ELT - MICADO

Phase B

MICADO Masks, Stops, and Filters Description

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CHANGE RECORD

ISSUE	DATE	SECTION/PARAGRAPH AFFECTED	REASON/INITIATION DOCUMENTS/REMARKS
0.1	15.09.2016	All	Draft distributed for comments; not an official release.
0.2	17.11.2016	All	Updated during consortium meeting

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1 Scope

The present document provides the specification for the masks and filters in MICADO from the astrophysical perspective. These will be used as the basis for the more technical specifications that are needed.

There are several aims:

- To provide sufficient explanation that, in the future when referring back to this document, the rationale for any specification can be understood.
- To know what masks, and hence how many, are needed on each of the mask wheel and pupil wheel; and whether or not a substrate is needed. This will enable appropriate engineering development, and whether specific manufacturing techniques are implied.
- To assess which filters can be used for multiple purposes, and whether the available number of filter slots can cover the needs of the priority science cases.
- To know which filter/mask combinations are likely to be used together. This is particularly important for the neutral density filter.
- To enable a reliable cost estimate for these components.

A responsible person has been assigned to each mask or filter, who provides a brief scientific (or technical) description as well as specifying as far as possible the mask or filter requirements. Initials used correspond to the following names:

RD	Ric Davies
ET	Eline Tolstoy
RN	Ramon Navarro
PB	Pierre Baudoz
MF	Maximilian Fabricius
FM	Frédéric Merlin
NMFS	Natascha Förster Schreiber
JT	Jens Thomas
WK	Wolfgang Kausch
JS	Josef Schubert
MH	Mike Hartl
EG	Eric Gendron

2 References

2.1 Applicable documents

RD Nr	Doc. Nr	Doc .Title	Is-sue	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	1.0	
RD3	ELT-PLA-MCD-56301-0003	Observing Use Cases for MICADO	1.0	
RD4	ELT-PLA-MCD-56301-0004	MICADO Operational Concept Description	1.0	

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

3.1 MICADO wheels

The MICADO cold instrument contains 4 wheels that hold masks or filters that require astrophysical specifications. These are listed below and illustrated in Figure 1.

1 Focal Plane Mask Wheel
2 Upper Filter Wheel
3 Lower Filter Wheel
4 Pupil Wheel

The focal plane mask wheel is used in conjunction with the field stop wheel. However, the field stop wheel requires only an engineering specification and so is not included here. The two filter wheels are used together, and so appear as a single mechanism. However, it is important to know whether specific filters must be used together since this implies constraints about in which wheel they are located. As such they are considered separately here. The astrophysical description and specification for the masks and filters in these wheels are given in the sections below.

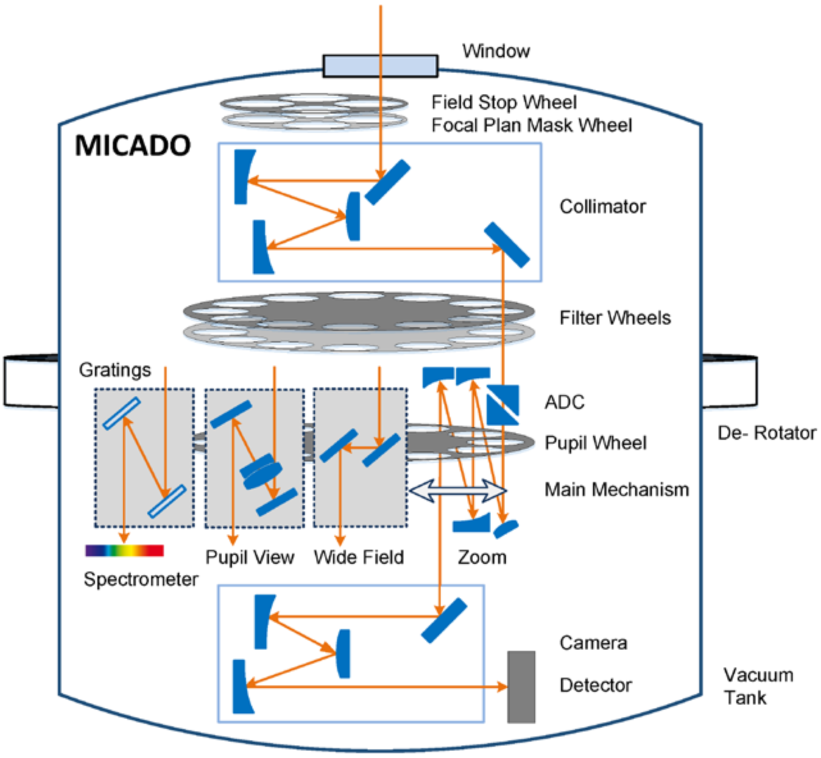

Figure 1: Functional optical overview of the MICADO cold instrument, showing where the various mechanisms are located in the context of the optical design. Note that this sketch does not include optics or functions in the calibration unit, the MAORY relay, or the SCAO module.

3.2 Atmospheric Transmission

An overview of the atmospheric transmission across the full envelope of MICADO science wavelengths is given here for reference.

