ELT - MICADO

Phase B

Operational Concept Description

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1 Scope

The present document defines the Operational Concept for MICADO. The intended audience is Observatory staff who are new to MICADO and will be supporting observations, and also the science users in the community. The aim is to provide a clear and concise overview of how MICADO will be used. This document approaches MICADO from the operational (functional) perspective, and will form the basis of the future Operations Manual. It includes a description of some calibration tasks related to the observations, but explicitly excludes any maintenance tasks.

Throughout this document, SCAO refers to the AO capability developed jointly by the MICADO and MAORY consortia; MCAO refers to the AO capability developed by the MAORY consortium. The MICADO operational concept does not distinguish between MCAO with just NGS or using also LGS.

2 References

2.1 Applicable documents

RD Nr	Doc. Nr	Doc .Title	Issue	Date
AD1	ESO-193104	Top Level Requirements for ELT-CAM	2	30.03.2015
AD2	ESO-244537	MICADO (ELT-CAM) Technical Specification	1	16.09.2015
AD3	ESO-257871	MICADO (ELT-CAM) Statement of Work	1	16.09.2015
AD4	64364/ESO/15/67002/JSC	Collaboration Agreement		18.09.2016

2.2 Reference documents

The following reference documents (RD) contain useful information relevant to the subject of the present document.

RD Nr	Doc. Nr	Doc .Title	Issue	Date
RD1	ELT-PLA-MCD-56300-0005	MICADO Executive Summary	1.0	25.01.2016
RD2	ELT-TRE-MCD-56305-0001	MICADO Science Report		
RD3	ELT-PLA-MCD-56301-0003	Observing Use Cases for MICADO		
RD4		MICADO Template Manual		
RD5		MICADO Calibration Plan		

Acronyms

AD	Applicable Document
ANF	Antofagasta
AOWFC	Adaptive Optics Wave-Front-sensor Camera
CAD	Computer-Aided Design
CIDL	Configuration Item Data List
CMMS	Computerized Maintenance Management System
Co-Pi	Co-Principal Investigator
CPL	Common Pipeline Library
CRE	Change Request
DD	Deliverable Document
DFS	Data Flow System
DICB	Data Interface Control Board
DRD	Document Requirements Definition
E-ELT	European Extremely Large Telescope
EMC	Electromagnetic Compatibility
ESO	European Southern Observatory
ETC	Exposure Time Calculator
FEA	Finite Element Analysis
FMECA	Failure Mode Effect and Criticality Analysis
FDR	Final Design Review
GTO	Guaranteed Time Observations
HDRL	High Level Data Reduction library
ICD	Interface Control Document
ICS	Instrument Control Software
IRM	Integration Readiness Meeting
KM	Key Milestone
KOM	Kick Off Meeting
LPO	La Silla Paranal Observatory
LRU	Line Replacement Unit
M4	4^{th} mirror in E-ELT
M5	5^{th} mirror in E-ELT
MAIT	Manufacturing Assembly Integration and Test
MAORY	Multi-conjugate Adaptive Optics RelaY
MCAO	Multi-conjugate Adaptive Optics
MICADO	Multi-AO Imaging Camera for Deep Observations

MTBF	Mean Time Between Failure
OCD	Operations Concept Description
PAE	Preliminary Acceptance Europe
PA	Product Assurance
PAC	Provisional Acceptance Chile
PDR	Preliminary Design Review
PI	Principal Investigator
POA	Paranal or Armazones
RAM	Reliability Availability Maintainability
RD	Reference Document
RFW	Request for Waiver
RTC	Real-Time Computer
QA	Quality Assurance
SCAO	Single-conjugate Adaptive Optics
SCL	Santiago de Chile
SOW	Statement of Work
SV	Science Verification
TBC	To Be Confirmed
TBD	To Be Defined
TCS	Telescope Control Software
TRL	Technology Readiness Level
TRM	Test Readiness Meeting
TS	Technical Specification
VLT	Very Large Telescope
WBS	Work Breakdown Structure
WFRTC	Wave-Front Real-Time Computer
WP	Work Package

3 Overview

MICADO is the Multi-AO Imaging Camera for Deep Observations. It will equip the E-ELT with a first light capability for diffraction limited imaging at near-infrared wavelengths. The instrument is optimised to work with the laser guide star multi-conjugate adaptive optics module MAORY. It also includes a jointly developed single-conjugate adaptive optics mode that uses just a single natural guide star, with which it will, if needed, be able to function in a “stand-alone” mode. This mode involves operating with the SCAO wavefront sensor but without the full MAORY bench.

3.1 Instrument

The key capabilities of MICADO exploit the most unique features of the E-ELT: sensitivity and resolution, precision astrometry, and wide wavelength coverage spectroscopy.

The primary observing mode is imaging, with a focus on astrometry. To achieve this, the instrument is supported above the Nasmyth platform in a gravity invariant orientation, includes an optical path comprising entirely of fixed mirrors, uses a state-of-the-art atmospheric dispersion corrector, and has a dedicated astrometric calibration plan and data pipeline. The array of detectors at the focal plane enables imaging of a small field of about 20arcsec with a fine pixel sampling that is especially useful in very crowded fields or at short wavelengths; or a large field, which is nearly 1arcmin across, with a coarser pixel scale that still fully samples the H- and K-band diffraction limit. In both cases, a wide selection of broad and narrow band filters are available. This mode will provide comparable sensitivity to the James Webb Space Telescope at 6 times better spatial resolution, and enable proper motions as small as 5km/s to be measured at distances of up to 100kpc.

High contrast imaging is enabled via a classical configuration of coronagraph and Lyot stop, and is envisaged to make use of angular differential imaging techniques. Its novel feature will be the very small angular scales on which is will be possible to detect exoplanets.

The spectroscopic mode is optimised for compact objects, and emphasises simultaneous wavelength coverage at moderately high resolution: covering H and K bands together at a spectral resolution exceeding R~15000 for slit widths less than 10mas (matching the FWHM of the diffraction limited PSF in H-band). Slit widths suitable for compact and extended objects will be provided.

Time resolved imaging is enabled by defining suitable windows on the detector which enable the frame rate to be in the range 1-100Hz, and providing precise time stamping of the frames.

