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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 P103. 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 with the p2 application on the web. 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 GRAVITY User Manual for P103, which can be found at:

<http://www.eso.org/sci/facilities/paranal/instruments/gravity/doc>

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

Finally, the VLTI manual needs to be consulted for a description of those parts of the interferometer which are not instrument specific (e.g. AT configurations, limited magnitudes for field guiding, etc.) that one needs for preparing VLTI observations: [link to VLTI User Manual](#)

1.2 Contact information

In case of questions or suggestions related to Phase-2 preparation, please contact the ESO User Support Department (usd-help@eso.org).

1.3 Period of validity of this manual

This manual is valid for observations with GRAVITY starting with ESO Period 103, which begins on April 1st, 2019.

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, one Observation Block includes one target acquisition and up to three exposure templates.

- **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 CfP (Call-for-Proposals) 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 (P2PP)**

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:

<https://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 sub-systems.

- **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 P103

For P103, the following template changes are implemented with respect to the templates from the previous period:

- A new acquisition template, the dither template (*GRAVITY_dual_acq_dither*), has been made available in Visitor Mode. It allows a fast acquisition within the stroke of the STS. For more information, see Sect. 2.2.
- A keyword to manually specify the half wave plate rotation, `SEQ.HWPOFF`, has been added to all exposure templates (Sect. 3.2).

2 GRAVITY TEMPLATES

The number of GRAVITY observing templates for P103 is minimal and grouped according to the mode, i.e. either single-field (SF, on-axis fringe-tracking using the science star) or dual field (DF, off-axis fringe tracking using a reference star). Thus there are a SF and DF template for (1) preset, acquisition and fringe search and for (2) fringe observation each. There are two additional templates for dual-field mode: one template which allows to swap the fringe-tracking and science objects as well as one template to acquire a source within the range of the STS without presetting the telescopes. Furthermore there are different templates for fringe observation for either science or calibrator. Hence there are eight observing 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 mode). This observing strategy allows exposures of up to 30s on the science spectrometer without losing significant fringe contrast. The observing wavelength is for both channels the K-band ($2.0 - 2.45 \mu\text{m}$). The following setups of GRAVITY can be currently used:

- Two distinct field modes: the dual-field (DF) and the single-field (SF). In single-field mode the light of a single science target is split 50/50 between fringe-tracker and the science channel. In dual-field mode a nearby object (separation with the science target $d \leq 4''$ for the ATs and $d \leq 2''$ for the UTs) is used for fringe-tracking.
- Three spectral setups for the science spectrometer :
 1. Low Resolution $R \sim 20$
 2. Medium Resolution $R \sim 500$
 3. High Resolution $R \sim 4000$

Note, the resolution of the fringe-tracker is fixed at $R \sim 20$ 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 1 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 MACAO or CIAO, both on the UTs (see Sect. 2.2.4), or NAOMI on the ATs (see Sect. 2.2.5) 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 closer than $\sim 15''$ from 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 either *GRAVITY_single_acq* or *GRAVITY_dual_acq*. The sequence of these two templates are 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 fibers. 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, ideally using coordinates from the same catalogue (e.g. 2MASS). 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 two standard acquisition templates mentioned above, there is a third acquisition template, the *GRAVITY_dual_acq_dither* template, which acts like small small dual field acquisition template. It allows offsetting the field within the stroke of the star separator (STS) actuator ($8''$ in any direction; $\sim 20''$ 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_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.

2.2.1 Which star is which in single-field mode?

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 two subsections details on how the different objects are defined in the acquisition template.

In GRAVITY SF mode, the science target and the FT object are the same object. Therefore

the SF acquisition template only lists the keywords related to the science object. For standard observations, one can either chose telescope on-axis or off-axis Coudé guiding for the telescope adaptive optics correction. In telescope on-axis guiding (using NAOMI or MACAO), 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 (using NAOMI, MACAO or CIAO). 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), GRAVITY DF observations are preset at the telescope 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.) This implementation means that Coudé guiding in dual-field is by definition **always** off-axis. Therefore, the user has to set `COU.AG.GSSOURCE = SETUPFILE` in dual-field model and provide the properties of the Coudé guide star. 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/MACAO) and in the near-IR (for fringe tracking). However the guide star can also be a third object (distance restrictions apply, see [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 V for adaptive optics correction.

2.2.3 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.