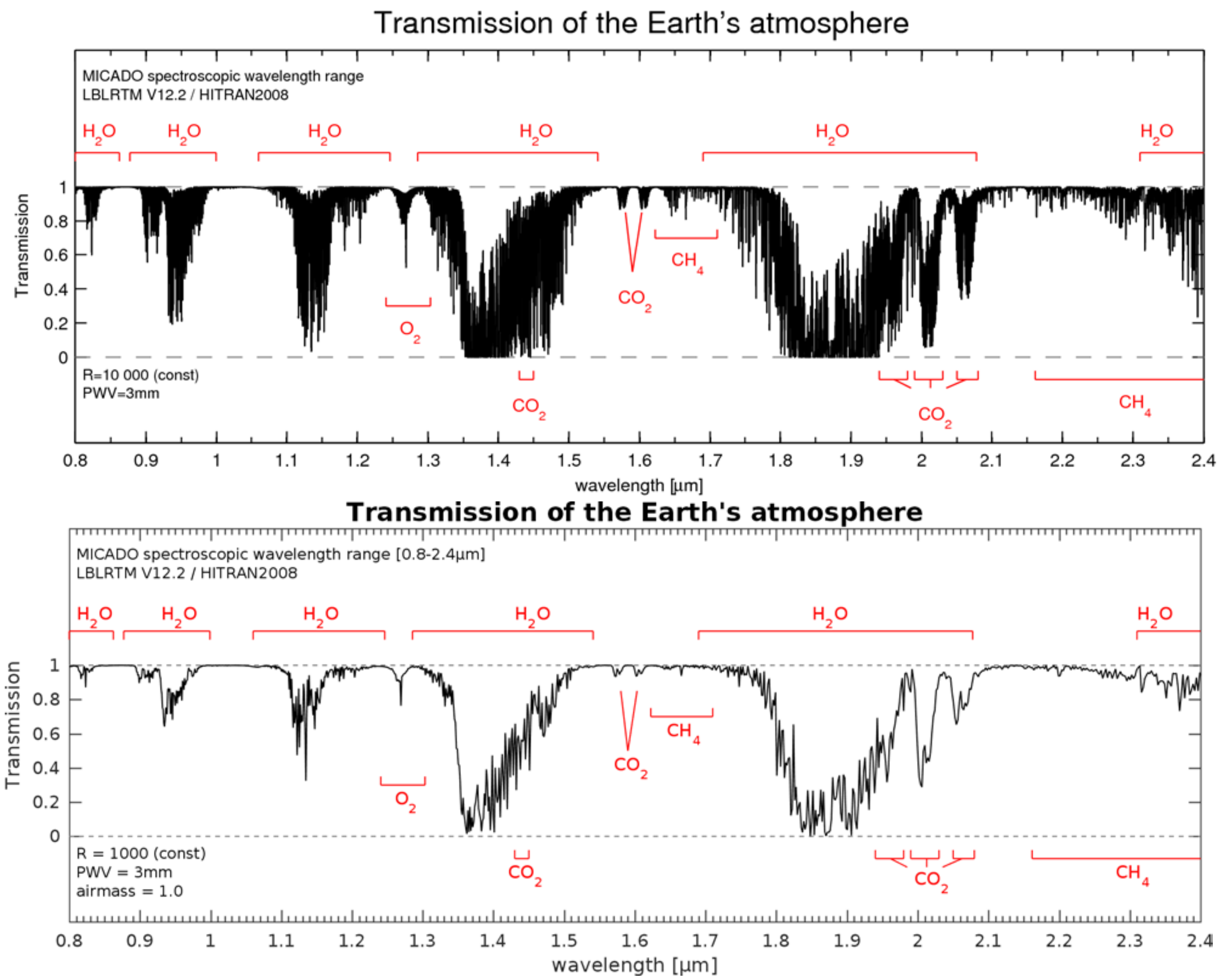

Figure 2: Atmospheric transmission across the full 0.8-2.4µm envelope of the MICADO range, at very high resolution (top) and R=1000 (bottom). These show the deep and continuous absorption between the J, H, and K bands; and also that the absorption comprises numerous narrow lines. While individually these may be deep, their combined effect across a filter bandpass may still be moderate.

3.3 The E-ELT and MICADO pupils

Some of mask definitions require knowledge about the E-ELT or MICADO pupil, and some miscellaneous information is summarised here.

3.3.1 Size

Figure 2 shows the various sizes of the entrance pupil (strictly, the intersection of the entrance pupil with M1). It is important to realise that there are 3 definitions for the diameter of the entrance pupil and central obscuration:

Description	Pupil diameter	Central Obscuration diameter
Nominal	38.542 m	10.952 m
Maximum area	39.146 m	9.418 m
All glass (i.e. fully filled) area	36.905 m	13.213 m

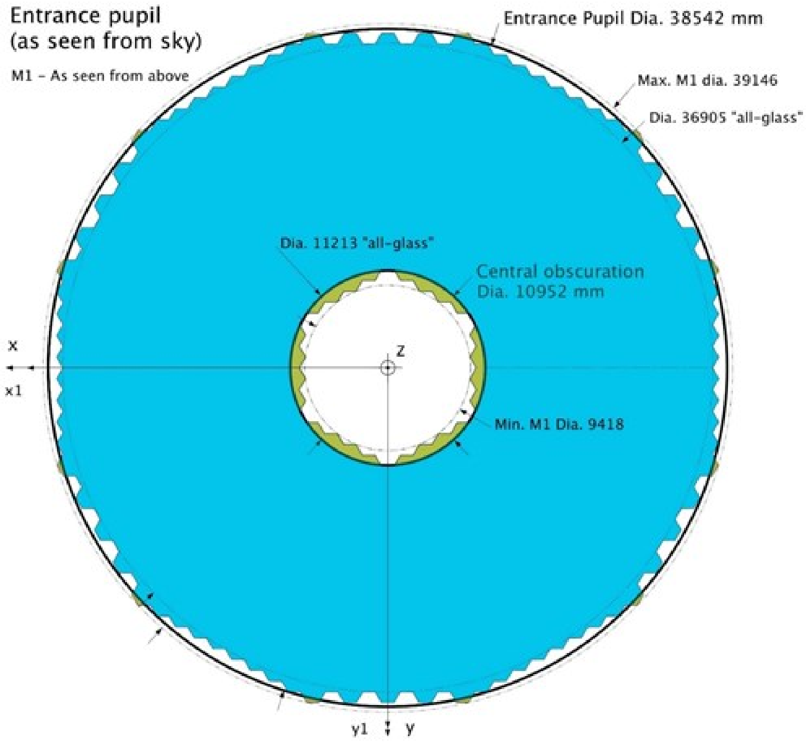

Figure 3: Intersection between the E-ELT entrance pupil and primary mirror. Image and caption are taken directly from the *Common ICD between the E-ELT and Namyth Instruments and the Rest of the E-ELT System* (version 2).

3.3.2 Spider Arms

Figure 3 shows that the spider arms are oriented such that one is aligned vertically, and the others are 60° either side. As such, the resulting diffraction spikes should extend outside the limits of a slit that is aligned along the parallactic angle. The location and size of the spider arms, together with image quality in the pupil, has implications on the design and alignment of the mask for high contrast imaging.

