E-ELT PROGRAMME

MICADO Phase A
Design Trade-Off and Risk Assessment

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CHANGE RECORD

ISSUE	DATE	SECTION/PAGE AFFECTED	REASON/ REMARKS
1	21.11.08	All	First issue
1.1	22.12.08	Section 5	Updated according to RIX 77 from Phase A1 review
1.2	09.10.09	All	New trade-offs performed during Phase 2 added; those from Phase 1 put in a single section
2.0	23.10.09	All	Rationale for SCAO module and detailed risk assessment for final Phase A design added

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ABBREVIATIONS AND ACRONYMS

AO	adaptive optics
CAD	computer aided design
CAE	computer aided engineering
CoG	centre of gravity
ECSS	European Cooperation for Space Standardization
E-ELT	European Extremely Large Telescope
ESO	European Southern Observatory
FDR	Final Design Review
FTE	Full Time Equivalent (year)
GLAO	ground layer adaptive optics
GMT	Giant Magellan Telescope
JWST	James Web Space Telescope
LESIA	Laboratoire d'Etudes Spatiales et Instrumentations pour l'Astrophysique
LTAO	laser tomography adaptive optics
MAIT	Manufacture, Assembly, Integration, Test
MAORY	Multi-conjugate Adaptive Optics Relay
MCAO	multi-conjugate adaptive optics
MICADO	Multi-adaptive optics Imaging Camera for Deep Observations
MPE	Max-Planck-Institut für extraterrestrische Physik
MPIA	Max-Planck-Institut für Astronomie
NOVA	Nederlandse Onderzoekschool voor Astronomie
OAPD	Osservatorio Astronomico di Padova
PAE	Preliminary Acceptance in Europe
PAO	Preliminary Acceptance at the Observatory
PA/QA	Product Assurance / Quality Assurance
PDR	Preliminary Design Review
PSF	Point Spread Function
RTD	Real Time Display
SCAO	single-conjugate adaptive optics
TMT	Thirty Meter Telescope
USM	Universitäts-Sternwarte München
WP	Workpackage

1 SCOPE

This document reports on the trade-off study and risk assessment carried out during MICADO Phase A in order to select an instrument design concept to be pursued in the upcoming project phases. It introduces the decision criteria and gives an overview on the different design concepts which have been studied. Furthermore, it describes the way in which the trade-off has taken place and summarizes the results. Finally, this document includes a preliminary risk assessment for the design concept chosen at the end of Phase A.

2 APPLICABLE AND REFERENCE DOCUMENTS

2.1 Applicable Documents

The following applicable documents form a part of the present document to the extent specified herein. In the event of conflict between applicable documents and the content of the present document, the present document shall be taken as superseding.

AD1 Common definitions and acronyms , E-ESO-SPE-313-0066, Issue 1

AD2 E-ELT Interfaces for Scientific Instruments, E-TRE-ESO-586-0252, issue 1

AD3 Call for Proposal For a Phase A Study of a High Angular Resolution Camera for the E-ELT, Specifications of the Instrument to be studied, E-ESO-SPE-561-0097, v2.0

AD4 Statement of Work for the Phase A Design of MICADO, E-SOW-ESO-561-0127, v1.0

2.2 Reference Documents

RD1 Proposal “MICADO: the MCAO Imaging Camera for Deep Observations”, 12 Nov 2007, in response to the call CFP/ESO/07/17768/LCO

RD2 Standard Procedure for Design Reviews, VLT-INS-ESO-00000-0251, issue 2

RD3 Guideline for Review of PDR Data Packages, VLT-INS-ESO-00000-0313, issue 1

RD4 Science Case and Requirements for the ESO ELT- Report of the ELT Science WG, dated 30.4.2006

RD5 MICADO Instrument Development and Management Plan, E-PLA-MCD-561-0020, v1.0

RD6 MICADO Scientific Analysis Report, E-TRE-MCD-561-0007, v 2.0

RD7 MICADO System Overview, E-TRE-MCD-561-0009, v 2.0

RD8 MICADO Single Conjugate Adaptive Optics Module, E-TRE-MCD-561-0022, v1.0

RD9 MICADO Opto-Mechanical Design and Analysis, E-TRE-MCD-561-0011, v5.0

RD10 MICADO Control Electronics Design, E-TRE-MCD-561-0013, v1.0

RD11 MICADO Top Level Instrument Software User Requirements, E-TRE-MCD-561-001, v1.0

RD12 MICADO Top Level Data Reduction User Requirements, E-TRE-MCD-561-0024, v1.0

RD13 MICADO Compliance Matrix, E-TRE-MCD-561-0008, v2.0

RD14 MICADO-MAORY Phase A Interface Specification, E-SPE-MCD-561-0014, v1.0

RD15 MICADO-EELT Phase A Interface Information and Requests, E-SPE-MCD-561-0015, v1.0