2.2.4 MACAO or CIAO guiding with the UTs

On the Unit Telescopes, adaptive optics correction is provided either by MACAO in the optical or by CIAO in the infrared, both located in the Coudé foci of the telescopes. Details on MACAO and CIAO 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.

MACAO (Multi-Application Curvature Adaptive Optics) is a 60 element curvature adaptive optic system working in the visible. It has the following requirements:

- The guide star must be fainter than $V = 1^m$ and brighter than $V = 16^m$. Note that the Strehl drops significantly in K with a Coudé guide star fainter than the 13-14th magnitude.
- The guide star must be within a radius of 57.5 arcsec from the science target.

- The faintest (if variable) V magnitude of the Coudé guide star should be given in the keyword `COU.GS.MAG`.

CIAO (Coudé Infrared Adaptive Optics) is an infrared Shack-Hartmann type adaptive optics system. From P101 on, CIAO is offered for observations with GRAVITY in CIAO off-axis mode only, which has the following requirements:

- The guide star must be brighter than $K = 10^m$.
- The separation of the guide star from the science target must be between 4 and 60 arcsec. On-axis Coudé guiding with CIAO (separation < 4 arcsec) is currently not offered.
- Seeing ≤ 1.1 arcsec and coherence time > 1.5 ms, both at $500 \mu\text{m}$.

The respective AO system is selected using the keyword `COU.AG.TYPE` in the acquisition template. By default (`COU.AG.TYPE = DEFAULT`) MACAO will be used for the UTs, which is equivalent to specifically setting `COU.AG.TYPE = ADAPT_OPT`. To select CIAO off-axis guiding, the keyword has to be set to `IR_AO_OFFAXIS` (see Sect. 3.1).

2.2.5 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 $V = 13^m$. Note however that the tip-tilt correction drops significantly in K with guide star fainter than 11th magnitude and that by Coudé guiding on a star of $V = 13^m$, the K -band limit for the SC object drops by 1 magnitude.
- The guide star should be within a radius of $< 15''$ from the science target, implementing the limits for fringe-tracking at the VLTI. 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) V magnitude of the guide star is given in the keyword `COU.GS.MAG`.

The NAOMI units are used by default when observing with the ATs (`COU.AG.TYPE = DEFAULT`). This is equivalent to specifically setting `COU.AG.TYPE = ADAPT_OPT` (see Sect. 3.1).

2.2.6 Science and fringe-tracking K magnitudes

In dual-field mode, the `SEQ.FT.ROBJ.MAG` keyword must be used to specify the **total** K -band magnitude, K_{tot} , of the fringe-tracking object. From this the correlated magnitude $K_{\text{cor}} = K_{\text{tot}} - 2.5 \times \log_{10}(V)$ 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_{cor} is used to set up the fringe tracker (see Sect. 2.2.10). The total K magnitude of the science target should be independently provided using the keyword `SEQ.INS.SOBJ.MAG`. In single-field mode the **total** K-band fringe tracking magnitude is equivalent to the science target K-band magnitude. Hence only the keyword `SEQ.INS.SOBJ.MAG` is available in the template *GRAVITY_single_acq*.

2.2.7 Field guiding H-band magnitude

The `SEQ.FI.HMAG` keyword should be used to specify the uncorrelated H-band magnitude of the science source (in single field) or the H-band brightest of the two objects (SC or FT) in dual field. The *Acquisition Camera* uses the H-band light for the object acquisition and slow field guiding.

2.2.8 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*: Wallaston prism insterted. The combined mode is chosen with *OUT*: Wollaston prism out.

2.2.9 Selecting the resolution mode

In P103 in SF two spectral resolutions are offered (medium and high), whereas in DF 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 resolution mode depends on whether it is SF or DF, the target brightness, science goals, desired visibility accuracy (SNR) and available observing time. As a “rule-of-thumb” the user should consider high resolution (and combined polarisation) only for targets brighter than $K < 5.5^m$. 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 polarization is imposed).

2.2.10 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

Table 1: Currently defined fringe tracker modes. Magnitude ranges are given for the ATs; for the UTs, the same modes apply but for 3^m fainter magnitudes.