3.2 Science

MICADO has the potential to address a large number of science topics that span the key elements of modern astrophysics: using its wide field, high resolution, and remarkable sensitivity to study the environment and internal structure of galaxies and AGN at high redshift; using its ability to perform ac-curate photometry in highly crowded fields to derive star formation history of local galaxies through studies of spatially resolved stellar populations; using the exquisite astrometric accuracy to trace the orbits and internal kinematics of nearby galaxies and star clusters, and to probe ever closer to the central massive black hole in the Galactic Centre; using its coronagraphic mode to characterise planets at very small separations from their host star, and even to directly image planets with radial velocity measurements; using high resolution spectra to measure multiple emission line ratios of supernova and AGN at high redshift or to fit continuum absorption features in the cores of elliptical galaxies in the early universe; using the high time resolution to probe the cause of the pulsations in anomalous x-ray pulsars and magnetars.

The science drivers for MICADO cover six main themes: galaxy evolution at high redshift, black holes in galaxy centres (including the Galactic Center), resolved stellar populations (including photometry in galaxy nuclei, the IMF in young star clusters, and intermediate mass black holes in globular clusters), characterisation of exoplanets and circumnuclear disks at small angular scales, the solar system, and time resolved phenomena around neutron stars and stellar mass black holes.

4 Observing Modes and Instrument Configuration

MICADO is a workhorse instrument for the E-ELT. Therefore, while its primary focus is imaging, it provides a high level of flexibility for more specialist modes that are not necessarily offered by other E-ELT instruments, and that may lead to observations with a major scientific impact. The operational concept tries to find a balance between keeping the operation and calibration of the instrument relatively simple while allowing it to encompass a wide variety of observational options. This is achieved by limiting the configuration options for the various observing modes to those that make most sense. Much of the complexity is handled by the preparation tools described in Section 4.1, so that the remaining configuration is limited to more usual issues such as choice of filter and exposure time.

4.1 Proposal & Observation Preparation

It is expected that proposal and observation preparation will follow a scheme similar to that currently used for VLT instruments. A number of tools will be provided to assist both in Phase 1 (i.e. proposal preparation) and Phase 2 (i.e. observation preparation). These tools, described below, refer to the focal plane arrangement illustrated in Figure 1.

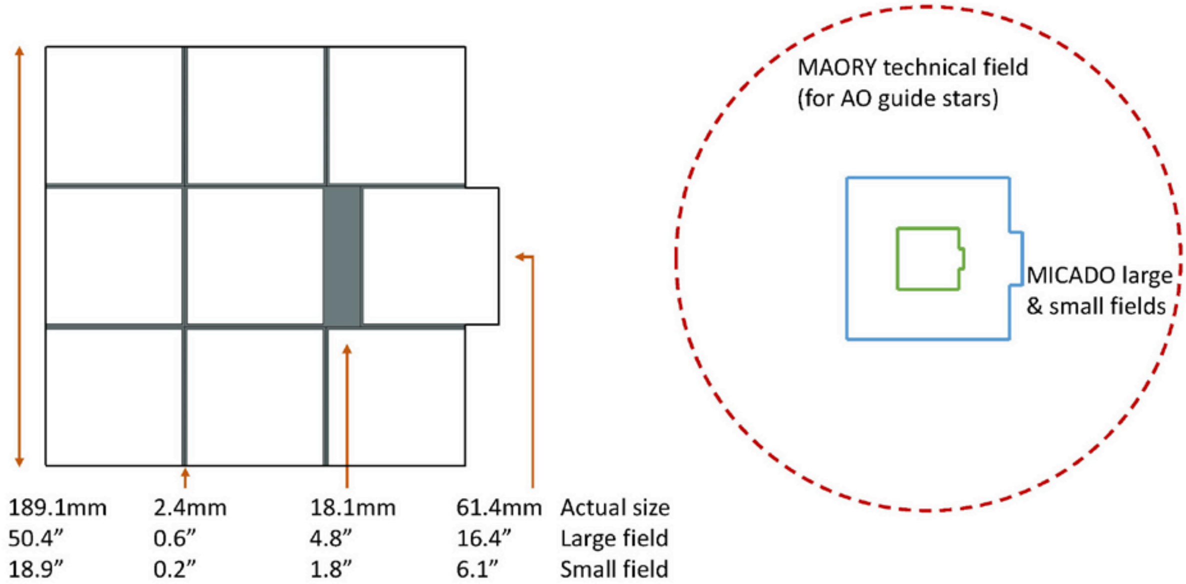

Figure 1. Left: the focal plane arrangement for the 9 MICADO detectors (gaps due to detector housings are shown in grey). The numbers given below refer to the actual size of the focal plane array (top row), the projected angular size when using the larger 4mas pixel scale (middle row), and the projected angular size for the smaller 1.5mas pixel scale (bottom row). Right: respective sizes and positionings of the MICADO field of view for the two pixel scales, and the technical field of MAORY within which NGS are selected. When dithering, the NGS must be beyond the full extent of the dithered MICADO fields and within the overlapping region of all the dithered technical fields.