RD16 Guidelines for the post-focal SCAO NGS wavefront sensor for the E-ELT AO based instrumentation, E-TRE-ESO-528-0462, v0.4

3 PROJECT OVERVIEW

MICADO is the Multi-AO Imaging Camera for Deep Observations, which is being designed to work with adaptive optics on the European Extremely large Telescope. The instrument is intended to image, through selected wide and narrow-band near infrared filters, a wide (approximately 60arcsec) field of view at the diffraction limit of the E-ELT. The goal of the consortium is to design a camera that will initially work with SCAO (with wavefront sensing provided by its own SCAO module) and GLAO (provided by the E-ELT; note that the instrument is not optimised for this mode); and later to work with MCAO (specifically the MAORY concept).

In addition to the primary imaging field, MICADO will have a second arm which provides additional capabilities over a smaller (of order 10arcsec) field over view. These capabilities will include imaging at different pixel scales, and simple long-slit spectroscopy for compact objects.

4 PHASE 1 TRADE-OFFS

4.1 Technique of Instrument Concept Selection

4.1.1 Design Concepts

During Phase A1, two design options have been elaborated in parallel and subjected to a trade-off study and risk assessment:

1. Monolithic (‘Offner’) design
2. Segmented design

4.1.2 Decision Criteria

The criteria which have been taken into account for the trade-off are:

- Simple and robust design
  - minimize complexity
  - avoid unproven technology, as far as possible
  - avoid uncontrollable risks
- address as many of primary science cases as possible:
  - Astrometry
  - Sensitivity, which can surpass that achieved by JWST
  - Photometry in crowded fields
  - Basic spectroscopic capability,
- availability at first light of E-ELT
- cost and manpower required for implementation (development, design and MAIV)

4.1.3 Trade-off Tables

From these criteria the trade-off tables in section 4.2 have been compiled to make as clear as possible the relative performance of each instrument concept – both from the technical and science perspectives.

4.2 Phase 1 Trade-off and Risk Assessment

In this section, the decision criteria are systematically listed in scientific and technical trade-off tables. The compliance with requirements and the extent to which each of the two design concepts is likely to support additional goals or optional cases is illustrated by colours from green ('full compliance, ideal') over yellow ('minimum requirement fulfilled') to red ('requirement not met, showstopper').

4.2.1 Science Support

The compliance of the two instrument concepts with the top-level requirements as derived from the science trade-off is illustrated in Table 1:

Top-level requirement	Goal / min spec.	Monolithic design	Segmented design
TLR1 Field of view	60" / 30"	49"	48"
TLR2 Spatial sampling	2 mas / 3 mas	3 mas	4 mas (entire field); 4 / 2 mas (central channel with zoom mode)
TLR3: Total wavelength coverage	0.8 – 2.5 µm / 1.0 - 2.5 µm	0-8 – 2.32 µm 2.5 µm possible	0-8 – 2.32 µm 2.5 µm possible
TLR4: Throughput / sensitivity (instrument only)	65 % / 60 %	96 % (with IR gold coating of mirrors)	91 % ext channels; 94 % / 91 % central channel with zoom x1 / x2
TLR5: Instrumental distortions	to allow routine astrometry with 50 / 100µarcsec	max. 5.12 % (over entire FoV)	Max. -1.8 % (over entire FoV)
TLR6: Ghosts & scattered light	TBD / <2% of the sky+thermal background at the detector. Focused ghosts $<10^{-4}$ of the source brightness	Full reflective, ghosts can only be caused by filters (avoided by tilting), windows, detectors	

TLR7: Number of filters	Additional ~20 NB / 6 broad-band and ~15 NB filters,	small pupil size (55 mm) allows allocation of all desired filters (> 20)	pupil size (129 mm) may cause problems to filters allocation (except central channel), volume optimization has to be studied
TLR8: Number of masks	TBD / none	TBD	TBD
TLR9: Instrument background	TBD / <10% in H and K of the thermal background of the telescope	To be investigated	
TLR10: Image quality	TBD / <20% degradation of the FWHM of the diffraction-limited core of the PSF delivered by MAORY (for whole wavelength range)	worst case Strehl ratio 94.5%	worst case Strehl ratio 81.4%
TLR11: Photometric accuracy	few (eg. 3) % / 1 %	To be investigated, but likely depends more on data analysis method than instrument design	
TLR12: Astrometric accuracy	50 / 100 μarcsec	Relative flexure is minimised by monolithic optics & a single detector mount	Relative flexure between arms is unknown
TLR13: Spectroscopic capability	one long slit ~6 mas wide + grism with R=2000-3000 / none	can be implemented in auxiliary arm	can be implemented in central channel

Table 1. Trade off table – top-level requirements

From the science perspective, there is little to choose between the two designs studied. The monolithic design may offer the better mechanical stability needed for astrometry. However, it appears that either design would be able to fulfil the science requirements as given.

