase the amount of time on source, use additional O(bject) exposures (i.e. O O S O).
- The 1 hour recommendation for a CAL-SCI sequence is only a recommendation. For objects with particularly low correlated magnitudes, OBs can be 15-20mins in length. This is both more efficient for observatory operations and allows users to observe more objects/pointings in the same amount of time.

3 TEMPLATE KEYWORDS

In the following tables, we give for each template the keywords that have to be set by the user during Phase 2 preparation.

3.1 Acquisition templates

3.1.1 GRAVITY_single_onaxis_acq

Parameter	Range *(Default)*	Label
SEQ.FT.MODE	AUTO 1 2 7 9 *(AUTO)*	Fringe Tracker mode
SEQ.MET.MODE	ON FAINT OFF *(ON)*	Metrology laser mode
TEL.TARG.NAME	(Name)	SC object name
TEL.TARG.MAG.K	-10...30 *(0.0)*	SC object K band magnitude
STEL.TARG.MAG.H	-10...30 *(0.0)*	SC object H band magnitude
TEL.TARG.DIAMETER	0...300 *(0.0)*	SC object diameter (mas). Only required for **calibrator** OBs.
TEL.TARG.VIS	0...1 *(1.0)*	SC object visibility
TEL.TARG.PARALLAX	-20...20 *(0.0)*	SC object parallax (arcseconds)
INS.SPEC.RES	LOW MED HIGH *(MED)*	Science spectrometer resolution LOW, MED or HIGH
INS.FT.POL	IN OUT *(OUT)*	Fringe-tracker polarisation mode split (IN) or combined (OUT)
INS.SPEC.POL	IN OUT *(OUT)*	Science spectrometer polarisation mode split (IN) or combined (OUT)
COU.AO.TYPE	NGS_VIS NGS_VIS_TCCD NGS_IR NGS_IR_TCCD	Type of Coude guiding
COU.NGS.SOURCE	SCIENCE SETUPFILE *(SCIENCE)*	Coude guide star (GS) input
COU.NGS.ALPHA	RA *(00:00:00.000)*	GS RA if SETUPFILE
COU.NGS.DELTA	DEC *(00:00:00.000)*	GS DEC if SETUPFILE
COU.NGS.PARALLAX	-20...20 *(0.0)*	GS parallax in arcsec if SETUPFILE
COU.NGS.PMA	-10...10 *(0.0)*	GS proper motion in RA if SETUPFILE
COU.NGS.PMD	-10...10 *(0.0)*	GS proper motion in DEC if SETUPFILE
COU.NGS.EPOCH	-2000...3000 *(2000)*	GS epoch if setupfile
COU.NGS.MAG	-3...25 *(0.0)*	GS G band magnitude
COU.LGS.SOURCE	SCIENCE SETUPFILE *(SCIENCE)*	Laser guide star (LGS) position
COU.LGS.ALPHA	RA *(00:00:00.000)*	LGS RA if SETUPFILE
COU.LGS.DELTA	DEC *(00:00:00.000)*	LGS DEC if SETUPFILE
COU.LGS.PARALLAX	-20...20 *(0.0)*	LGS
COU.LGS.PMA	-10...10 *(0.0)*	LGS proper motion in RA if SETUPFILE
COU.LGS.PMD	-10...10 *(0.0)*	LGS proper motion in DEC if SETUPFILE
COU.LGS.EPOCH	-2000...3000 *(2000)*	LGS epoch if setupfile
ISS.BASELINE	small medium large extended UTs *(NODEFAULT)*	Interferometric Array
ISS.VLTITYPE	snapshot imaging time-series astrometry *(NODEFAULT)*	Types of interferometric observations