- Exposure Time Calculator: a simple, standard tool analogous to those available for VLT instruments. This should estimate S/N for unresolved or extended sources for a given integration sequence, and also indicate some important timescales (e.g. time in which brightest star saturates, time to background limited performance, total times for exposures & overheads).
- SimCADO: a simulator to assess S/N in complex situations (including high contrast imaging, and time resolved imaging), astrometric performance, or other data quality metrics; and to optimise observation strategy. For some programmes, the standard Exposure Time Calculator will be sufficient; other programmes may benefit from, or even require, the use of SimCADO.
- Observation Configuration:
  - Sequence of dithers (rotational & lateral) & sky offsets. The focal plane layout, including distortions, gaps between detectors and a bad pixel map, are necessary for this tool, to allow for precise positioning (e.g. of specific objects in good areas or of bright objects in the gaps). The tool should allow manual or automatic configuration of dithers. For sky offsets, the AO loop is expected to be open in the offset pointing (but is it practical to offer the option to close the AO loop with a different set of guide stars?).
  - For spectroscopy, the format of the spectral traces needs to be known; some way to indicate which wavelengths ranges are compromised by the detector gaps; and being able to set dithers in order to work through a sequence of targets that are accessible with the same set of guide stars; pre-imaging may be useful.
  - SCAO/MCAO natural guide stars. Requires magnitude and position constraints for guide stars (via direct link to an external catalogue/s), but also that guide stars are all accessible for every dither position. It is assumed that the AO loop remains open for sky offsets, which are expected to be large)
  - For high contrast imaging (mostly with SCAO, but maybe also with MCAO?), pupil tracking is used. So it is useful to see the parallactic angle etc as a function of time, as well as any constraints from the guide stars.
  - Secondary guiding. Requires definition of which stars on the science detectors will be used (TBC: whether their position needs to read faster than the frame rate).
  - Generating basic finding charts (for science targets and guide stars).
- MCAO performance [provided by MAORY]: provides estimation of strehl and FWHM (perhaps also a more complete description of the PSF shape) across the field for a given NGS configuration.
- SCAO performance: provides an estimation of the strehl and FWHM (perhaps also a more complete description of the PSF shape) on-axis and off-axis for the selected NGS.
- Mosaicing tool (perhaps as part of the Observation Configuration): generate multiple observing blocks which may require different sets of guide stars, but which are linked in the sense that the data should be combined so as to cover an extended field.
- HTRA tool: a specific instance of the Observation Configuration tool above that defines windows for science and reference targets, and provides additional information about frame rates, dead times, etc, for time resolved observations with frame rates of 1-100Hz.
- Non-sidereal observations: requires accepting input from external tools (linking directly or reading, for example, an ephemeris table from a file produced by such a tool) in order to automatically generate a set of possible guide star configurations for moving targets. The role of this tool for time critical observations, such as when the AO guide star is a satellite of a giant planet, needs to be assessed since that operational model is likely to be obsolete with LGS-MCAO.

Phase 1: the user submits a proposal that has been prepared using either SimCADO or the ETC to estimate the time required for the programme. As for other AO instruments, the user should already at this stage identify which natural guide stars are to be used with each target field. It is up to the user to define suitable guide stars, and to check the expected AO performance across the field of view, using the tools provided.

Phase 2: the details of all the OBs will be configured using the P2PP tool provided by ESO. This will involve filling in templates based on the information provided at Phase 1 as well as attaching a configuration file created by the preparation tools. Specific points are noted below:

- Every separate OB will require a configuration file from the preparation tool.
- It should remain possible for a user to generate plain text OBs from their own scripts as long as they match the required format, include a reference to the configuration file, and pass any consistency checks
- The AO configuration (MCAO vs SCAO, and selection of guide stars) cannot be changed between templates within a single OB.
- Only one observing mode (see Section 4.5) can be used in a single OB. This is because templates may require different guiding or AO modes which are set during acquisition.

4.2 Guiding Options

There are several guiding options that can be configured, and which determine how MICADO is controlled during an observation. To ensure a common understanding of these terms in this document, they are summarised below, together with the typical situations in which they might be used (detailed usage is according to the templates which are listed in Section 5).

4.2.1 Focal Plane Rotation

For most observations, it is required that the orientation of the sky on the science detectors remains fixed: field stabilisation. This is achieved by rotating the entire MICADO cryostat at an appropriate rate, and is set as the only option available in most templates. However, in some circumstances, it is preferred that MICADO rotates so that the pupil (e.g. the wavefront aberrations from the telescope optics, and the image of the spider in the telescope) maintain a fixed orientation on the science detectors. This option for pupil stabilisation is only offered in a limited number templates.

Field stabilisation	The standard focal plane rotation mode, in which the orientation of the field (sky) on the instrument focal plane remains constant. In this mode, secondary guiding (see Section 4.2.3) is an option.
Pupil stabilisation	In this mode, the orientation of the pupil on the instrument focal plane remains constant. This is used for (i) the pupil imaging mode (for alignment purposes), or (ii) Angular Differential Imaging (ADI), the primary application of which is for high contrast imaging with the coronagraph.

Table 1: Summary of focal plane rotation modes.

4.2.2 Differential Tracking

This affects how the pointings of the instrument and AO system track across the sky. Most observations follow a fixed point on the sky and so track at the sidereal rate. However, solar system bodies move at a measurable rate with respect to the sky and so require non-sidereal tracking. There are various possibilities, depending on the AO mode being used:

- SCAO and MCAO: the science target moves non-sidereally while the AO system uses fixed stars as reference sources. This is expected to be the only non-sidereal option offered for MCAO.
- SCAO only: the science target is the AO reference source, and it moves non-sidereally.
- SCAO only: the science target and the AO reference source are different objects which both move non-sidereally.
- SCAO only: the science target does not move with respect to the sky, but the AO reference source does move non-sidereally.

These require different combinations of adjustment to the telescope tracking and compensation with the AO system which depend on the details of the instrument and AO design.

The most useful way to incorporate this functionality into the templates has not yet been decided. Note that while, in principle, the tracking mode is independent of the focal plane rotation mode, non-sidereal tracking is only offered with field stabilisation.

Sidereal tracking	The standard sky tracking mode, in which the telescope (+instrument) and AO system follow targets at a fixed right ascension and declination.
Non-sidereal tracking	This covers all situations in which the AO guide (or tip-tilt) star is moving relative to the science target. Typically, it is the science target that is moving with respect to the sky. But with SCAO, the sky coordinates of the AO guide star may also/instead be changing.

Table 2: Summary of differential tracking modes.

4.2.3 Secondary Guiding

The telescope provides a distortion precision (including plate scale and rotation) that corresponds to a drift of up to approximately 0.5 pixels at the edge of the MICADO field on a 5 minute timescale; and a repeatability between observations corresponding to 3.5 pixels. There are two situations where this may be insufficient:

- There may be a requirement to maintain a more precise stability during observations;
- A new observation may have to be obtained with the same plate scale as a previous one.

If there are enough stars (currently it is expected that there will need to be a minimum of 3 stars with K_{Vega} ~ 21mag or brighter) then the position of those stars on the science detectors can be monitored and – after appropriate correction of instrument distortion – used to provide feedback about centring, plate scale, and rotation. This is called secondary guiding.