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

on the correlated K-band magnitude, K_{cor} , calculated from both the total K-band magnitude, K_{tot} , and expected visibility V specified by the user according to: $K_{\text{cor}} = K_{\text{tot}} - 2.5 \times \log_{10}(V)$. Currently, fringe-tracking is feasible under the following conditions:

- Seeing below 1.5".
- The transparency should be CLR or better.
- τ_0 above 1.5 ms.
- Altitude above 40 degrees.
- Offered limiting correlated magnitudes for the fringe tracker are listed on the [GRAVITY instrument website](#).
- The maximum correlated magnitude has to be fulfilled on at least three baselines that do not form a triangle (e.g. 13/23/24, or 12/13/14). In this case 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: $\text{FT mode} = \text{floor}(K_{\text{cor}} - K_{\text{AT/UT}})$, where the magnitude is modified by $K_{\text{AT/UT}}$ which takes the value $K_{\text{AT/UT}} = 0^m$ when observing with the ATs and $K_{\text{AT/UT}} = 3^m$ when observing with the UTs, i.e. a certain fringe tracker mode is activated for 3^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 1. This corresponds to the default procedure when $\text{FT.MODE} = \text{AUTO}$.

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, 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 $K_{\text{cor}}^{\text{FT}} = 10.2^m$ the corresponding FT mode is 7. An associated calibrator in SF with a correlated magnitude of $K_{\text{cor}}^{\text{cal}} = 9.3^m$ would imply FT mode 2. To ensure that both the science and calibrator use the same fringe tracker setup, $\text{FT.MODE} = 7$ 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 3^m .

2.2.11 Dual-field mode

In dual-field mode, 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, these coordinates also need to be filled out in the “target” tab of the OB (i.e. the `TEL.TARG` keywords). The binary separation should be accurate to better than 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 are:

- Science target correlated K magnitude must not differ more than 3^m from the fringe-tracker source.
- The separation between fringe-tracker source and science target must be within the range $[0.4'', 2.0'']$ for the UTs and $[1.5'', 4.0'']$ for the ATs.

2.3 Observing templates

Following the acquisition template, the user has to choose a science 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 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). 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. 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. Also, make sure that in dual-field the sky offset will not position the SC star on the FT fibre or vice versa. 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 2 lists the suggested DITs for the various modes and magnitudes. 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.

The following requirements apply:

1. The total exposure time ($\text{DIT} \times \text{NDIT}$) must not exceed 300 s.
2. The number of science frames (NDIT) must not exceed 300 and be more than 10.

Note: Stability of the instrument assessed during the commissioning shows that the DIT of the Science and Calibrator targets need not be the same, contrary to VLTI practice and experience with the other instruments.

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. **Note:** The calibrator has to be observed with the same configuration and thus 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:

$$\text{exectime} = 600 \text{ sec} + \text{DIT} \times \text{NDIT} \times \text{NEXP} + 40 \text{ sec} \times \text{NEXP} \quad (1)$$

and for DF:

$$\text{exectime} = 900 \text{ sec} + \text{DIT} \times \text{NDIT} \times \text{NEXP} + 40 \text{ sec} \times \text{NEXP}, \quad (2)$$

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:

In single-field: If we have a OSO sequence, we have to subtract 600 min offset and 3×40 sec offset, leaving 1080 sec, or 360 seconds for each exposure, which is too much.

So, we typically need to use OSOS, leaving 1040 sec, or 260 sec per exposure. So, for magnitude 1 in MR, this would typically be $\text{DIT}=1\text{s}$ and $\text{NDIT}=260$. Or, for magnitude 1 in HR, this would typically be $\text{DIT}=30\text{s}$ and $\text{NDIT}=8$.

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 $\text{DIT}=0.7\text{s}$. This means the user obtains H-band images of the science target with roughly $4''$ field-of-view during the entire integration time.

2.3.4 The swapping template

The swapping template, *GRAVITY_dual_obs_swap*, is only used for dual-field 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

Table 2: Summary of available modes, spectral and polarisation configurations, telescopes (Tel), uncorrelated K magnitudes (K) and suggested DITs for the science spectrometer. In DF the same DITs are adopted as in single-field except that the appropriate DF DIT corresponds to that of a star 0.7^m brighter ($K_{df} = K - 0.7^m$). This reflects that in dual-field the light is not split 50/50 between FT and SC. Likewise for UT observations, one chooses a AT SF DIT that corresponds to a star 3 (or 3.7) magnitudes brighter than the UT science target. Note that the DIT for the calibrator **can** be different from the one used for the science object. **Performances are strongly seeing dependent.**