3.1.2 GRAVITY_single_offaxis_acq

Parameter	Range *(Default)*	Label
SEQ.FT.MODE	AUTO 1 2 7 9 *(AUTO)*	Fringe Tracker mode
SEQ.MET.MODE	ON FAINT OFF *(OFF)*	Metrology laser mode
TEL.TARG.NAME	(Name)	SC object name
TEL.TARG.MAG.K	-10...30 *(0.0)*	SC object K band magnitude
TEL.TARG.MAG.H	-10...30 *(0.0)*	SC object H band magnitude
TEL.TARG.DIAMETER	0...300 *(0.0)*	SC object diameter (mas). Only required for **calibrator** OBs.
TEL.TARG.VIS	0...1 *(1.0)*	SC object visibility
TEL.TARG.PARALLAX	-20...20 *(0.0)*	SC object parallax (arcseconds)
INS.FT.POL	IN OUT *(OUT)*	Fringe-tracker polarisation mode split (IN) or combined (OUT)
COU.AO.TYPE	NGS_VIS NGS_VIS_TCCD NGS_IR NGS_IR_TCCD	Type of Coude guiding
COU.NGS.GSSOURCE	SCIENCE SETUPFILE *(SCIENCE)*	Coude guide star (GS) input
COU.NGS.ALPHA	RA *(00:00:00.000)*	GS RA if SETUPFILE
COU.NGS.DELTA	DEC *(00:00:00.000)*	GS DEC if SETUPFILE
COU.NGS.PARALLAX	-20...20 *(0.0)*	GS parallax in arcsec if SETUPFILE
COU.NGS.PMA	-10...10 *(0.0)*	GS proper motion in RA if SETUPFILE
COU.NGS.PMD	-10...10 *(0.0)*	GS proper motion in DEC if SETUPFILE
COU.NGS.EPOCH	-2000...3000 *(2000)*	GS epoch if setupfile
COU.NGS.MAG	-3...25 *(0.0)*	GS G band magnitude
COU.LGS.SOURCE	FTS SETUPFILE *(FTS)*	Laser guide star (LGS) position
COU.LGS.ALPHA	RA *(00:00:00.000)*	LGS RA if SETUPFILE
COU.LGS.DELTA	DEC *(00:00:00.000)*	LGS DEC if SETUPFILE
COU.LGS.PARALLAX	-20...20 *(0.0)*	LGS
COU.LGS.PMA	-10...10 *(0.0)*	LGS proper motion in RA if SETUPFILE
COU.LGS.PMD	-10...10 *(0.0)*	LGS proper motion in DEC if SETUPFILE
COU.LGS.EPOCH	-2000...3000 *(2000)*	LGS epoch if setupfile
ISS.BASELINE	small medium large extended UTs *(NODEFAULT)*	Interferometric Array
ISS.VLTITYPE	snapshot imaging time-series astrometry *(NODEFAULT)*	Types of interferometric observations

3.1.3 GRAVITY_dual_onaxis_acq

Parameter	Range *(Default)*	Label
SEQ.FT.MODE	AUTO 1 2 7 9 *(AUTO)*	Fringe Tracker mode
SEQ.MET.MODE	ON FAINT OFF *(ON)*	Metrology laser mode
SEQ.PICKSC	T A F (F)	SC object picking strategy
TEL.TARG.NAME	(Name)	FT object name
TEL.TARG.MAG.K	-10...30 *(0.0)*	FT object K band magnitude
TEL.TARG.MAG.H	-10...30 *(0.0)*	FT object H band magnitude
TEL.TARG.DIAMETER	0...300 *(0.0)*	FT object diameter (mas). Only required for **calibrator** OBs.
TEL.TARG.VIS	0...1 *(1.0)*	FT object expected visibility
SEQ.INS.SOBJ.NAME	(Name)	SC object name
SEQ.INS.SOBJ.MAG.K	-10...30 *(0.0)*	SC object K band magnitude
SEQ.INS.SOBJ.MAG.H	-10...30 *(0.0)*	SC object H band magnitude
SEQ.INS.SOBJ.DIAMETER	0...300 *(0.0)*	SC object diameter (mas). Only required for **calibrator** OBs.
SEQ.INS.SOBJ.VIS	0...1 *(1.0)*	SC object expected visibility
SEQ.INS.SOBJ.X	-60000...60000 *(0.0)*	SC object RA offset from FT object in mas
SEQ.INS.SOBJ.Y	-60000...60000 *(0.0)*	SC object DEC offset from FT object in mas
TEL.TARG.PARALLAX	-20...20 *(0.0)*	FT object parallax (arcseconds)
INS.SPEC.RES	LOW MED HIGH *(MED)*	Science spectrometer resolution LOW, MED or HIGH
INS.FT.POL	IN OUT *(OUT)*	Fringe-tracker polarisation mode split (IN) or combined (OUT)
INS.SPEC.POL	IN OUT *(OUT)*	Science spectrometer polarisation mode split (IN) or combined (OUT)
COU.AO.TYPE	NGS_VIS NGS_VIS_TCCD NGS_IR NGS_IR_TCCD	Type of Coude guiding
COU.NGS.SOURCE	SCIENCE SETUPFILE *(SCIENCE)*	Coude guide star (GS) input
COU.NGS.ALPHA	RA *(00:00:00.000)*	GS RA if SETUPFILE
COU.NGS.DELTA	DEC *(00:00:00.000)*	GS DEC if SETUPFILE
COU.NGS.PARALLAX	-20...20 *(0.0)*	GS parallax in arcsec if SETUPFILE
COU.NGS.PMA	-10...10 *(0.0)*	GS proper motion in RA if SETUPFILE
COU.NGS.PMD	-10...10 *(0.0)*	GS proper motion in DEC if SETUPFILE
COU.NGS.EPOCH	-2000...3000 *(2000)*	GS epoch if setupfile
COU.NGS.MAG	-3...25 *(0.0)*	GS G band magnitude
COU.LGS.SOURCE	SCIENCE FTS SETUPFILE *(SCIENCE)*	Laser guide star (LGS) position
COU.LGS.ALPHA	RA *(00:00:00.000)*	LGS RA if SETUPFILE
COU.LGS.DELTA	DEC *(00:00:00.000)*	LGS DEC if SETUPFILE
COU.LGS.PARALLAX	-20...20 *(0.0)*	LGS
COU.LGS.PMA	-10...10 *(0.0)*	LGS proper motion in RA if SETUPFILE
COU.LGS.PMD	-10...10 *(0.0)*	LGS proper motion in DEC if SETUPFILE
COU.LGS.EPOCH	-2000...3000 *(2000)*	LGS epoch if setupfile
ISS.BASELINE	small large UTs *(NODEFAULT)*	Interferometric Array
ISS.VLTITYPE	snapshot imaging time-series astrometry *(NODEFAULT)*	Types of interferometric observations