When an observation block requires secondary guiding, it must be configured in advance using the appropriate observation preparation tool.

A summary of when secondary guiding can be used is given below; a more detailed assessment of when it might be needed is on-going. In practice, centroiding on the selected stars can be achieved either by setting small windows around the stars and reading these out interleaved with the science exposure (see Section 4.4) or by accessing the individual non-destructive reads during a long integration (which then does not make use windowing).

Observation mode	*Secondary guiding option*
Standard Imaging	Can be used if there are appropriate stars (but note that at high galactic latitudes one may expect to find on average only 2-3 such stars in a 1arcmin field). It is unlikely that the colour of the star plays a role since, at the positioning precision required in this mode, this will be compensated by the ADC.
Astrometric Imaging	Can be used if there are appropriate stars. The impact on a star's position of its colour and the residual atmospheric dispersion after the ADC needs to be assessed before confirming this option.
Coronagraphic Imaging	Cannot be used. Instead the central star itself (the image of which is modified by the coronagraph) is used to provide centring feedback only.
Time Resolve Imaging	Can be used if there are appropriate stars, and might be needed to ensure that science and reference sources remain on clean areas of the detectors.
Slit spectroscopy	Cannot be used.

Table 3: Summary of secondary guiding options.

4.3 Adaptive Optics

MICADO can be used with 2 AO systems: SCAO and MCAO. In addition, it can be used without AO, taking the image quality provided directly by the guide cameras and control system of the telescope. The strengths and limitations of these 3 modes are described below.

4.3.1 Single conjugate adaptive optics

SCAO is the simplest and most robust form of adaptive optics. It uses a single natural guide star to provide AO correction in the direction of the guide star, but the performance deteriorates with distance from the guide star due to anisoplanatism. The wavefront sensing is done at optical wavelengths, so the light to the wavefront sensor is split off by a large dichroic that covers the whole MICADO field of view. And the guide star has to be in the range V ~ 7-16 mag. The primary rationale for this mode is to provide the highest strehl ratios for the most effective coronagraphic imaging in order to achieve high contrast. For this, it will normally be used in pupil stabilisation mode (see Section 4.2.1).

SCAO can be used for other types of observations. But, to ensure flexure is within tight tolerances, the guide star has to remain within a few arcsec of the field center. And this has implications on the observing techniques and applications.

The wide field of MICADO will enable one to image science targets more than 25" off-axis. However, anisoplanatism has to be taken into account when estimating performance on the science target. And, because the guide star must remain close to the centre of the field, rotational rather than translational dithering will be needed.

Time resolved observations using windows are in principle possible, if there is a suitable guide star and the translational dithers can be kept small. But anisoplanatism has to be taken into account for comparative photometry of the science and reference sources.

Non-sidereal tracking is very versatile with SCAO, although keeping the guide star close to the center of the field has an impact on observing technique: it requires a sequence in which the science target is held still on the science detectors for a short while, followed by a jump to a new position.

Spectroscopy has limited use with SCAO for 2 reasons: (i) the slit is in the center of the field, so the science target must also be the guide star; and (ii) the ADC is located after the slit, so the slit must be aligned along the parallactic angle. The spectroscopic mode is optimised for compact sources, but with SCAO the science target should be relatively bright. However, there may be applications if the aim is to obtain spectra of a companion or circumnuclear material that is either faint or at small angular separations.

4.3.2 Multi conjugate adaptive optics

MCAO is a more complex form of adaptive optics that uses multiple (4-6) laser guide stars as well as 3 natural guide stars to provide AO correction that is fairly uniform across the entire field of view of MICADO. The wavefront sensing is done at near-infrared wavelengths in order to benefit from image sharpening. This means that the stars, which are located in a technical field out to a radius of 1.3arcmin can be as faint as H ~ 21 mag. Because they are outside the MICADO field of view, the light is picked off using small mirrors. The faint magnitude limit and the wide technical field mean that sky coverage for good performance is moderately high.

A more complete description of how MCAO can be used is given in the MAORY documentation. Only a brief summary of a few key points in the context of the MICADO observing modes is given here.

MCAO is the primary choice of adaptive optics for standard imaging, astrometric imaging, and time resolved imaging – because the PSF is fairly uniform across the field. This is important not just for extended science targets which cover the field, but also if the science target is compact because it provides an opportunity to exploit PSF information from faint stars around the science target.

Coronagraphic imaging would not typically be used with MCAO because the pupil stabilisation mode will lead to difficulties with keeping the NGS pick-off arms on the guide stars. However, with some targets (e.g. QSOs), coronagraphic imaging is foreseen with field stabilisation. One cannot then apply special processing routines to enhance the contrast, but one gains from the suppression of flux from the unresolved central point source.

Spectroscopy is much more flexible with MCAO because the restriction that the science target must be bright enough to use as a guide star is lifted. However, the slit must still be aligned along the parallactic angle. The typical usage would involve either nodding a compact object back and forth along the slit (length 3-5arcsec), or dithering to different positions in the slit combined with offsetting to sky.

4.3.3 No-AO / seeing limited

There may be situations (especially during commissioning, but also during the initial steps of an observation sequence) when it is useful to take data without using either SCAO or MCAO adaptive optics correction. In these cases the image quality is that provided by the telescope guide cameras and control systems, which can be considered ‘seeing limited’.

Because the field of view with the large pixel scale is nearly 1arcmin, there would be ~100 resolution elements across the field (for a FWHM of 0.5arcsec). But the PSF would cover more than 100 pixels. In these circumstances, the only observing mode that makes sense is standard imaging, most likely in a technical or calibration role. And so no-AO seeing limited observations are only offered for that mode.

4.4 Detector Modes

MICADO has an array of 3x3 detectors which are arranged as shown in Figure 1. Each detector has 4096x4096 pixels that are read out via 64 simultaneous channels, each channel having 64x4096 pixels. It should be noted that the pixels in each channel are read sequentially, which has implications for time resolved imaging as described in Section 4.5.4.