4.2.2 Technical Trade-off

The technical trade-off is illustrated in Table 2. Only a small number of technical criteria can be compared quantitatively, and therefore most of the trade-off is purely qualitative, making use of our experience from previous instruments.

Criterion	**Monolithic design**	**Segmented design**
Mass (instrument & cryostat)	Less heavy: ~2820 kg	Heavy: ~4355 kg
Dimensions	Smaller: Ø1900 x 1600 mm	Larger: Ø1600 x 4000 mm
Optics complexity / no. of opt. elements	Fewer optical elements	More optical elements
	auxiliary arm contains more folding optics	"Center" arm contains less folding optics
Optics dimensions	Larger optics	Smaller optics
General configuration / access	More compact design → easier manufacturing, → good access during assembly, → accuracy and stability of opto-mechanics easier achievable	Very tall cryostat with detectors on top (due to inefficient use of space) → long cabling, bad access
	Outside mounting[1] of optics & detectors possible	Outside mounting of optics not always an option → could result in alignment issues as the mounting interface and mirror surface are not on the same side
		Many optical elements close to cryostat axis (impedes access during assembly and integration). Modular outer arms will lead to a weight penalty and possible alignment issues (interference) with wheels inside the second platform
Detector layout	Detector layout ideal for simple and low weight cooling: short distances mean low mass in copper	Detectors far apart: long copper bars or braids needed (weight penalty)
Complexity of mechanisms	Linear mechanisms required (more complex / less reliable than rotational mechanisms)	No linear mechanisms

[1] Mounting interface same side as optical surface, mounted on outside of structure.

Impact on schedule / parallel activities	Three-level layout is well suited for engineering, manufacturing, assembly and testing in parallel	Three-level layout is well suited for engineering and manufacturing in parallel
		Layout is not well suited for parallel assembly and testing: all instrument sub-structures are needed including the cylinder wall.
	Verification of the two separate modules is possible. Once one module is finished, AIT may start	Verification of modules difficult. Large amount of optics does not lead to advantages in production time (every mirror needs individual attention) Since all parts of a segment need to be finished, AIT cannot start before end of the production phase
	Accessibility of all parts due to the compact design may reduce optional overhaul time, especially in comparison to the segmented design	As accessibility is limited the assembly order becomes more complex and less flexible, therefore AIT time is vulnerable to changes/ setbacks. Accessibility of all parts due to the extended design will increase optional overhaul time
Cross impact in case of changes	Independency between the three levels due to simple planar interfaces: cross impact minor in case of changes in the later stages of the opto-mechanical design	Cross impact severe in case of changes in the later stages of the opto-mechanical design
	Single optical elements (no series): outsourcing/manufacturing might be more difficult	Series of optical elements: outsourcing/manufacturing might be easier
Cryogenic design / cooling method	Liquid nitrogen for cool down (to avoid excessive number of cryo-coolers; see below), cryo-coolers during steady state.	
Temperatures	Detectors 60 K; Optical bench 100 K; Radiation shield 120 K	
Cooldown time	38 h	48 h
No. of cryocoolers	[Cooldown: 6] steady state: 5	[Cooldown: 10] steady state: 5
GSE	Complexity is limited due to the compact design	Complexity and safety issues are severe due to the extended design

Table 2 Technical trade-off between monolithic and segmented design

The segmented design was pursued because initially it appeared to offer a number of simplifications with respect to the monolithic design. However, the perceived simplifications were not borne out in reality: the mechanical design is already close to the weight limit, and the cost greater than that of the monolithic design; the eight outer arms are no longer all identical; diagonally crossing the arms was optically complex and risky; the pupils, although well defined, are more than two times larger than for the monolithic design. It should also be noted that while both designs enable imaging of the same field of view, the segmented design does so with a larger pixel scale (4mas, rather than 3mas) and hence uses nine detectors rather than 16 for the primary field in the monolithic design. If the segmented design were modified by reducing the pixel scale to 3mas then additional arms would be needed, which would very significantly increase the complexity and cost.

The conclusion of this technical comparison is that the monolithic design appears to offer significant advantages with respect to the segmented design.