Mode	Spec	Pol	Tel	K	DIT [s]
Single-field	MR	Comb	AT	$-1.0 < K \leq 1.0$	0.3
Single-field	MR	Comb	AT	$1.0 < K \leq 2.5$	1.0
Single-field	MR	Comb	AT	$2.5 < K \leq 3.0$	3.0
Single-field	MR	Comb	AT	$3.0 < K \leq 3.5$	5.0
Single-field	MR	Comb	AT	$3.5 < K \leq 4.5$	10.0
Single-field	MR	Comb	AT	$5.0 < K \leq 9.0$	30.0
Single-field	MR	Split	AT	$-2.0 < K \leq 0.0$	0.3
Single-field	MR	Split	AT	$0.0 < K \leq 1.5$	1.0
Single-field	MR	Split	AT	$1.5 < K \leq 2.5$	3.0
Single-field	MR	Split	AT	$2.5 < K \leq 3.0$	5.0
Single-field	MR	Split	AT	$3.0 < K \leq 4.0$	10.0
Single-field	MR	Split	AT	$4.0 < K \leq 9.0$	30.0
Single-field	HR	Comb	AT	$-2.0 < K \leq -0.5$	1.0
Single-field	HR	Comb	AT	$-0.5 < K \leq 0.5$	5.0
Single-field	HR	Comb	AT	$0.5 < K \leq 2.0$	10.0
Single-field	HR	Comb	AT	$2.0 < K \leq 9.0$	30.0
Single-field	HR	Split	AT	$-2.0 < K \leq -0.5$	3.0
Single-field	HR	Split	AT	$-0.5 < K \leq 0.0$	5.0
Single-field	HR	Split	AT	$0.0 < K \leq 1.0$	10.0
Single-field	HR	Split	AT	$1.0 < K \leq 4.5$	30.0
Dual-field	all	all	AT	$K - 0.7$	-
Single-field	all	all	UT	$K - 3.0$	-
Dual-field	all	all	UT	$K - 3.7$	-

Table 3: Overview of DIT and recommended NDIT values for different number of exposures for SF and DF mode. The value $DIT \times NDIT$ should be less than 300 seconds, while the total execution time of the OB is ≤ 1800 seconds. The number of science frames (NDIT) must not exceed 300.

DIT (s)	Nexp (O S ..)	NDIT SF	Execution time SF	NDIT DF	Execution time DF
1.0	2	300	1280	300	1580
	3	300	1620	260	1800
	4	260	1800	185	1800
	5	200	1800	140	1800
3.0	2	100	1280	100	1580
	3	100	1620	85	1785
	4	85	1780	60	1780
	5	65	1775	45	1775
5.0	2	60	1280	60	1580
	3	60	1620	50	1770
	4	50	1760	35	1760
	5	40	1800	25	1725
10.0	2	30	1280	30	1580
	3	30	1620	25	1770
	4	25	1760	18	1780
	5	20	1800	14	1800
30.0	2	10	1280	10	1580
	3	10	1620	-	-

case, the template avoids using a full acquisition and saves observing time. This template is also required for astrometry, however note that the astrometric mode of GRAVITY is currently still under commissioning, meaning that the use of this template for astrometric observations is not supported by ESO.

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_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)