4.4.1 Slow and Fast Read Modes

In the normal slow read mode, the minimum full frame exposure time is 2.6sec (the time to read 64x4096 pixels at 100kHz pixel rate). As shown in Table 4, during this time and assuming reasonable AO performance, any star brighter than ~15.5 mag (Vega) that is observed through a broad band filter will saturate. For the smaller pixel scale and a 1% narrow band filter, Table 5 shows that saturation occurs only for stars that are about 2 and 3 mag brighter respectively. But the use of narrow band filters implies a significant loss in S/N, limiting sensitivity.

As such, a fast read mode is also available which means that with a broad band filter, saturation occurs at 12-12.5 mag (and ~9 mag for a narrow band filter). While this mode is associated with a higher noise in short exposures, for longer background limited exposures, the impact on the data is small. But the fast read mode is accompanied by an extreme requirement on cooling, and so may be offered in only a restricted sense. This could be a limit to the total number of channels that can be read, e.g. a single detector, or a few channels on each detector.

Read mode	Pixel rate	Minimum DIT	Broad band saturation magnitude (Vega)		
			K (40% strehl)	H (20% strehl)	J (5% strehl)
Slow	100 kHz	2.6 sec	15.2	15.7	15.4
Fast	2 MHz	0.13 sec	12.0	12.5	12.1

Table 4: summary of detector read modes. Saturation refers to the Vega magnitude for which the counts in the central pixel of a PSF exceed 50000 in the full frame minimum DIT, when observed with a broad band filter, and assuming 40/20/5% strehl ratio in K/H/J-band.

Read mode	H-band saturation magnitude (Vega) for 20% strehl			
	4mas pixel scale		1.5mas pixel scale	
	Broadband filter	Narrow (1%) filter	Broadband filter	Narrow (1%) filter
Slow	15.7	12.6	13.7	10.5
Fast	12.5	9.3	10.4	7.3

Table 5: Saturation magnitude in H-band for different filter & pixel scale configurations.

4.4.2 Windowing

Windowing is available, and can be applied in two ways.

It is possible to set specific windows, and only these are read out, while all other pixels are continually reset. This is essential for high time resolution applications, in which case the windows are read out in fast mode. For example, a 1” x 1” window requiring 256 x 256 pixels crosses 4 readout channels. 16000 pixels are read in each channel, which means a frame rate for the window of 125Hz is achieved. If multiple windows are set – either covering different readout channels of the same detector, or on another detector – they can be read out simultaneously and so do not affect the window frame rate. For this application, precise (<1msec) timestamps are provided for each exposure. Windowing may also be useful for sparse aperture masking applications. In order to remove 10Hz vibrations, the exposure time should be no longer than 50ms. With the fast mode, this can be achieved with a window size of 6” with the 4mas pixel scale.

The second option is to define windows that are read out via a single additional channel and therefore interleaved with full frame exposures. The interleaving can be defined so that the windows are read out multiply during a single full frame exposure. But can they be clocked at a different speed (no)? This may be useful for secondary guiding, or if there are a few bright stars in the field that would otherwise saturate. Need to understand this mode better.

4.5 Instrument Modes & Configuration Options

Common to all observations is the preparation to select the AO mode and pick the guide star/s (and, if secondary guiding is required, select suitable stars in the field of view), checking that they are all accessible at all dither positions and orientations while also ensuring that the location of the detector gaps and bad pixels is appropriate. These tasks are assisted by the preparation tool as described in Section 4.1.

There are 3 AO modes available for MICADO:

SCAO	Uses a single (bright) NGS to reach the highest strehl ratios over a field that is defined by anisoplanatism, and with limited sky coverage. As such, it is optimal for coronagraphic imaging.
MCAO	Uses multiple LGS and 3 (faint) NGS to achieve uniform performance over the whole field of view of MICADO, with good sky coverage.
No-AO	This seeing limited mode accepts the image quality by the telescope guide cameras and no additional guide stars are needed. It is expected to be used mainly as a technical or calibration mode.

There are 4 types of dithers/offsets available for MICADO:

Small dithers	Shifts of +/-0.3arcsec to move targets onto different pixels (for reducing systematics), performed in closed loop and associated with the shortest overheads of around 1-2sec.

Large dithers	Shifts of up to 60arcsec from the initial pointing (in practice, it is expected that these dithers will normally be within 15arcsec of the initial pointing to ensure a large overlap between frames). Enables the background to be derived from the object frames via, for example, a running median; and allows regions of sky that fall in the gaps between detectors to be covered. This involves opening the AO loops and offsetting the telescope and so is associated with a larger overhead of 10-15sec. Short large dithers of 1-2arcsec will be used in spectroscopic mode for nodding back and forth along the slit.
Sky offsets	Shifts in the range 1-15arcmin from the initial pointing to take separate sky frames. The AO loop is open at the offset position (because the guide stars may no longer be accessible), and re-closes on the return. The overhead for these will be large, and is likely to exceed 30sec.
Rotational dithers	These are envisaged primarily for SCAO where options for translational dithering may be limited; on the other hand, with MCAO, the NGS probes may constrain the allowed rotation angles. The time taken for a rotational dither depends on the angle, and is limited by the rotational speed of the cryostat.

4.5.1 Standard imaging

The standard imaging mode of MICADO is straightforward. The main configuration parameters to set are the pixel scale, filter, and exposure time. While the choice of AO mode (SCAO, MCAO, or no-AO) and dithers/offsets (which may depend on the AO mode) strongly affect the data quality, they have no impact on the configuration of standard imaging – finding a set of dithers and guide stars that are consistent with each other is handled by the preparation tool. Secondary guiding is optional and, if need, is defined with the preparation tool. Standard imaging is offered only with field tracking.

The pixel scales are 1.5 mas and 4 mas giving fields of view of ~19 arcsec and ~50 arcsec respectively. The smaller pixel scale is designed to provide sufficient over-sampling so that, even at the shortest operational wavelength of 0.8µm, pixelisation does not impact the measured PSF shape. This scale is suitable for working in very crowded fields, or fields that include bright targets for which it is helpful to distribute the flux over more pixels. The larger pixel scale accesses a wider field that optimally exploit the MCAO capability of MAORY while still providing Nyquist sampling of the PSF at wavelengths longer than 1.3µm (i.e. H- and K-bands, and marginally the J-band). Both pixel scales are available for all imaging filters without restriction.