3.1.4 GRAVITY_dual_offaxis_acq

Parameter	Range *(Default)*	Label
SEQ.FT.MODE	AUTO 1 2 7 9 *(AUTO)*	Fringe Tracker mode
SEQ.MET.MODE	ON FAINT OFF *(ON)*	Metrology laser mode
SEQ.PICKSC	T A F (T)	SC object picking strategy
TEL.TARG.NAME	(Name)	FT object name
TEL.TARG.MAG.K	-10...30 *(0.0)*	FT object K band magnitude
TEL.TARG.MAG.H	-10...30 *(0.0)*	FT object H band magnitude
TEL.TARG.DIAMETER	0...300 *(0.0)*	FT object diameter (mas). Only required for **calibrator** OBs.
STEL.TARG.VIS	0...1 *(1.0)*	FT object expected visibility
SEQ.INS.SOBJ.NAME	(Name)	SC object name
SEQ.INS.SOBJ.MAG.K	-10...30 *(0.0)*	SC object K band magnitude
SEQ.INS.SOBJ.MAG.H	-10...30 *(0.0)*	SC object H band magnitude
SEQ.INS.SOBJ.DIAMETER	0...300 *(0.0)*	SC object diameter (mas). Only required for **calibrator** OBs.
SEQ.INS.SOBJ.VIS	0...1 *(1.0)*	SC object expected visibility
SEQ.INS.SOBJ.X	-60000...60000 *(0.0)*	SC object RA offset from FT object in mas
SEQ.INS.SOBJ.Y	-60000...60000 *(0.0)*	SC object DEC offset from FT object in mas
TEL.TARG.PARALLAX	-20...20 *(0.0)*	FT object parallax (arcseconds)
INS.SPEC.RES	LOW MED HIGH *(MED)*	Science spectrometer resolution LOW, MED or HIGH
INS.FT.POL	IN OUT *(OUT)*	Fringe-tracker polarisation mode split (IN) or combined (OUT)
INS.SPEC.POL	IN OUT *(OUT)*	Science spectrometer polarisation mode split (IN) or combined (OUT)
COU.AO.TYPE	NGS_VIS NGS_VIS_TCCD NGS_IR NGS_IR_TCCD	Type of Coude guiding
COU.NGS.SOURCE	SCIENCE FT SETUPFILE *(FT)*	Coude guide star (GS) input
COU.NGS.ALPHA	RA *(00:00:00.000)*	GS RA if SETUPFILE
COU.NGS.DELTA	DEC *(00:00:00.000)*	GS DEC if SETUPFILE
COU.NGS.PARALLAX	-20...20 *(0.0)*	GS parallax in arcsec if setupfile
COU.NGS.PMA	-10...10 *(0.0)*	GS proper motion in RA if setupfile
COU.NGS.PMD	-10...10 *(0.0)*	GS proper motion in DEC if setupfile
COU.NGS.EPOCH	-2000...3000 *(2000)*	GS epoch if setupfile
COU.NGS.MAG	-3...25 *(0.0)*	GS G band magnitude
COU.LGS.SOURCE	SCIENCE FTS SETUPFILE *(SCIENCE)*	Laser guide star (LGS) position
COU.LGS.ALPHA	RA *(00:00:00.000)*	LGS RA if SETUPFILE
COU.LGS.DELTA	DEC *(00:00:00.000)*	LGS DEC if SETUPFILE
COU.LGS.PARALLAX	-20...20 *(0.0)*	LGS
COU.LGS.PMA	-10...10 *(0.0)*	LGS proper motion in RA if SETUPFILE
COU.LGS.PMD	-10...10 *(0.0)*	LGS proper motion in DEC if SETUPFILE
COU.LGS.EPOCH	-2000...3000 *(2000)*	LGS epoch if setupfile
ISS.BASELINE	small large UTs *(NODEFAULT)*	Interferometric Array
ISS.VLTITYPE	snapshot imaging time-series astrometry *(NODEFAULT)*	Types of interferometric observations