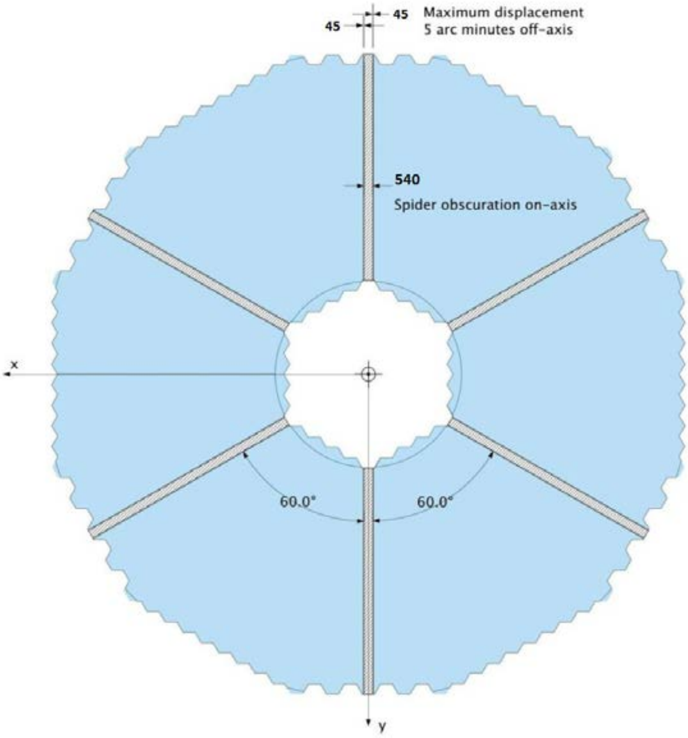

Figure 4: Maximum allowable obscuration by spiders and/or on-baord cranes, as projected onto the entrance pupil (as seens from sky); units are given in millimetres. Image and caption are taken directly from the *Common ICD between the E-ELT and Namyth Instruments and the Rest of the E-ELT System* (version 2).

3.3.3 Positioning Precision

The following estimates are given as guidelines and may differ for specific masks.

Focal plane mask wheel

Strongest requirements come from coronagraph and slit.

Narrowest slit is 16mas wide, corresponding to 4 pixels. It should be within ±3% of its nominal location 2/3 of the time. This is a peak-to-valley repeatability of 13%, corresponding to 0.5 of a pixel, or 8 µm on the detector. The slit is located halfway from the centre to the edge of the mask wheel, so the P-V requirement on positioning the wheel edge is 16 µm. The rms precision is therefore 3 µm.

Coronagraph positioning requirement?

Filter wheels

No strong positioning requirements. As a guideline, diameter of filters is approximately 10cm. For alignment to 1% of diameter, peak-to-valley, is 1000 µm. So rms precision is about 200 µm.

Pupil wheel

The cold pupil in MICADO is approximately 80mm diameter. There are approximately 30 segments across the diameter of M1. For reference, a positioning requirement corresponding to 1/10 of a segment is therefore 0.33% of the pupil diameter, which would be about 250 µm.

This is the peak-to-valley requirement, so the rms precision is about 50 µm.

Similarly, the spider arms are approximately 540mm width, or 1.3% of the pupil diameter. Masking these efficiently implies precisions of hundreds of microns.

4 Focal Plane Mask Wheel

4.1 Summary

The following table provides a summary of the positions in the focal plane mask wheel.

Pos.	*Mask*	*Short Description*	*Resp.*
1	Large field	Transmits the full imaging field for the 4mas pixel scale (c. 50”)	RD
2	Small field	Transmits the full imaging field for the 1.5mas pixel scale (c. 20”)	RD
3	High contrast field	Transmits a ~6” imaging field for pupil plane coronagraphy and SAM modes.	RD
4	Narrow slit	Spectroscopic slit that is 4” long and 16mas wide	WK
5	Wide slit	Spectroscopic slit that is 4” long and 48mas wide	WK
6	Narrow offset slit	As for narrow slit, position in focal plane offset for spectral dithering	WK
7	Wide offset slit	As for wide slit, position in focal plane offset for spectral dithering	WK
8	Long slit	10-20” long, ~30mas wide for HK or H only	JT
9	Coro 1	coronagraph for high contrast imaging in K-band	PB
10	Coro 2	coronagraph for high contrast imaging in H-band TBC	PB
11	Coro 3	coronagraph for high contrast imaging in J-band TBC	PB
12	Pinhole mask	Numerous holes across the large field to provide point sources for astrometric calibration of internal instrument distortions.	MF
13	Alignment 1	Small thing (central pinhole?) for warm alignment	RN/JS
14	Alignment 2	Ditto for cold alignment	RN/JS

4.2 Descriptions

Large Field

Mask for the full imaging field covered by the 4mas pixel scale (approx. 50”).

Size	x by y arcsec	Depends on opto-mechanical design
Edge roughness		
Straightness of edges		
Alignment precision/re-peatability		

Small Field

Mask for the full imaging field covered by the 1.5mas pixel scale (approx. 20”).

Size	x by y arcsec	Depends on opto-mechanical design
Edge roughness		
Straightness of edges		
Alignment precision/re-peatability		

High Contrast Field

Mask for high contrast imaging with the pupil plane coronagraph and SAM modes, to improve image quality in the pupil by reducing the field size. Ideally, should cover the central detector at the 4mas pixel scale, i.e. ~6" across.

Size	x by y arcsec	Depends on opto-mechanical design
Edge roughness		
Straightness of edges		
Alignment precision/repeatability		

Narrow Slit

Narrow slit for unresolved objects. Slit width is optimised for maximum S/N in K-band integrated over a fixed length of the slit, adjusted to the closest integer number of pixels.

length	4 arcsec	Depends on opto-mechanical design
width	16 mas (=60um)	= 60um
Edge roughness	±1µm rms between averages over 15um (1 pix) lengths.	This means width will vary by ±1.4µm, corresponding to 1σ uncertainty of 2.3% in the photometric precision, which is small with respect to the total photometry error budget. And this can partly be calibrated, e.g. using measured spatial variations in the flux and spectral width of OH sky lines. Variations on lengths <15um are less important.
Straightness of slit	±1µm	Same requirement as for edge roughness but over full length of slit. Curvature can in principle be measured/calibrated and taken into account in operations & data processing.
How parallel should sides be?	±1µm	Same requirement as for edge roughness but over full length of slit. This is important because it has an impact on spectral resolution.
Alignment precision/repeatability	±1mas (±4µm)	PSF should be centered to 10% of its FWHM in K or H-band, which is ±1mas. This keeps velocity shift to ±2km/s, which is consistent with the required precision of 3.5km/s (1/10 of the spectral resolution).
Operational issues	Slit should be aligned along parallactic angle (and tracking the field). Provisionally, it is required that the slit orientation should be updated at the start of each science exposure to match the expected mid-time of that exposure. (Note that it needs to be checked whether the simpler alternative of a single setting for each (1-hr) observing block might be sufficient).	