There is a wide range of filters to choose from, which are mounted in 2 large wheels relatively close to, but not in, the pupil plane. When a filter in one wheel is chosen, the other is set to its open position. The selection of filters available is given in Table 11 and Table 12.

The following ‘hidden’ mechanisms are configured automatically based on the choice of pixel scale and filter:

Entrance focal plane mask	Set to the small field for the 1.5mas pixel scale and large field for the 1.5mas pixel scale.
ADC	Set to normal tracking mode (astrometric precision ~1mas).
Pupil wheel	Set according to filter (for longer wavelengths background is minimised with a penalty on throughput; for shorter wavelengths throughput is maximised since background is low).

4.5.2 Astrometric imaging

The astrometric imaging mode of MICADO has similar options as for standard imaging – pixel scale, filter, exposure time – and differs primarily in that it requires more complex data processing. Similarly, the choice of AO mode (SCAO vs MCAO only) and dithers/offsets are defined with the preparation tool and have no impact on the configuration of the mode although they may strongly affect the astrometric precision that can be achieved. Secondary guiding, if required, is also defined with the preparation tool.

As for standard imaging, the pixel scales are 1.5 mas and 4 mas giving fields of view of ~19 arcsec and ~50 arcsec respectively. The smaller pixel scale is associated with the most stable optical path: all the mirrors are fixed, and the only movable optical elements in the path are the filter, ADC, and cold stop. The larger pixel scale is also very stable, differing only in that 2 flat fold mirrors are moved into the path to bypass the 4 mirrors comprising the zoom optics (since these are fixed). The choice depends on the preference for better sampling, for example in very crowded fields, versus larger field size,

The available filters are the same as for standard imaging, given in Table 11 and Table 12.

The hidden mechanisms are configured automatically, as for standard imaging, according to the choice of pixel scale and filter.

[in what ways might this mode differ from standard imaging, e.g. would one typically expect to take lots of short exposure images?]

[need a short summary here of the main differences in data processing, e.g. applying a distortion model (and a physical model) of the ADC offline to enable more precise stacking of images]

4.5.3 Coronagraphic Imaging

The coronagraphic imaging mode (also known as high contrast imaging) includes sparse aperture masking because they are both concerned with making measurements close around a bright point source. Because of the techniques involved, there are restrictions to the configuration that apply to all, or at least some of, the options listed below in Table 6.

For this mode, which is concerned only with detecting structures close to the parent star and primarily within the central arcsec, the field of view may have to be limited to about 6”. This corresponds to a single detector with the 1.5mas pixel scale, or a window of 1500 pixels for the 4mas pixel scale. This restriction may be required to ensure a high image quality in the pupil. The first case provides better sampling of the structures in the PSF and reduces the counts per pixel for the brightest sources; the latter case enables faster exposure times of 50ms (with the fast read mode).

The location of the ADC is just before cold pupil, i.e. after the entrance mask where the focal plane coronagraphs are mounted. This means that to ensure the PSF is sufficiently point like, rather than elongated by atmospheric dispersion, broad-band filters cannot be used with the focal plane coronagraphs. This restriction does not apply to the pure pupil plane coronagraphy or sparse aperture masking configurations.

Dithering is not possible with focal plane coronagraphy since the star must remain behind the coronagraph which is always on-axis; instead dedicated sky background exposures are taken. For the pure pupil plane options, dithering is possible because the masking or apodisation applies equally to all objects in the field.

There are 4 options, for each of which the basic configuration is fixed and only the filter needs to be chosen.

Table 6: coronagraphic and sparse aperture masking options.

Focal plane coronagraphy with SCAO	There are 3 coronagraphs from which to choose, and all are used in pupil stablisation mode, with a Lyot stop in the pupil wheel. Broadband filters are not offered. It may be possible to configure this as a 'mixed mode' to use an APP in the pupil instead of the Lyot stop.	For bright stars with exoplanets or circumstellar material.
Pupil plane coronagraphy with SCAO	Used in pupil stabilisation mode (since the APPs are in the pupil wheel), and with an empty mask in the entrance focal plane.	For bright stars with exoplanets or circumstellar material.
Sparse Aperture Masking with SCAO	There are 2 SAMs from which to choose, and all are used in pupil stabilisation mode (since the SAMs are in the pupil wheel), with an empty mask in the entrance focal plane. Broad band filters are not offered.	For bright stars with exoplanets or circumstellar material.
Focal plane coronagraphy with MCAO	There are 3 coronagraphs from which to choose, and all are used in field stabilisation mode, with the normal undersized cold stop. Broadband filters are not offered.	For faint sources, such as AGN

Typically 3 sets of exposures are obtained:

- Coronagraphic data, where the star is attenuated by the coronagraph. This requires precise centering of the star to be maintained throughout an observation sequence. These data include the longest sequences of exposures since it is necessary for the field to rotate through a significant angle with respect to the pupil for the data processing to be successful.
- Photometric data, where the star is moved away from the coronagraph in order to measure its total flux (in order to calibrate the circumstellar flux in the coronagraphic data). This may be performed several times during an observation block in order to monitor the photometric stability.
- Sky data, where the star is moved out of the field of view to obtain background exposures.

In addition, pupil imaging may be performed to check alignment of the mask in the pupil. This is considered a calibration rather than a distinct observing mode.

4.5.4 Time Resolved Imaging

The aim of this mode of to obtain long (minutes to hours) sequences of small frames taken at a rapid rate (1-250Hz) of the target source and several reference sources. The frames need to be synchronised between sources and assigned a time stamp, with a precision of <1ms at the fastest frame rates. The data are then used to derive a light curve of the target. For brighter targets, one can measure aperiodic light curves. Periodic light curves of much fainter targets can be found by folding the data appropriately.