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_dual_acq.tsf

Parameter	Range (<i>Default</i>)	Label
SEQ.FT.MODE	AUTO 1 2 7 9 (<i>AUTO</i>)	Fringe Tracker mode
SEQ.FT.ROBJ.NAME	(Name)	FT object name
SEQ.FT.ROBJ.MAG	-10... 30 (<i>0</i>)	FT object total magnitude
SEQ.FT.ROBJ.DIAMETER	0... 300 (<i>0</i>)	FT object diameter (mas). Only required for calibrator OBs.
SEQ.FT.ROBJ.VIS	-0... 1.0 (<i>0</i>)	FT object expected visibility
SEQ.INS.SOBJ.NAME	(Name)	SC object name
SEQ.INS.SOBJ.MAG	-10... 30 (<i>0</i>)	SC object total magitude
SEQ.INS.SOBJ.DIAMETER	0... 300 (<i>0</i>)	SC object diameter (mas). Only required for calibrator OBs.
SEQ.INS.SOBJ.VIS	-0... 1.0 (<i>0</i>)	SC object expected visibility
SEQ.INS.SOBJ.X	150... 7000 (<i>0</i>)	RA offset from FT to SC object in mas.
SEQ.INS.SOBJ.Y	150... 7000 (<i>0</i>)	DEC offset from FT to SC object in mas.
SEQ.FI.HMAG	-10... 25 (<i>0</i>)	AcqCam guide star magnitude in H
TEL.TARG.PARALLAX	-20... 20 (<i>0</i>)	FT object parallax (arcseconds)
INS.SPEC.RES	LOW MED HIGH (<i>MED</i>)	Science spectrometer resolution LOW, MED or HIGH.
INS.FT.POL	IN OUT (<i>IN</i>)	Fringe-tracker polarisation mode split (IN) or combined (OUT).
INS.SPEC.POL	IN OUT (<i>IN</i>)	Science spectrometer polarisation mode split (IN) or combined (OUT).
COU.AG.TYPE	DEFAULT ADAPT_OPT ADAPT_OPT_TCCD IR_AO_OFFAXIS (<i>DEFAULT</i>)	Type of Coude guiding.
COU.AG.GSSOURCE	SETUPFILE SCI- ENCE (<i>SCIENCE</i>)	Coude guide star (GS) input.
COU.AG.ALPHA	RA (<i>0.</i>)	GS RA if SETUPFILE
COU.AG.DELTA	DEC (<i>0.</i>)	GS DEC if SETUPFILE
COU.GS.MAG	0... 25 (<i>0.</i>)	GS magnitude.
COU.AG.PMA	-10... 10 (<i>0</i>)	GS proper motion in RA
COU.AG.PMD	-10... 10 (<i>0</i>)	GS proper motion in DEC

3.1.2 GRAVITY_single_acq.tsf

Parameter	Range (<i>Default</i>)	Label
SEQ.FT.MODE	AUTO 1 2 7 9 (<i>AUTO</i>)	Fringe Tracker mode
SEQ.INS.SOBJ.NAME	(Name)	SC object name
SEQ.INS.SOBJ.MAG	-10... 30 (<i>0</i>)	SC object total magnitude
SEQ.INS.SOBJ.DIAMETER	0... 300 (<i>0</i>)	SC object diameter (mas). Only required for calibrator OBs.
SEQ.INS.SOBJ.VIS	-0... 1.0 (<i>0</i>)	SC object visibility
SEQ.FI.HMAG	-10... 25 (<i>0</i>)	AcqCam guide star magnitude in H
TEL.TARG.PARALLAX	-20... 20 (<i>0</i>)	SC object parallax (arcseconds)
INS.SPEC.RES	LOW MED HIGH (<i>MED</i>)	Science spectrometer resolution LOW, MED or HIGH.
INS.FT.POL	IN OUT (<i>IN</i>)	Fringe-tracker polarisation mode split (IN) or combined (OUT).
INS.SPEC.POL	IN OUT (<i>IN</i>)	Science spectrometer polarisation mode split (IN) or combined (OUT).
COU.AG.TYPE	DEFAULT ADAPT_OPT ADAPT_OPT_TCCD IR_AO_OFFAXIS (<i>DEFAULT</i>)	Type of Coude guiding.
COU.AG.GSSOURCE	SETUPFILE SCIENCE (<i>SCIENCE</i>)	Coude guide star (GS) input.
COU.AG.ALPHA	RA (<i>0.</i>)	GS RA if SETUPFILE
COU.AG.DELTA	DEC (<i>0.</i>)	GS DEC if SETUPFILE
COU.GS.MAG	0... 25 (<i>0.</i>)	GS magnitude.
COU.AG.PMA	-10... 10 (<i>0</i>)	GS proper motion in RA
COU.AG.PMD	-10... 10 (<i>0</i>)	GS proper motion in DEC