Wide Slit

Wide slit for slightly extended objects, such as local galaxy nuclei or the centres of high redshift galaxies. The width balances increasing the S/N by include more light from the object while keeping the spectral resolution sufficiently high to allow working between OH lines and measuring kinematics.

Size	4 arcsec	Depends on opto-mechanical design
width	48 mas	
Edge roughness		
Straightness of slit		
How parallel should sides be?		
Alignment precision/repeatability		

Narrow Offset slit

Same requirements as the Narrow Slit; but position both perpendicular and parallel to slit is offset by up to a few arcsec. This allows the spectral ranges between gaps to be covered.

Wide Offset slit

Same requirements as the Wide Slit; but position both perpendicular and parallel to slit is offset by up to a few arcsec. This allows the spectral ranges between gaps to be covered.

Long Slit

Short rationale

length		Should be consistent with spectral traces. Note that a 10" slit will be ~38mm long.
width		4mas = 15um. If the slit is 32mas wide, the aspect ratio is 1:300.
Edge roughness		
Straightness of slit		
How parallel should sides be?		.
Alignment precision/repeatability		
Operational issues	Slit should be aligned along parallactic angle (and tracking the field). Provisionally, it is required that the slit orientation should be updated at the start of each science exposure to match the expected mid-time of that exposure. (Note that it needs to be checked whether the simpler alternative of a single setting for each (1-hr) observing block might be sufficient).	

Coro 1

Coro 2

Coro 3

5 Filter Wheels

OUT-OF-BAND BLOCKING

The out-of-band blocking is not defined for individual filters unless there is an exception to this note. It is assumed that blocking across the full sensitivity range of the detectors (c. 0.5-2.5µm; may be necessary to extend to 2.6 or 2.7µm, depending on tail of QE curve) is blocked to a level of 10^4 (TBC whether this can be relaxed to 10^3 in some or all cases). This includes the transmission of other wavelength dependent optics in the beam path, including the visible/infrared dichroic etc (i.e. it may be sufficient for the filter to block to ~0.7µm).

SCAO DICHROIC

The baseline assumed here is that the SCAO dichroic is removable. This means that for MCAO, the dichroic has no impact because it is out of the optical path. But for SCAO, the dichroic is in the beam path and reflects optical light to the SCAO WFS. In order to achieve sufficient sensitivity, the cut-off wavelength between transmitted and reflected light is currently set at 0.965um – to allow full transmission of the Y-band; but I-band is blocked.

5.1 Summary

Science notes

High redshift filters

High-resolution narrow-band imaging of all of Ha, [NII], Hb, [OIII], [OII], [NeIII] (at least 4-5 of them) in the same galaxies has been scientifically argued for resolved metallicities, excitation, extinction on ~100 pc scales). For filter widths of R ~ 200 - 300, one could access all these lines between sky lines and telluric opaque intervals for 5 redshift slices between 2.15um and 2.40um. That obviously implies a lot of different filters, and possibly limited applicability given the strong redshift slices restrictions combined with the MICADO FOV. As such, this science can arguably be better addressed with HARMONI.

Instead, the idea here is to probe the *continuum* with the medium bands, not the line emission. What is amply demonstrated in the literature is the improvement in redshift determinations - the main aim of surveys such as NMBS from 4-8m class no-AO telescopes. With HST, we have now started to apply spatially-resolved SED modeling to derive resolved maps of stellar mass, SFRs, Av, ages. In principle, 1 single but suitably chosen color can constrain well a M/L ratio (hence a M since the L is known from one of the bands), irrespective of details of SFHs, Av, age (the M/L vs color relation is tight when straddling an age sensitive feature such as the Balmer/4000A break, with effects of SFHs, age, Av, even metallicity highly degenerate). However, a next step would be to have more finely sampled spatially-resolved SEDs such than one would be able to start constrain age, SFHs, Av in addition to Mstar (that would be key to investigate how/when quenching happens in a galaxy, for instance).

Filter summary

The following tables provide a summary of the filters in the two wheels.

Pos.	*Filter*	λ_{cen} *(µm)*	$\Delta\lambda$ *(µm)*	λ_{cuton} *(µm)*	λ_{cutoff} *(µm)*	*Short description*	*Resp.*
1	I	0.880	0.160	0.800	0.960	Broad band	ET
2	Y	1.020	0.100	0.970	1.070	Broad band	RN
3	J	1.245	0.180	1.155	1.335	Broad band	RN

4	H	1.635	0.290	1.490	1.780	Broad band	RN
5	Ks	2.145	0.350	1.970	2.320	Broad band	RN
6	J1 (short)	1.19	~.05			Coro + high-z stellar pops + continuum for J-band emission lines	NMFS/ PB
7	J2 (mid)	1.27	~.05			Coro + high-z stellar pops	NMFS/ PB
8	J3 (long)		~.08			High-z stellar pops	NMFS
9	H-cont	1.580	0.023	1.5685	1.5915	Solar system, deep continuum (10bar); cont for H-band emission lines	FM
10	CH4-short	1.592	0.126	1.5295	1.6552	Solar system, exoplanets, brown dwarfs Slightly narrower is better for coro & highz	FM/ NMFS
11	CH4-long	1.681	0.137	1.6125	1.7493	Solar system, exoplanets, brown dwarfs Slightly narrower is better for coro & highz	FM/ NMFS
12	H2O_K	2.060	0.060	2.0300	2.0900	Solar system, exoplanets, brown dwarfs	FM
13	COabs	2.3080	0.044	2.2859	2.3300	z=0 stellar abs. 2.2935 & 32265um, -1000/+3000km/s; use IB-K-cont for continuum; Is this also ok for CH4 for solar system bodies? Cont for H2O_K	FM
14	K-coro		~.08			Intermediate band for coronagrpahy	PB
15	K-cont	2.2657	0.040	2.2455	2.2859	Continuum for Br-g, H2, and CO	RD
16	open	-	-	-	-	Automatically set when selected filter is on lower wheel	RD
17	Spare						RD
18	Spare						RD