3.1.5 GRAVITY_dual_wide_acq

Parameter	Range *(Default)*	Label
SEQ.FT.MODE	AUTO 1 2 7 9 *(AUTO)*	Fringe Tracker mode
SEQ.MET.MODE	ON FAINT OFF *(ON)*	Metrology laser mode
COU.FTS.NAME	(Name)	FT object name
COU.FTS.MAG.K	-10...30 *(0.0)*	FT object K band magnitude
COU.FTS.MAG.H	-10...30 *(0.0)*	FT object H band magnitude
COU.FTS.DIAMETER	0...300 *(0.0)*	FT object diameter (mas). Not required.
COU.FTS.VIS	0...1 *(1.0)*	FT object expected visibility
COU.FTS.ALPHA	0...240000 *(00:00:00.000)*	FT object RA
COU.FTS.DELTA	-900000...900000 *(00:00:00.000)*	FT object DEC
COU.FTS.PARALLAX	-20...20 *(0)*	FT object parallax in arcseconds
COU.FTS.PMA	-10...10 *(0)*	FT object proper motion in RA
COU.FTS.PMD	-10...10 *(0)*	FT object proper motion in DEC
COU.FTS.EPOCH	-2000...3000 *(2000)*	FT object epoch
COU.LGS.SOURCE	SCIENCE FTS SETUPFILE *(SCIENCE)*	Laser guide star (LGS) position
COU.LGS.ALPHA	RA *(00:00:00.000)*	LGS RA if SETUPFILE
COU.LGS.DELTA	DEC *(00:00:00.000)*	LGS DEC if SETUPFILE
COU.LGS.PARALLAX	-20...20 *(0.0)*	LGS
COU.LGS.PMA	-10...10 *(0.0)*	LGS proper motion in RA if SETUPFILE
COU.LGS.PMD	-10...10 *(0.0)*	LGS proper motion in DEC if SETUPFILE
COU.LGS.EPOCH	-2000...3000 *(2000)*	LGS epoch if setupfile
TEL.TARG.NAME	(Name)	SC object name
TEL.TARG.MAG.K	-10...30 *(0.0)*	SC object K band magnitude
TEL.TARG.MAG.H	-10...30 *(0.0)*	SC object H band magnitude
TEL.TARG.DIAMETER	0...300 *(0.0)*	SC object diameter (mas). Not required.
TEL.TARG.VIS	0...1 *(1.0)*	SC object expected visibility
TEL.TARG.PARALLAX	-20...20 *(0.0)*	SC object parallax (arcseconds)
INS.SPEC.RES	LOW MED HIGH *(MED)*	Science spectrometer resolution LOW, MED or HIGH
INS.FT.POL	IN OUT *(OUT)*	Fringe-tracker polarisation mode split (IN) or combined (OUT)
INS.SPEC.POL	IN OUT *(OUT)*	Science spectrometer polarisation mode split (IN) or combined (OUT)
COU.AO.TYPE	NGS_VIS NGS_VIS_TCCD NGS_IR NGS_IR_TCCD	Type of Coude guiding
COU.NGS.SOURCE	SCIENCE FT SETUPFILE *(FT)*	Coude guide star (GS) input
COU.NGS.ALPHA	RA *(00:00:00.000)*	GS RA if SETUPFILE
COU.NGS.DELTA	DEC *(00:00:00.000)*	GS DEC if SETUPFILE
COU.NGS.PARALLAX	-20...20 *(0.0)*	GS parallax in arcsec if setupfile
COU.NGS.PMA	-10...10 *(0.0)*	GS proper motion in RA if setupfile
COU.NGS.PMD	-10...10 *(0.0)*	GS proper motion in DEC if setupfile
COU.NGS.EPOCH	-2000...3000 *(2000)*	GS epoch if setupfile
COU.NGS.MAG	-3...25 *(0.0)*	GS G band magnitude
ISS.BASELINE	small large UTs *(NODEFAULT)*	Interferometric Array
ISS.VLTITYPE	snapshot time-series *(NODEFAULT)*	Types of interferometric observations