Preparation for this mode is more complex than for standard imaging because it requires setting windows on target and reference sources for synchronised reading at rapid rates; and, optionally, additional windows for background measurements to enable dithering. One critical issue is that the frame rate is directly related to the window size, which must therefore be set appropriately as described in Section 4.4. Once this is done, the remaining configuration options are straightforward. As for standard imaging, one can select the pixel scale and the filter; however one would normally expect to the use the large pixel scale (using the wider field to increase the number of reference sources, to be able to read the same angular size region in a faster time, and to increase the sensitivity at these fast rates by reducing the sampling) and choose a broad band filter (to increase sensitivity)

An important aspect of this mode is that every frame is used individually. This means that the regions of the detectors where the windows are defined must be responsive and cosmetically clean, since there is no option to remove systematics afterwards by combining shifted frames. As such, dithering is unlikely to be a useful technique, and may even be detrimental since it will cause the time sequence to be interrupted. On the other hand, to enable good background subtraction, it is useful either to obtain a sequence of sky exposures before or after the target observations, or to nod between windows a few times during an observing block.

One important aspect of the detectors for this mode is that pixels in each channel are read sequentially. This means that the last pixel of one frame is read closer in time to the first pixel of the next frame than the first pixel of the same frame. This needs to be taken into account when extracting photometry from sources and generating light curves.

4.5.5 Slit Spectroscopy

The spectroscopy mode in MICADO is designed for compact (i.e. unresolved) targets, and disperses the light transmitted through a slit. The length of the slit is limited by the location of the cross-dispersed traces on the detectors, but is sufficient (at least 3arcsec) to allow nodding of a point source back and forth for optimal sky subtraction. The resolution is dependent on the slit width, and 2 slits are offered. Either of the slits can be used with either spectral band.

It is not yet decided whether we should have more slits, so that the 3” length corresponds to IJ band and a longer 5-6” pair of slits is available HK band.

Table 7: slit options for the spectroscopic mode

Slit (width x length)	*Notes*
16mas x 3arcsec	For point sources. This width maximises S/N in K-band[a] for a fixed 2-pixel sampling along the slit; yields R~8000 integrated across the slit[b], but 11000 < R < 18000 for a point source within the slit.
50mas x 3arcsec	For compact resolved targets; yields R~2500[b]

[a] A narrower 8mas slit matched to J-band is impractical.

[b] This is the resolution integrated across the slit; for sources that do not fill the slit width uniformly, the resolution will depend on the source width.

In nearly all cases, the slits are wider than the FWHM of a point source. This has two implications. While the OH sky lines are integrated across the slit and will be observed at the resolutions given in Table 7, sources that are narrower (i) will be observed at higher resolution, and (ii) may be offset in velocity with respect to the OH lines if not centered perfectly. In the context of point (i) above, independent of the slit used, the FWHM resolution for a J-band point source (7mas FWHM) will be R~18000, and for a K-band point source (12mas FWHM) will be R~11000. With respect to point (ii), caution may need to be applied for observations which require deriving precise (i.e. <10km/s) velocity of a target with respect to an absolute reference, or which rely on relative velocities of components with different spatial distributions.

The spectrograph module itself is a fixed unit without any configurable mechanisms, but it is designed to allow spectra in 2 wavelength regimes, depending on the order sorting filter chosen. Because it is a cross-dispersed design, the resolution is approximately constant across the entire wavelength range of both the short and long setting. There are only 2 options for configuring the wavelength coverage.

Table 8: wavelength settings for the spectroscopic mode

Wavelength coverage	*Notes*
0.8-1.45µm	IzJ bands simultaneously
1.45-2.4µm	HK bands simultaneously

There are finite gaps between the detectors in the focal plane of MICADO. The spectrograph module has been designed to minimise the impact of the gaps. But it is inevitable that for some targets an important part of the spectral range may be lost. Because of this, some limited flexibility for spectral dithering is available – by adjusting slightly the position of the slit. The details of this option, and whether it fully resolves the concern about lost spectral ranges, are still to be investigated

[do we want to offer any of these:

A longer (~5arcsec) 12mas slit for HK band

A narrower or intermediate width slit, e.g. 8mas or 30mas

‘inner’ and ‘outer’ slits (with respect to slit mask) which enable one to have the spectral traces in different places on the focal plane

My preference would only be for the last of these options.]

5 Templates

The full list of templates, with technical descriptions, is given in the MICADO Template Manual (RD4). Here we only summarise those relevant for observations and routine night-time and day-time calibrations.

5.1 Acquisition and Observation

Provide a table summarising the acquisition and observing templates. Include (i) an indication of which can go together, and (ii) a short description of each (longer descriptions, including the parameters, will be given later in the Operation Manual).

5.2 Calibration

Full details of the calibrations required for MICADO are given in the Calibration Plan (RD5). Here, we summarise those for routine night-time and day-time use.

Provide a table summarising the calibration templates. Include (i) an indication of which can go together, and (ii) a short description of each (longer descriptions, including the parameters, will be given later in the Operation Manual).

Notes about calibrations – should probably go in Calibration Plan.

Night-time:

Photometric fields

Astrometric fields?

PSF calibration (to assist in PSF reconstruction by measuring telescope/instrument aberrations which need to be combined with reconstructed WFS data)

Day-time:

Flatfielding: internal uniformity is very good, so twilight sky flats are not required.

Wavelength calibration

Cold Astrometric Mask: for measuring instrument distortions internal to MICADO

Warm Astrometric Mask: for measuring distortions due to AO system (which may be dependent on the ambient temperature; and position angle dependent with respect to the distortions internal to MICADO)

Dark frames: in which mechanisms do we have ‘block’ options (entrance mask, filter wheels, pupil mask?)

Non-common Path Aberrations: is this a calibration or maintenance task?

Etc.

6 Recipes

Link between observing templates & data reduction pipeline recipes. Can only be put in once both templates and recipes are defined.

Mention specific tools, e.g. one provided by MAORY to support pipeline processing & PSF reconstruction.

7 Observing Scenarios

These cover the observing modes described in this document for SCAO and MCAO, and can be found in the MICADO Observing Use Cases document (RD3).

8 Summary of Configurable Mechanisms

The MICADO cold instrument contains 4 mechanisms (or pairs of mechanisms) that are configurable for observations. The focal plane and blocking wheel are used together, as are the upper and lower filter wheels. A such, from the users perspective, these pairs appear as single mechanisms (although they can be driven independently from the engineering interface)

- 1a Focal plane wheel
- 1b Blocking wheel
- 2a Upper filter wheel
- 2b Lower filter wheel
- 3 Pupil wheel
- 4 Main mechanism

The following tables list all the positions available for these mechanisms.