Pos.	*Filter*	*λ_{cen} (µm)*	*$\Delta\lambda$ (µm)*	*λ_{cuton} (µm)*	*λ_{cutoff} (µm)*	*Short description*	*Resp.*
1	Br-g	2.1733	0.029	2.1589	2.1878	z=0 line emission 2.1661um, -1000/+3000km/s; use K-cont for continuum	RD
2	H_2 1-0S(1)	2.1289	0.028	2.1147	2.1430	z=0 line emission 2.1218um, -1000/+3000km/s; use K-cont for continuum	RD
3	[FeII] H	1.6495	0.022	1.6385	1.6604	z=0 line 1.6440um, -1000/+3000km/s; use NB-H-cont for continuum	RD
4	Pa-beta	1.2864	0.017	1.2779	1.2950	z=0 line 1.2822um, -1000/+3000km/s	RD
5	He I	~1.08	~.02			z=0 line at 1.083um, -1000/+3000km/s	RN
6	I1 (short)		~.05			High-z stellar pops	NMFS
7	I2 (long)		~.05			High-z stellar pops	NMFS
8	Y1 (short)		~.05			High-z stellar pops	NMFS
9	Y2 (long)		~.05			High-z stellar pops	NMFS

10	Z		~.08			High-z stellar pops + generic	NMFS
11	K1 (short)		~.08			High-z; short end of K-band (but lower priority)	NMFS
12							
13							
14	ND3	1.738	1.165	1.155	2.320	Neutral density filter; factor 1000 flux reduction over JHK	PB
15	ND2	1.738	1.165	1.155	2.320	Neutral density filter; factor 100 flux reduction over JHK	PB
16	Open	-	-	-	-	Automatically set when selected filter is on upper wheel	RD
17	Spec_IJ	1.110	0.680	0.770	1.450	Order sorting for spectroscopy	
18	Spec_HK	1.950	1.100	1.400	2.500	Order sorting for spectroscopy	

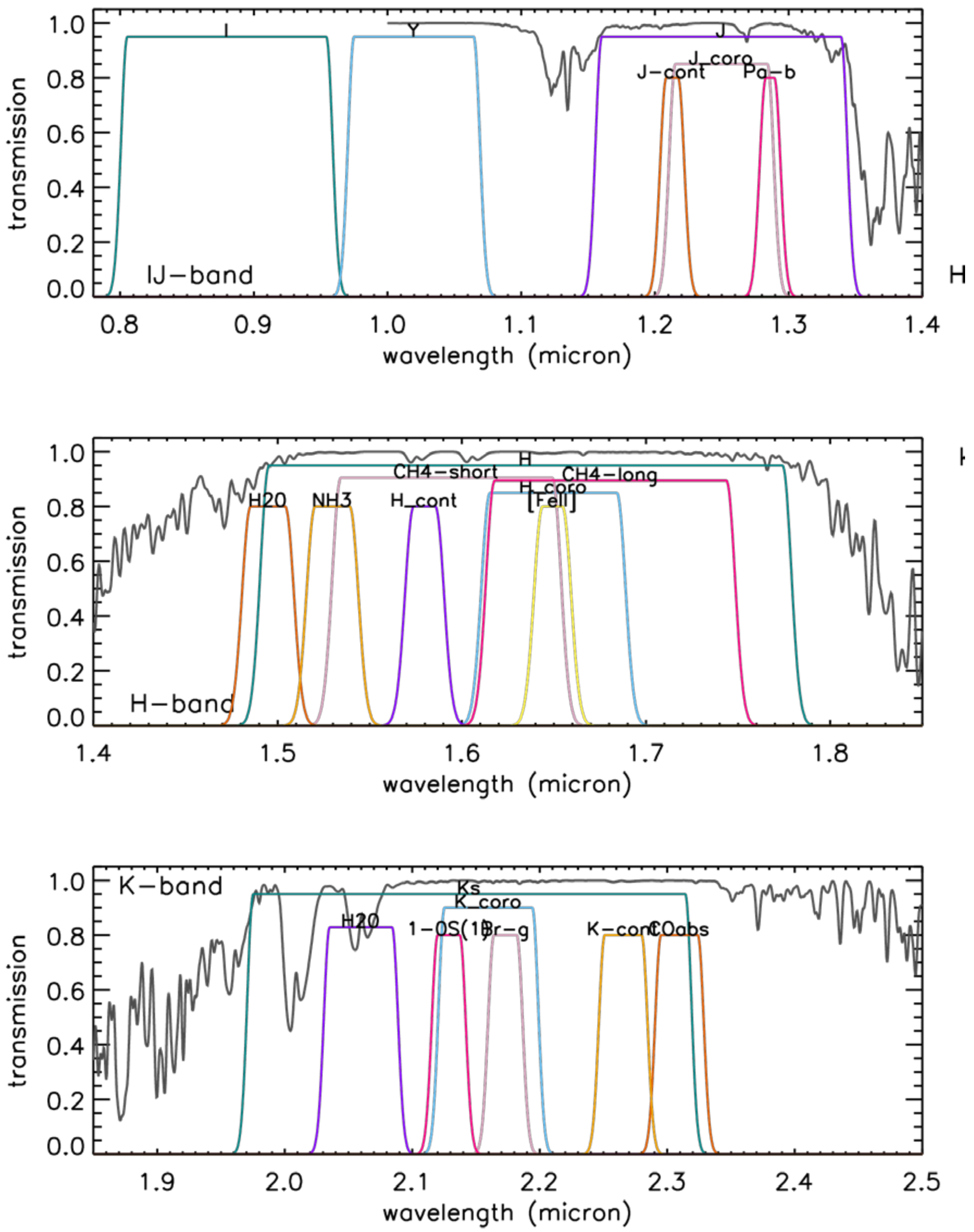

Figure 5: Illustration of the filter curves defined in the Tables above. This is only to indicate the relative location and width of the filter bandpasses, it does not realistically represent the details oif the filter transmission curve shapes.