3.1.6 GRAVITY_dual_acq_dither

Parameter	Range *(Default)*	Label
SEQ.FT.MODE	AUTO 1 2 7 9 *(AUTO)*	Fringe Tracker mode
SEQ.FT.ROBJ.NAME	(Name)	FT object name
SEQ.FT.ROBJ.MAG.K	-10...30 *(0)*	FT object K band magnitude
SEQ.FT.ROBJ.MAG.H	-10...30 *(0)*	FT object H band magnitude
SEQ.FT.ROBJ.DIAMETER	0...300 *(0)*	FT object diameter (mas). Only required for **calibrator** OBs.
SEQ.FT.ROBJ.VIS	0...1 *(1.0)*	FT object expected visibility
SEQ.INS.SOBJ.NAME	(Name)	SC object name
SEQ.INS.SOBJ.MAG.K	-10...30 *(0)*	SC object K band magnitude
SEQ.INS.SOBJ.DIAMETER	0...300 *(0)*	SC object diameter (mas). Only required for **calibrator** OBs.
SEQ.INS.SOBJ.VIS	0...1 *(1.0)*	SC object visibility
SEQ.INS.SOBJ.X	-60000...60000 *(0.0)*	RA offset from FT to SC object in mas
SEQ.INS.SOBJ.Y	-60000...60000 *(0.0)*	DEC offset from FT to SC object in mas
SEQ.DITHER.X	-20000...20000 *(0.0)*	FT object dRA offset to previous FT object in mas.
SEQ.DITHER.Y	-20000...20000 *(0.0)*	FT object dDEC offset to previous FT object in mas.

3.1.7 Acquisition keywords

Below follows a more detailed description of the keywords in the acquisition templates:

- `SEQ.FT.MODE`: Set the fringe-tracker mode automatically depending on the magnitude of the fringe-tracking object (for `SEQ.FT.MODE = AUTO`), or manually set the mode (see Sect. 2.2.13).
- `SEQ.MET.MODE`: controls the metrology laser. The dominant noise source in GRAVITY is the back scattering of the metrology laser in the optical fibres in the instrument. The metrology system is not necessary for spectraldifferential observations. To avoid unnecessary noise in those observations at the shortest wavelengths the laser amplifier of the the metrology laser can be turned OFF or used in FAINT mode to reduce the background. (see Sect. 2.2.5 for more information on the different modes)
- `SEQ.PICKSC`: Selects how the science target is picked and placed into the science fibre in the dual-field on-axis and off-axis modes. The options are:
  - `T`: Instrument operator picks the science target in the acquisition camera image.
  - `A`: The instrument acquires the brightest target in the field of view around the SC fibre position, without operator intervention.
  - `F`: The instrument does not use the acquisition camera to track the SC target, instead it relies on the separation being accurate and the separation metrology. This requires that the separation between the fringe tracker target and science target is very well known.
- `TEL.TARG.MAG.K`: is the total K magnitude of the fringe-tracking object in dual-field and dual-field wide modes. This parameter is required to automatically set the mode of the fringe-tracker.
- `TEL.TARG.MAG.MAG.H`: is the total H magnitude of the fringe-tracking object in dual-field and dual-field wide modes. This parameter is required for guiding.
- `TEL.TARG.DIAMETER`: This keyword is only required for calibrator observed in dual-field mode. It is used by the pipeline to correct for the calibrator intrinsic size and visibility. It is however suggested to observe calibrators in single-field mode (also if used for dual-field science targets). Therefore this keyword is normally not required.
- `TEL.TARG.VIS`: is the expected visibility of the fringe-tracking object in dual-field and dual-field wide modes. In single-field mode, this parameter is required when automatically setting the mode of the fringe-tracker.
- `SEQ.INS.SOBJ.X/Y`: RA/DEC offsets in milli-arcsecond of the science target relative to fringe-tracking object in dual-field mode. The offsets have to be known to better than 100 mas in order to avoid delays in the fringe search. If this value is calculated from the positions of each component, the distance in RA (in mas) should include the cos(DEC) term. The offsets have to be provided for the epoch of the observation. For binaries with high differential proper motion this offset can change significantly within one period.
- `SEQ.FT.ROBJ.ALPHA`: is the fringe tracker object right ascension in the dual-field wide mode. The format is HHMMSS.TTT.
- `SEQ.FT.ROBJ.DELTA`: is the fringe tracker object declination in the dual-field wide mode. The format is DDMMSS.TTT.
- `TEL.TARG.PARALLAX`: This keyword specifies the parallax of the target given in the target tab in p2. For dual-field on-axis and dual-field off-axis this is the fringe tracker target and for single-field modes and dual-field wide this is the science target. It is required for accurate fringe positioning if the parallax exceeds 100 mas.