3.1.3 GRAVITY_single_acq_dither.tsf

Parameter	Range (<i>Default</i>)	Label
SEQ.DITHER.X	-20000... 20000 (<i>0</i>)	FT object dRA offset in mas.
SEQ.DITHER.Y	-20000... 20000 (<i>0</i>)	FT object dDEC offset in mas.
SEQ.FT.MODE	AUTO 1 2 7 9 (<i>AUTO</i>)	Fringe Tracker mode
SEQ.FT.ROBJ.NAME	(Name)	FT object name
SEQ.FT.ROBJ.MAG	-10... 30 (<i>0</i>)	FT object total magnitude
SEQ.FT.ROBJ.DIAMETER	0... 300 (<i>0</i>)	FT object diameter (mas). Only required for calibrator OBs.
SEQ.FT.ROBJ.VIS	-0... 1.0 (<i>0</i>)	FT object expected visibility
SEQ.INS.SOBJ.NAME	(Name)	SC object name
SEQ.INS.SOBJ.MAG	-10... 30 (<i>0</i>)	SC object total magnitude
SEQ.INS.SOBJ.DIAMETER	0... 300 (<i>0</i>)	SC object diameter (mas). Only required for calibrator OBs.
SEQ.INS.SOBJ.VIS	-0... 1.0 (<i>0</i>)	SC object visibility
SEQ.INS.SOBJ.X	150... 7000 (<i>0</i>)	RA offset from FT to SC object in mas.
SEQ.INS.SOBJ.Y	150... 7000 (<i>0</i>)	DEC offset from FT to SC object in mas.

3.1.4 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. 2.2.10).
- `SEQ.FT.ROBJ.MAG`: is the total K magnitude of the fringe-tracking object in dual-field mode. This parameter is required to automatically set the mode of the fringe tracker.
- `SEQ.FT.ROBJ.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.
- `SEQ.FT.ROBJ.VIS`: is the expected visibility of the fringe tracking object in dual-field mode. In single-field mode, this parameter is required when automatically setting the mode of the fringe tracker.
- `SEQ.INS.SOBJ.MAG`: is the correlated 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 mode, this parameter is required to set the parameters for the science spectrometer fringe guiding.
- `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 mode to set the parameters for the science spectrometer fringe guiding.
- `SEQ.INS.SOBJ.X/Y`: RA/DEC offsets in milli-arcsecond of the science target relative to fringe-tracking object. 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 $\cos(\text{DEC})$ 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.FI.HMAG`: is the H-band magnitudes of the brightest target in the field (usually the fringe-tracking target). This target will be used for slow field guiding with the *Acquisition Camera*.
- `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 $\sim 20''$ perpendicular to the roof edge of the roof-mirror.
- `TEL.TARG.PARALLAX`: This keyword specifies the parallax of the fringe-tracking target. It is required for accurate fringe positioning if the parallax exceeds 100 mas.
- `INS.SPEC.RES`: This keyword sets the desired SC spectral configuration. It can be:
 - `LOW`: The medium resolution grism is used ($R \sim 20$).

- MED: The medium resolution grism is used ($R \sim 500$).
- HIGH: The high resolution grism is used ($R \sim 4000$).
- 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 very faint targets.

Note: Currently the polarisation setting for FT and SC have to be the same.

- COU.AG.TYPE: This keyword defines the type of Coudé guiding to be used. The default setting, `COU.AG.TYPE = DEFAULT`, implies that, for the ATs, NAOMI or, for the UTs, MACAO will be used (equivalent to `COU.AG.TYPE = ADAPT_OPT`). If on the UTs offset Coudé guiding in the infrared (“CIAO off-axis”) is required, the keyword has to be specifically set to `COU.AG.TYPE = IR_AO_OFFAXIS`. In this case, an offset Coudé guide star has to be specified, that is `COU.AG.GSSOURCE = SETUPFILE` has to also be specified (see below).

Under special circumstances (e.g. for crowded fields) it might be necessary to use MACAO with the technical CCD (TCCD) by setting `COU.AG.TYPE = ADAPT_OPT_TCCD`, respectively, with the disadvantage that not all light is sent to the adaptive optics system. However this is not necessary for most programmes. Therefore, users are advised to leave `COU.AG.TYPE = DEFAULT`, unless they are sure that CIAO off-axis is required (`COU.AG.TYPE = IR_AO_OFFAXIS`) or the specific setting has been discussed with the instrument scientist and USD before phase 2 submission.

- COU.AG.GSSOURCE: 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. The coordinates are those given by the RA/DEC fields of the target.
 - * SETUPFILE: Coudé guiding on a chosen guide star different from the science object. The coordinates are those given in the `COU.AG.ALPHA/DELTA` fields in the acquisition template. Please note the constraints for NAOMI/MACAO guide star in Sect. 2.2.5 and 2.2.4 and that these constraints are also pertinent if Coudé guiding are attempted on the SCIENCE object.
 - In **dual-field mode** it must always be `SETUPFILE`. The coordinates given in `COU.AG.ALPHA/DELTA` can either be the fringe-tracking target coordinates or the coordinates of a different guide star (Sect. 2.2.2).
- COU.AG.ALPHA/DELTA: Coordinates of the Coudé guide star. These keywords should only be specified if the keyword `COU.AG.GSSOURCE` is set to `SETUPFILE`. Otherwise they should be 0.0 as the Coudé Guiding will use the science target to guide on.