Focal Plane and Blocking Wheels

The focal plane and blocking wheels are used together. In most cases, the user selects the option for the focal plane wheel from those given in Table 9. And the blocking wheel, the options for which are listed in Table 10, is automatically moved to match. The only exception is when the 'blocking' option is selected, for example to take dark exposures. In this case the blocking wheel position is selected and the focal plane wheel is moved to match.

The reason to have 2 wheels, is to enable the items on the focal plane wheel to be located closer together, and hence fit more into the limited space available.

For spectroscopy, it is not yet decided if there should be 2 short (3") slits for IJ and 2 longer (5-6") slits for HK – i.e. 4 total rather than 2.

Table 9: All positions on focal plane wheel

Large field	Transmits an imaging field of approx. 53" x 53"

Small field	Transmits an imaging field of approx. 20” x 20”
Slit 1	Spectroscopic slit that is 3” long and 16mas wide
Slit 2	Spectroscopic slit that is 3” long and 50mas wide
Coro 1	Vortex coronagraph for high contrast imaging in K-band
Coro 2	Vortex coronagraph for high contrast imaging in H-band
Coro 3	Vortex coronagraph for high contrast imaging in J-band
Pinhole mask	Numerous holes across the large field to provide point sources for astrometric calibration of internal instrument distortions.

Table 10: All positions on the blocking wheel

Large opening	Used with the large & small fields of the focal plane mask, as well as the pinhole mask.
Small opening	Used with the coronagraphs in the focal plane mask
Tiny opening	Used with the lists in the focal plane mask
Block	Blocks external light, e.g. for dark exposures. Used with small field in focal plane mask.

Upper and Lower Filter Wheels

There are two filter wheels, which are used together. When the user selects which filter to use, the wheel that contains the filter is positioned appropriately and the other wheel is set to ‘open’. For spectroscopy, both wheels are set automatically in a similar way once the wavelength range is selected. Note that at the current time, 2 slots in each wheel are deliberately left as spare. This leaves 30 slots for imaging filters.

The selection of filters listed in Table 11 and Table 12 is preliminary, and will be reviewed & revised by the science team. Similarly, the location of filters on the upper vs lower wheel has not yet been decided.

Table 11: All 18 positions on Upper Filter Wheel (the filters are all TBC)

Filter	λ_{cen} *(µm)*	*Δλ (µm)*	Note
Iz	0.90 ?	0.20 ?	Broad band
J	1.27	0.18	Broad band
H	1.66	0.31	Broad band
Ks	2.16	0.32	Broad band
K_coro	2.16	0.08	coronagraphic/SAM imaging
H_coro	1.65	0.08	coronagraphic/SAM imaging
J_coro	1.25	0.08	coronagraphic/SAM imaging

Br-gamma	2.166		z=0 line emission imaging
Br-g cont			Continuum for Br-gamma
H2 1-0S(1)	2.122		z=0 line emission imaging
H2 cont			Continuum for H2 1-0S(1)
[FeII]_H	1.644		z=0 line emission imaging
[FeII] cont			Continuum for [FeII]_H
Pa-beta	1.28		z=0 line emission imaging
Pa-b cont			Continuum for Pa-beta
open	-	-	Automatically set when selected filter is on lower wheel
Spare			
Spare			

Table 12: All 18 positions on Lower Filter Wheel (the filters are all TBC)

Filter	λ_{cen} *(μm)*	*Δλ (μm)*	Note
IB cont H	1.580	0.023	Solar system, deep continuum (10bar)
CH4_H	1.690	0.113	Solar system, exoplanets, brown dwarfs
CH4_K	2.30		Solar system, exoplanets, brown dwarfs
H20_K	2.06	0.08	Solar system, exoplanets, brown dwarfs
H20_J	1.495		Solar system, exoplanets, brown dwarfs
NH3	1.53		Brown dwarfs, stellar pops
Spec_IJ	1.05 ?	0.60 ?	Order sorting for spectroscopy
Spec_HK	1.9 ?	1.0 ?	Order sorting for spectroscopy
Open	-	-	Automatically set when selected filter is on upper wheel
Spare			
Spare			

Pupil Wheel

The pupil wheel is set according to the observing mode and waveband selected. It is typically not set explicitly.

The preliminary baseline is for the 8 positions given in Table 13. It is likely that more positions will be available in the pupil wheel, but these currently would be left empty. Whether we decide these should be filled depends results of analyses during the design phases. Possibilities include additional cold stops or Lyot stops optimised for different situations (by under/over-sizing masked regions differently), or various 'knife-edge' masks for measuring NCPAs.

Table 13: All positions on the pupil wheel

Stop_K	Undersized stop with central obscuration for better background blocking. TBC whether it can also be used as a Lyot stop for field stabilised coronagraphic imaging
Stop_IJH	Oversized stop, with undersized (or possibly without) central obscuration for maximum throughput
Lyot	Undersized with spider arms and central obscuration for coronagraphic imaging with pupil stabilisation.
SAM1	Sparse aperture mask for smallest inner working angles giving high dynamic range. Fully non-redundant, matching 30 segments on M1, making use of closure phase.
SAM2	Sparse aperture mask providing more complete *uv* coverage. Matches 93 segments on M1, making use of kernel phase imaging.
vAPP1	Vector apodizing phase plate (for high contrast imaging over whole field, but limited by field angle dependence of pupil position); TBC optimised for best contrast over limited region.
Apodised pupil or vAPP2	TBC optimised for suppression of halo all around PSF.
Vortex	Phase diversity measurements, for NCPA calibration

Main Mechanism

The main mechanism sets the primary observing mode. There are 4 positions on the wheel as indicated in Table 14.

Table 14: All positions for main mechanism

Standard	Moves in 2 fold mirrors to provide imaging over the larger field with the nominal 4mas pixel scale.
Zoom	An 'open' position so the light passes through the zoom optics to provide imaging with a finer 1.5mas pixel scale over a smaller field
Spectroscopy	Moves in the 2 gratings for the cross-dispersing spectroscopic module
Pupil imaging	Moves in fold mirrors and a lens for the pupil imager.

9 Status of Compliance

N/A (yet).

End of document