- `SEQ.FT.ROBJ.PARALLAX`: is the fringe tracker object parallax in arcseconds in the dual-field wide mode.
- `SEQ.FT.ROBJ.PMA`: is the fringe tracker object proper motion in right ascension in arcseconds per year. This is only used for the dual-field wide mode.
- `SEQ.FT.ROBJ.PMD`: is the fringe tracker object proper motion in declination in arcseconds per year. This is only used for the dual-field wide mode.
- `SEQ.INS.SOBJ.MAG.K`: is the total K magnitude of the science target. In single-field mode, this parameter is required to automatically set the mode of the fringe-tracker. In dual-field modes, this parameter is required to set the parameters for the science spectrometer fringe guiding.
- `SEQ.INS.SOBJ.MAG.H`: is the H-band magnitude of the science target. This paramater is needed for guiding with the acquisition camera and keeping the science target in the fibre in the dual-field wide mode.
- `SEQ.INS.SOBJ.DIAMETER`: This keyword is only required for a calibrator (if available). It is used by the pipeline to correct for the calibrator intrinsic size and visibility.
- `SEQ.INS.SOBJ.VIS`: is the expected visibility of the science target. It is required in single-field mode when automatically setting the mode of the fringe-tracker and in dual-field modes to set the parameters for the science spectrometer fringe guiding.
- `SEQ.DITHER.X/Y`: RA/DEC offsets in milli-arcsecond of the new FT object relative to the previous FT object in the dither template. The allowed offsets are 8" in any direction; or ~ 20" perpendicular to the roof edge of the beam splitter (reflective part of the roof-prism).
- `INS.SPEC.RES`: This keyword sets the desired SC spectral configuration. It can be:
  - `LOW`: The medium resolution grism is used ($\mathcal{R}$ ~ 22).
  - `MED`: The medium resolution grism is used ($\mathcal{R}$ ~ 500).
  - `HIGH`: The high resolution grism is used ($\mathcal{R}$ ~ 4000).
- `INS.FT.POL` and `INS.SPEC.POL`: These keywords set the desired FT and SC polarisation configuration. It can be:
  - `IN`: Wollaston prism is moved in. The s and p polarisation are split on the detector. This mode offers the highest visibility accuracy at the cost of higher read noise since the light is split over twice as many pixels. This mode is suggested for brighter targets.
  - `OUT`: Wollaston prism is moved out. Both polarisations are combined on the detector. This mode is suggested for faint targets.

  Note: Currently the polarisation setting for FT and SC have to be the same.
- `COU.AO.TYPE`: This keyword defines the type of Coudé guiding to be used. The default setting, `COU.AO.TYPE = NGS_VIS`, implies that, for the ATs, NAOMI or, for the UTs, GPAO will be used with a visible natural guide star. For offset Coudé guiding in the infrared, `COU.AO.TYPE = NGS_IR` has to be set. In this case, an offset Coudé guide star has to be specified, that is `COU.NGS.SOURCE = SETUPFILE` has to also be specified (see below).

  Under special circumstances (e.g. for crowded fields) it might be necessary to use NAOMI with the technical CCD (TCCD) by setting `COU.AO.TYPE = NGS_VIS_TCCD`, respectively, in order to carry out a manual acquisition and to accurately centre the chosen Coudé guide star before closing the respective AO loop. However this is not necessary for most programmes. Therefore, users are advised to leave `COU.AO.TYPE = NGS_VIS`, unless they are sure that IR off-axis is

required (`COU.AO.TYPE = NGS_IR`) or the specific setting has been discussed with the instrument scientist and USD before phase 2 submission.