5.2 Descriptions, Upper Wheel

I

Broad band filter for I-band. This band is not typically found on near-IR instruments but is included here to provide sensitive imaging at as a short a wavelength as possible, which is especially useful for stellar population analysis. The central wavelength of the standard Johnson R-band is 0.880um; and for MICADO the lower cut-off is set to be 0.80um. Together these fix the upper cut-off at 0.96um. The width is then 0.16um, somewhat less than the standard width of 0.29um.

Should the long cut-off be at 0.925um to avoid the worst absorption features?

Lower Cut-off wavelength	0.800 um	
Upper Cut-off wavelength	0.960 um	
Sharpness of cut-on & cut-off		
Central wavelength	0.880 um	
Feature wavelength	NA	zero redshift assumed unless stated.
transmission (min/goal)	Min 90%, Goal 95%	
Variation of transmission across band	<5% full range	

Y

Broad band filter for Y-band (similar to z-band). Various versions of this exist on other instruments, for example

HAWK-I 0.970-1.071um (λ_{cen} 1.021um),
NIRC2 0.968-1.068um (λ_{cen} 1.018um).

Here, a similar bandpass is adopted. If we have I-band, do we need a separate Y-band filter?

Lower Cut-off wavelength	0.970 um	
Upper Cut-off wavelength	1.070 um	
Sharpness of cut-on & cut-off		
Central wavelength	1.020 um	
Feature wavelength	NA	zero redshift assumed unless stated.
transmission (min/goal)	Min 90%, Goal 95%	
Variation of transmission across band	<5% full range	

J

Broad band filter for J-band. This is a standard broad band that is mandatory to include. Definitions include

HAWK-I 1.181-1.335um (λ_{cen} 1.258um),
NIRC2 1.166-1.330um (λ_{cen} 1.248um),
ISAAC 1.105-1.395um (λ_{cen} 1.250um),

NACO	1.140-1.390um	(λ_{cen} 1.265um),
Mauna Kea standard	1.177-1.319um	(λ_{cen} 1.248um).

Here we have set the upper cut-off to according to atmospheric transmission and made the filter as broad as possible while keeping a central wavelength close to 1.25um.

Lower Cut-off wavelength	1.155 um	
Upper Cut-off wavelength	1.335 um	
Sharpness of cut-on & cut-off		
Central wavelength	1.245 um	
Feature wavelength	NA	zero redshift assumed unless stated.
transmission (min/goal)	Min 90%, Goal 95%	
Variation of transmission across band	<5% full range	

H

Broad band filter for H-band. This is a standard broad band that is mandatory to include. Definitions include

HAWK-I	1.475-1.765um	(λ_{cen} 1.620um),
NIRC2	1.485-1.781um	(λ_{cen} 1.633um),
ISAAC	1.500-1.800um	(λ_{cen} 1.650um),
NACO	1.495-1.825um	(λ_{cen} 1.66um),
Mauna Kea standard	1.501-1.758um	(λ_{cen} 1.630um).

Here we have set the upper and lower cut-offs according to atmospheric transmission to have as broad a filter as possible, while keeping the central wavelength within the range of other filters.

Lower Cut-off wavelength	1.490 um	
Upper Cut-off wavelength	1.780 um	
Sharpness of cut-on & cut-off		
Central wavelength	1.635 um	
Feature wavelength	NA	zero redshift assumed unless stated.
transmission (min/goal)	Min 90%, Goal 95%	
Variation of transmission across band	<5% full range	

Ks

Broad band filter for K-band that avoids too much thermal background at the long end. This is a standard broad band that is mandatory to include. Definitions are varied, and include

HAWK-I	1.984-2.308um	(λ_{cen} 2.146um),
NIRC2	1.991-2.302um	(λ_{cen} 2.146um),
ISAAC	2.025-2.295um	(λ_{cen} 2.160um),
NACO	2.005-2.355um	(λ_{cen} 2.180um),
Mauna Kea standard	1.945-2.277um	(λ_{cen} 2.113um).

Here we have set the lower cut-off according to atmospheric transmission, and kept the central wavelength close to that for HAWK-I and NIRC2 as well as the upper cut-off reasonably short. This results in a broad filter. A detailed trade-off in terms of maximising sensitivity (width vs background vs atmospheric transmission) has not been done.

Lower Cut-off wavelength	1.970 um	
Upper Cut-off wavelength	2.320 um	
Sharpness of cut-on & cut-off		
Central wavelength	2.145 um	
Feature wavelength	NA	zero redshift assumed unless stated.
transmission (min/goal)	Min 90%, Goal 95%	
Variation of transmission across band	<5% full range	

K_CORO

A K-band filter for focal plane coronagraphy that has an intermediate width in order to reduce elongation of the PSF by differential atmospheric refraction.

Lower Cut-off wavelength		
Upper Cut-off wavelength		
Sharpness of cut-on & cut-off		
Central wavelength		
Feature wavelength	NA	zero redshift assumed unless stated.
transmission (min/goal)		
Variation of transmission across band		

H_CORO

A H-band filter for focal plane coronagraphy that has an intermediate width in order to reduce elongation of the PSF by differential atmospheric refraction.

Lower Cut-off wavelength		
Upper Cut-off wavelength		
Sharpness of cut-on & cut-off		
Central wavelength		
Feature wavelength	NA	zero redshift assumed unless stated.
transmission (min/goal)		
Variation of transmission across band		

J_CORO

A J-band filter for focal plane coronagraphy that has an intermediate width in order to reduce elongation of the PSF by differential atmospheric refraction.

Lower Cut-off wavelength		
Upper Cut-off wavelength		
Sharpness of cut-on & cut-off		
Central wavelength		
Feature wavelength	NA	zero redshift assumed unless stated.
transmission (min/goal)		
Variation of transmission across band		

H CONT

A narrow H-band filter that enables solar system science by probing deep continuum (10bar) of planetary atmospheres, and serves also as an off-line continuum bandpass for emission line imaging (e.g. [FeII]).