- `COU.GS.MAG`: Coudé guide star Visual (MACAO, NAOMI) or K-band (CIAO) magnitude. This should **always** be specified. In the case of a variable star the faintest magnitude should be given.
- `COU.AG.PMA/PMD`: RA/DEC proper motion of the Coudé guide star in arcsec/year. These keywords should only be specified if the keyword `COU.AG.GSSOURCE` is set to `SETUPFILE`. Otherwise they should be 0.0 as the Coudé Guiding will use the science target to guide on.

3.2 Observing templates

3.2.1 GRAVITY_dual_obs_exp.tsf

Parameter	Range (<i>Default</i>)	Label
<code>DET2.DIT</code>	0.3 1 3 5 10 30 60 (<i>0.3</i>)	SC frame integration time (DIT in s)
<code>DET2.NDIT.OBJECT</code>	10...300 (<i>25</i>)	Number of science target frames (NDIT)
<code>DET2.NDIT.SKY</code>	10...300 (<i>25</i>)	Number of sky frames (NDIT)
<code>SEQ.RELOFF.X</code>	-1000..1000 (<i>0.0</i>)	Sequence of SC relative RA offsets (mas)
<code>SEQ.RELOFF.Y</code>	-1000..1000 (<i>0.0</i>)	Sequence of SC relative DEC offsets (mas)
<code>SEQ.HWPOFF</code>	-180..180 (<i>0.0</i>)	Sequence of HWP offsets (deg)
<code>SEQ.SKY.X</code>	-4000...4000 (<i>2000</i>)	Sky offset in RA (mas).
<code>SEQ.SKY.Y</code>	-4000...4000 (<i>2000</i>)	Sky offset in DEC (mas).
<code>SEQ.OBSSEQ</code>	O S (<i>O S</i>)	Observing sequence of science (O) and sky (S) exposures.

3.2.2 GRAVITY_dual_obs_calibrator.tsf and GRAVITY_single_obs_*.tsf

All remaining observing templates, *GRAVITY_dual_obs_calibrator.tsf*, *GRAVITY_single_obs_exp.tsf* and *GRAVITY_single_obs_calibrator.tsf*, use the same set of keywords.

Parameter	Range (<i>Default</i>)	Label
<code>DET2.DIT</code>	0.3 1 3 5 10 30 60 (<i>0.3</i>)	SC frame integration time (DIT in s)
<code>DET2.NDIT.OBJECT</code>	10...300 (<i>25</i>)	Number of science target frames (NDIT)
<code>DET2.NDIT.SKY</code>	10...300 (<i>25</i>)	Number of sky frames (NDIT)
<code>SEQ.HWPOFF</code>	-180..180 (<i>0.0</i>)	Sequence of HWP offsets (deg)
<code>SEQ.SKY.X</code>	-4000...4000 (<i>1000</i>)	Sky offset in RA (mas).
<code>SEQ.SKY.Y</code>	-4000...4000 (<i>1000</i>)	Sky offset in DEC (mas).
<code>SEQ.OBSSEQ</code>	O S (<i>O S</i>)	Observing sequence of science (O) and sky (S) exposures.

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 300s. For the best accuracy it is suggested to use a similar number of frames for science and sky.

- **SEQ.RELOFF.X/Y**: Relative offset of the science fiber, while keeping the fringe-tracking object fixed. The science fiber 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 fiber 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**. For example for a sequence of **SEQ.OBSSEQ = 0 S 0 0 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.
- **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. These offsets will move the actuator in the given directions.
- **SEQ.OBSSEQ**: Observing sequence of science (*O*) and sky (*S*) exposures. Any sequence is possible as long as the total execution time does not exceed the limits discussed in section 2.3.2. As a tradeoff between efficiency and accuracy it is suggested to use a sequence like *O S O*.

3.2.4 GRAVITY_dual_obs_swap.tsf

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 (<i>Default</i>)	Label
SEQ.FT.MODE	AUTO 1 2 7 9 (<i>AUTO</i>)	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. 2.2.10).

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