- `COU.NGS.SOURCE`: This keyword is used to tell the system which source shall be used for Coudé guiding (see Sect. 2.2.2).
  - In **single-field mode** the keyword can have the following values:
    - `SCIENCE`: Coudé guiding on the science object.
    - `SETUPFILE`: Coudé guiding on a chosen guide star different from the science object. The coordinates are those given in the `COU.NGS.ALPHA/DELTA` fields in the acquisition template. Please note the constraints for NAOMI/GPAO guide star in Sect. 2.2.8 and 2.2.6 and that these constraints are also pertinent if Coudé guiding are attempted on the `SCIENCE` object.
  - In **dual-field on-axis, off-axis and wide** modes there is also option `FT`, which uses the fringe tracking object for Coudé guiding.
- `COU.NGS.ALPHA/DELTA`: Coordinates of the Coudé guide star. These keywords should only be specified if the keyword `COU.NGS.SOURCE` is set to `SETUPFILE`. Otherwise they should be `0` as the Coudé Guiding will use the science target to guide on.
- `COU.NGS.PMA/PMD`: RA/DEC proper motion of the Coudé guide star in arcsec/year. These keywords should only be specified if the keyword `COU.NGS.SOURCE` is set to `SETUPFILE`. Otherwise they should be `0.0` as the Coudé Guiding will use the science target to guide on.
- `COU.NGS.EPOCH`: Epoch for the Coudé guide star coordinates.
- `COU.NGS.MAG`: Coudé guide star V-band (GPAO), R-Band (NAOMI) or K-band (CIAO) magnitude. For GPAO and NAOMI also G band magnitude can be used, and is the one that is closest to the system wavelength response. This magnitude should **always** be given. In the case of a variable star the faintest magnitude should be given.
- `COU.LGS.SOURCE`: This keyword is used to tell the system which source shall be used for LGS positioning.
  - In **single-field mode** the keyword can have the following values:
    - `SCIENCE`: LGS position is on the science object.
    - `FTS`: LGS position is on the fringe tracker object.
    - `SETUPFILE`: LGS position is on a chosen guide star different from the science object. The coordinates are those given in the `COU.LGS.ALPHA/DELTA` fields in the acquisition template. Please note the constraints for the GPAO guide star in Sect. 2.2.6 and 2.2.7 and that these constraints are also pertinent if LGS position is attempted on the `SCIENCE` object.
- `COU.LGS.ALPHA/DELTA`: Coordinates of the laser guide star. These keywords should only be specified if the keyword `COU.LGS.SOURCE` is set to `SETUPFILE`.
- `COU.LGS.PMA/PMD`: RA/DEC proper motion of the laser guide star in arcsec/year. These keywords should only be specified if the keyword `COU.LGS.SOURCE` is set to `SETUPFILE`.
- `COU.LGS.EPOCH`: Epoch for the laser guide star coordinates.
- `ISS.BASELINE`: The requested VLTI array for the interferometric observations: `small`, `medium`, `large` or `extended` with the ATs, or `UTs` with the UTs. Note that the dual-field and dual-field wide modes can only use AT configurations `small` and `large`. See the VLTI configuration page.

- `ISS.VLTITYPE`: The requested type of interferometric observations: snapshot, imaging, time-series, and astrometry. Several options can be selected from this keyword list, e.g. "`imaging + timeseries`" for recurring imaging of a variable object. For details, see the VLTI user manual.

3.2 Observing templates

3.2.1 GRAVITY_single_obs_exp and GRAVITY_single_obs_calibrator

Parameter	Range *(Default)*	Label
`DET2.DIT`	0.3 1 3 10 30 100 300*(0.3)*	SC frame integration time (DIT in s)
`DET2.NDIT.OBJECT`	4...320 *(32)*	Number of science target frames (NDIT)
`DET2.NDIT.SKY`	4...320 *(32)*	Number of sky frames (NDIT)
`SEQ.SKY.X`	-8000...8000 *(2000)*	Sky offset in RA (mas).
`SEQ.SKY.Y`	-8000...8000 *(2000)*	Sky offset in DEC (mas).
`SEQ.HWPOFF`	-180..180 *(0.0)*	Sequence of HWP offsets (deg)
`SEQ.OBSSEQ`	O S *(O S)*	Observing sequence of science (O) and sky (S) exposures.