Lower Cut-off wavelength	1.5685um	
Upper Cut-off wavelength	1.5915um	
Sharpness of cut-on & cut-off		
Central wavelength	1.5800um	
Feature wavelength		zero redshift assumed unless stated.
transmission (min/goal)		
Variation of transmission across band	NA	

CH4 SHORT

A narrow filter that enables detection of the broad and deep methane band in solar system bodies, exoplanets, and brown dwarfs. This filter covers the short end of the broad methane band.

Lower Cut-off wavelength		
Upper Cut-off wavelength		
Sharpness of cut-on & cut-off		
Central wavelength	1.592um	
Feature wavelength		zero redshift assumed unless stated.
transmission (min/goal)		

Variation of transmission across band	NA	

CH4 LONG

Is it necessary to have a separate filter to cover the long end of the absorption band? What diagnostic power does it add?

Lower Cut-off wavelength		
Upper Cut-off wavelength		
Sharpness of cut-on & cut-off		
Central wavelength	1.681um	
Feature wavelength		zero redshift assumed unless stated.
transmission (min/goal)		
Variation of transmission across band	NA	

5.3 Descriptions, Lower Wheel

BR-G

Narrow filter for zero redshift Brackett γ emission line in K-band, useful for imaging ionised gas in galactic sources and also nearby galaxies. The line is not expected to have a velocity width more than ~300km/s FWHM, but the filter should be wider in order to allow for a range of line-of-sight velocities. On the other hand, a narrow filter provides better contrast with respect to the continuum. The filter specified here covers the velocity range -1000km/s to +3000km/s (which includes galaxies at distances up to ~40Mpc).

The default off-line continuum filter to use with this is K-cont.

Lower Cut-off wavelength	2.1589um	
Upper Cut-off wavelength	2.1878um	
Sharpness of cut-on & cut-off	10nm	The width is 29nm
Central wavelength	2.1733um	
Feature wavelength	2.1661um	zero redshift assumed unless stated.
transmission (min/goal)	Min 75%; Goal >80%	
Variation of transmission across band	NA	

H2 1-0S(1)

Narrow filter for zero redshift H_2 1-0S(1) emission line in K-band, useful for imaging warm molecular gas in galactic sources and also nearby galaxies. The line is not expected to have a velocity width more than ~300km/s FWHM, but the filter should be wider in order to allow for a range of line-of-sight velocities. On the other hand, a narrow filter provides better contrast with respect to the continuum. The filter specified here covers the velocity range -1000km/s to +3000km/s (which includes galaxies at distances up to ~40Mpc).

The default off-line continuum filter to use with this is K-cont.

Lower Cut-off wavelength	2.1147um	
Upper Cut-off wavelength	2.1430um	
Sharpness of cut-on & cut-off	10nm	The width is 28nm
Central wavelength	2.1289um	
Feature wavelength	2.1218um	zero redshift assumed unless stated.
transmission (min/goal)	Min 75%; Goal >80%	
Variation of transmission across band	NA	

CO ABS

Narrow filter for zero redshift CO absorption in K-band. It is useful for imaging late type stars, to distinguish them from early type stars or host dust continuum, in galactic sources and also nearby (active) galaxies. The filter covers the CO2-0 and CO3-1 bandheads at 2.2935um and 2.3227um respectively. As such it can also be used for nearby galaxies with a moderate recessional velocity. A similar filter is available for NIRC2, but covering only CO2-0 at 2.2757-2.3024um.

The default off-line continuum filter to use with this is K-cont.

Can this filter also be used as a CH4 filter for solar system studies?

Lower Cut-off wavelength	2.2859um	1000km/s shortward of CO2-0
Upper Cut-off wavelength	2.3300um	Covers deepest part of CO3-1 bandhead; & CO2-0 to cz=3500km/s
Sharpness of cut-on & cut-off	10nm	The width is 44nm
Central wavelength	2.3080um	
Feature wavelength	2.2935um	zero redshift assumed unless stated.
transmission (min/goal)	Min 75%; Goal >80%	
Variation of transmission across band	NA	

K CONT

Narrow filter as an off-line continuum band pass for emission line imaging in the K-band, especially Br-g, H2 1-0S(1), and CO abs. It has a moderate width and avoids the major emission lines.

Lower Cut-off wavelength	2.2455um	
Upper Cut-off wavelength	2.2859um	
Sharpness of cut-on & cut-off	10nm	The width is 40nm
Central wavelength	2.2657um	
Feature wavelength	NA	zero redshift assumed unless stated.
transmission (min/goal)	Min 75%; Goal >80%	
Variation of transmission across band	NA	

[FeII] H

Pa-b

J cont

ND2

A neutral density filter that provides a factor 100 flux attenuation across the J, H, and K bands. This is needed for observing or acquiring bright sources, e.g. in high contrast modes.

Lower Cut-off wavelength	1.155um	
Upper Cut-off wavelength	2.320um	
Sharpness of cut-on & cut-off	NA	
Central wavelength	NA	
Feature wavelength	NA	
transmission (min/goal)	0.01%	
Variation of transmission across band	?	

Spec IJ

Order sorting filter for short wavelength spectroscopy.

Lower Cut-off wavelength	0.80um	
Upper Cut-off wavelength	1.45um	1.55 to allow overlap?
Sharpness of cut-on & cut-off	NA	

Central wavelength	NA	
Feature wavelength	NA	
transmission (min/goal)	Min 90%; Goal >95%	
Variation of transmission across band	NA	

SPEC HK

Order sorting filter for long wavelength spectroscopy.

Lower Cut-off wavelength	1.45um	
Upper Cut-off wavelength	2.50um	
Sharpness of cut-on & cut-off	NA	
Central wavelength	NA	
Feature wavelength	NA	
transmission (min/goal)	Min 90%; Goal >95%	
Variation of transmission across band	NA	

6 Pupil Wheel

6.1 Summary

The following table provides a summary of the masks in the pupil wheel.