3.2.2 GRAVITY_dual_obs_exp and GRAVITY_dual_obs_calibrator

Parameter	Range *(Default)*	Label
`DET2.DIT`	0.3 1 3 10 30 100 300*(0.3)*	SC frame integration time (DIT in s)
`DET2.NDIT.OBJECT`	4...320 *(32)*	Number of science target frames (NDIT)
`DET2.NDIT.SKY`	4...320 *(32)*	Number of sky frames (NDIT)
`SEQ.SKY.X`	-8000...8000 *(2000)*	Sky offset in RA (mas).
`SEQ.SKY.Y`	-8000...8000 *(2000)*	Sky offset in DEC (mas).
`SEQ.HWPOFF`	-180..180 *(0)*	Sequence of HWP offsets (deg)
`SEQ.OBSSEQ`	O S D *(O S D)*	Observing sequence of object (O) and sky (S) and Dark Hole (D) exposures.
`SEQ.RELOFF.X`	-2000..2000 *(0)*	Sequence of SC relative RA offsets (mas)
`SEQ.RELOFF.Y`	-2000..2000 *(0)*	Sequence of SC relative DEC offsets (mas)

3.2.3 Observing keywords

A detailed explanation of the keywords in the observing template follows:

- `DET2.DIT`: SC frame integration time in seconds.
- `DET2.NDIT.OBJECT/SKY`: Number of science/sky frames per exposure. The total exposure time (DIT x NDIT) should not exceed 320s. For the best accuracy it is suggested to use a similar number of frames for science and sky and the number of frames should be a multiple of 4 or better 16, the minimum NDIT is 4 (see Sect. 2.3.1).
- `SEQ.RELOFF.X/Y`: Relative offset of the science fibre, while keeping the fringe-tracking object fixed. The science fibre can be moved by $\pm 1.0''$ in right ascension and declination. This allows observing several closely spaced science objects or mapping the field to search for faint companions etc. If a fibre offset is desired then the keywords `SEQ.RELOFF.X` and `SEQ.RELOFF.Y` need to be filled in the same sequence as in `SEQ.OBSSEQ`. In addition, the number of entries in all these keywords should be the same. For example for a sequence of `SEQ.OBSSEQ = O S O O S`, `SEQ.RELOFF.X = 0 0 -240 300 0` and `SEQ.RELOFF.Y = 0 0 140 -200 0` are valid offset sequences. The offsets are relative, i.e. the applied offset is the cumulative offset of all previous exposure offsets. That is in the example given here, the offset in the fourth exposure would be (+60, -60) with respect to the initial position. At the end of the template the fibres go back to

the acquisition position. This mean that a new template will start again from the acquisition position.

- `SEQ.HWPOFF`: Sequence of rotation offsets for the half wave plate (HWP). This allows observing a source with different half wave plate settings which can be used to infer the polarisation of the object. The keyword needs to be filled in the same sequence as in `SEQ.OBSSEQ`. Note that polarisation measurements are not officially supported and therefore the use of this keyword requires a waiver approval.

- `SEQ.SKY.X/Y`: Internal actuator sky offset in RA/DEC (mas), these offsets are used for taking the sky exposure. The total sky offset *sqrt*(`SEQ.SKY.X`^{2} + `SEQ.SKY.Y`^{2}) cannot be more than 8000 mas. These offsets will move the actuator in the given directions.

- `SEQ.OBSSEQ`: Observing sequence of science (*O*), sky (*S*) and Dark Hole (*D*) exposures. The Dark Hole (*D*) is only valid for dual-field on-axis observations with the UTs and AO mode NGS_VIS. Any sequence is possible as long as the total execution time does not exceed the limits discussed in section 2.3.2. As a trade-off between efficiency and accuracy, it is suggested to use a sequence like *O S O*.

3.2.4 GRAVITY_dual_obs_swap

The swapping template is a stand-alone template and only has one parameter, which can be changed by the user, the fringe-tracker mode.

Parameter	Range *(Default)*	Label
`SEQ.FT.MODE`	AUTO 1 2 7 9 *(AUTO)*	Fringe Tracker mode

As for the acquisition templates, the fringe-tracker mode is chosen automatically depending on the magnitude of the fringe-tracking object (for `SEQ.FT.MODE = AUTO`), or manually by selecting a specific mode (see Sect. 2.2.13).

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