Pos.	*Mask*	*Priority*	*Short description*	*Resp.*
1	Block	1	Blocks all light to detectors, for taking darks.	RD
2	Stop_K	1	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	RN/MH
3	Stop_IJH	1	Oversized stop, with undersized (or possibly without) central obscuration for maximum throughput	RN/MH
4	Lyot	1	Undersized stop with spider arms and central obscuration for coronagraphic imaging with pupil stabilisation.	PB
5	SAM1	2	Sparse aperture mask for smallest inner working angles giving high dynamic range. Fully non-redundant, matching 30 segments on M1; makes use of closure phase.	PB
6	SAM2	3	Sparse aperture mask with more complete *uv* coverage. Matches 93 segments on M1; makes use of kernel phase imaging.	PB
7	vAPP1	2	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.	PB
8	Apodised pupil or vAPP2	3	TBC optimised for suppression of halo all around PSF.	PB
9	NCPA-mask	3	Phase diversity measurements, for NCPA calibration (exactly what sort of mask is TBD)	EG
10	align		Technical mask for alignment	RN/JS

6.2 Descriptions

Block

Position is completely closed in order to block all light, e.g. for dark exposures.

Stop-K

Pupil stop with binary transmission optimised for K-band. Aim is to minimize the thermal background (from whatever the beam sees around the edges of M1) even though throughput is also reduced.

Is designed for imaging, can be used also for spectroscopy.

Ideally, this would also be used for high contrast imaging with focal plane coronagraph in field stabilisation mode, at any wavelength. However, calculations of high contrast performance may indicate a potential need for a separate stop.

The stop should be undersized so that it transmits only the ‘all glass’ part of the entrance pupil at all field angles. A calculation is needed to derive the optimum size.

FoV / pixel scale	Full field for 1.5mas and 4mas pixel scales
Mask spider?	No
Mask central obscuration?	Yes
Substrate needed?	Yes; AR coatings
Positioning accuracy	50 µm
Repeatability	10 µm

STOP-IJH

Pupil stop with binary transmission optimised for I, J, and H-band. Aim is to maximize throughput, because at these wavelengths the thermal background is negligible.

Is designed for imaging, can be used also for spectroscopy.

The stop should be sufficiently oversized that it transmits the entire entrance pupil at all field angles. A calculation is needed to derive the optimum size, as well as whether it makes sense to mask the central obscuration.

FoV / pixel scale	Full field for 1.5mas and 4mas pixel scales
Mask spider?	No
Mask central obscuration?	No (TBC)
Substrate needed?	No (TBC masking central obscuration)
Positioning accuracy	200 µm
Repeatability	50 µm

LYOT

Pupil stop with binary transmission optimised for high contrast imaging, which would be used with a focal plane coronagraph in pupil stabilisation mode.

The stop should be undersized to block light that is scattered to the edges of the pupil by the coronagraph. The spider arms need to be masked (with sufficient margin based on the image quality in the pupil as well as alignment precision). As such, even though the central obscuration is also masked, a substrate may not be necessary.

If variation of the pupil shape (distortion, size, etc wrt to wavelength) is too large, there may be a potential need for other Lyot stops. But the baseline is to define an optimized stop for H & K.

FoV / pixel scale	Central detector only for 1.5mas and 4mas pixel scales
Mask spider?	Yes
Mask central obscuration?	Yes
Substrate needed?	TBC
Positioning accuracy	20 µm

Repeatability	5 µm

SAM1

Sparse aperture mask with binary transmission optimised to achieve high dynamic range at high angular resolution. The aim is to have a fully non-redundant mask, and to make use of closure phase.

The mask contains 30 transmissive apertures, matched to segments on M1. As such, excellent image quality is required in the pupil, which imposes a strong constraint on the allowed field angles. A calculation is required to determine the maximum permissible field of view.

FoV / pixel scale	Central detector windowed to a few arcsec, with 1.5mas or 4mas pixel scale
Number of apertures	30, matched to M1 segments
Positioning accuracy	20 µm
Repeatability	5 µm

SAM2

Sparse aperture mask with binary transmission. With respect to SAM1, the aim is to achieve more complete uv-coverage (for direct imaging) with a minimum redundancy, and make use of kernel phase imaging.

The mask contains 93 transmissive apertures, matched to segments on M1. As for SAM1, excellent image quality is required in the pupil, which imposes a strong constraint on the allowed field angles. A calculation is required to determine the maximum permissible field of view.

FoV / pixel scale	Central detector windowed to a few arcsec, with 1.5mas or 4mas pixel scale
Number of apertures	93, matched to M1 segments
Positioning accuracy	20 µm
Repeatability	5 µm

vAPP1

Apodized phase plate that enables high contrast imaging over the whole field, to be used in pupil stabilisation mode. Aim is to suppress half of PSF (although less well than a vortex coronagraph), but applying equally to all objects in the field.

The field of view is limited by the imaging quality in the pupil. A calculation is needed to assess this trade-off.

FoV / pixel scale	Central detector with 1.5mas or 4mas pixel scale; is pupil image quality allows, full field with 1.5mas pixel scale.
Mask spider?	Yes
Mask central obscuration?	No
Substrate needed?	Yes

Positioning accuracy	20 µm
Repeatability	10 µm

Apodized Pupil (TBC)

Mask for which the transmission varies smoothly with diameter (blocking material is deposited on a substrate). Aim is to enable high contrast imaging over whole field with flux reduction (useful for bright targets); could be coupled with vortex focal plane mask and so is used in pupil stabilisation mode. It should remove the wings of all structures in the field (useful for diffracted light from gaps, missing segments, etc).

FoV / pixel scale	Central detector with 1.5mas or 4mas pixel scale
Mask spider?	Yes
Mask central obscuration?	Yes
Substrate needed?	Yes
Positioning accuracy	20 µm
Repeatability	10 µm

NCPA-mask

Mask for phase diversity measurements to enable measurement of non-common path aberrations. This is a calibration tool that would be used without tracking.

Need some more description of what it will achieve, which NCPAs it can measure, and what it might be like.

FoV / pixel scale	For calibration. Full field with 1.5mas or 4mas pixel scale
Mask spider?	No
Mask central obscuration?	No
Substrate needed?	Yes
Positioning accuracy	20 µm
Repeatability	10 µm

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