4.2.3 Risks and Showstoppers

For comparison of the two Phase A1 concepts a preliminary list of risks has been set up (see Table 3). No show-stoppers can be identified for either of the two design options. However, it should be noted that the requirement to re-design the optics for the segmented design to accommodate a common pupil is considered a significant risk, and may not be possible. On the other hand, without such a re-design the segmented design is considered impractical.

<table>
<tr><th>Monolithic design</th><th>Segmented design</th></tr>
<tr><td>Since no specifications are available on the large (530 mm) spherical mirror, production of this mirror is considered as challenging</td><td>If one common pupil is not possible, the segmented design becomes impractically large and expensive</td></tr>
<tr><td>Detector price might not go down to the predicted € 0.02 per pixel (16 detector Offner design has more than 112 000 000 extra pixels compared to segmented design)</td><td>Some off-axis parabolic mirrors have a vertex distance radius of 4 meter (not easy to verify)</td></tr>
<tr><td colspan="2">Opto-mechanical tolerances not investigated. Relation between mechanical accuracy & part/assembly size could lead to manufacturing/outsourcing and/or alignment issues</td></tr>
<tr><td colspan="2">Flexure: Gravity-invariant mounting is mandatory (vertical instrument rotation axis)</td></tr>
</table>

Table 3 Preliminary list of risks

4.2.4 Implementation Costs

A comparison of the manpower and cost needed for design and implementation of the two instrument options investigated in Phase A1 led to the result that the monolithic design can be implemented at significantly lower expenses.

The estimated total cost and manpower for the monolithic design was 17,7 MEuro / 148 FTE compared with 22 MEuro / 185 FTE for the segmented design (all figures including 30% contingency), i.e. in both cost and FTE the monolithic design will save around 20%.

4.3 Conclusions of Phase A1 Study

4.3.1 Design Concept Selection

The trade-off has not brought out a clear show stopper for either of the two design options. Both appear to be capable of supporting the main science one can tackle with the E-ELT.

However, we have identified a number of primarily qualitative drawbacks of the segmented design: it is already close to the weight limit and considerably higher than the monolithic design, thus compromising the opto-mechanical stability. Furthermore, the segmented design is significantly more complex: it requires a higher number of optical elements, the eight outer arms can not be all identical, diagonally crossing the arms is considered to be optically complex and risky. Extending the design to more than 3x3 detectors is not straightforward, the pupils, although well defined, are more than 2x larger than for the monolithic design. In addition to that, the cost for implementation of the segmented design is significantly higher than that of the monolithic design.

On the other hand, the monolithic design, complemented by the auxiliary arm, offers the same capabilities and performance for science, however at the advantage of lower mass and size and reduced complexity.

On the basis of this trade-off, the consortium has unanimously decided to focus on the monolithic design during Phase A2.

4.3.2 SCAO module

During the trade-offs carried out in Phase A1 the consortium has identified a need for a SCAO module that would make use of natural guide stars to provide diffraction limited imaging during the first phase of operations.

Although the SCAO module was not part of the original call for proposals ESO has recommended that the consortium should include this in part 2 of the MICADO Phase A study.

It was agreed that the study should address

- science requirements based on MICADO science analysis report

- perform SCAO system analysis, define WFE budget, and evaluate expected performance

- perform analysis of NGS WFS, select an appropriate detector, prepare opto-mechanical design including interface to MICADO and telescope.

Early on, the consortium decided to focus the Phase A study on an optical WFS that could work with as many science targets as possible. More complex options such as an IR WFS shall be left to Phase B, once the main issues for the module have been identified.

5 PHASE 2 TRADE-OFFS

5.1 Main Imaging Field Optical Design

In order to consolidate the optical design of the main imaging arm of MICADO, a number of different designs were considered in order to assess the feasibility and impact of the various options and issues. These include:

- Can the design accommodate the strong field curvature from MAORY? What is the impact on image quality and focal plane geometry?
- What can be done to minimise field dependent changes in pupil size/shape/location?
- Are there implications when imaging with narrow band filters?
- How complex is the design, as well as the shape and size of the optics? What are the implications on folding?

These issues have been addressed in different ways in 5 specific designs developed by David Freeman, and their respective pros and cons have been assessed. Here we first present the individual designs, and then compare their most important characteristics in a trade-off table.

5.1.1 Designs Considered

All the designs are developed around the following requirements:

1. optimised for MAORY optical interface (i.e. 1293mm curvature radius)
2. will work sufficiently well with the much flatter telescope optical interface over a smaller field
3. assume an input field size of 191x191mm (53arcsec at 3.605mm/arcsec)
4. image the field onto 3mas pixels at the output field centre (output field nominally 261x261mm)

We note that *all* designs require an undersized pupil in order to block unwanted background.

The first 2 designs were direct developments of the 3-mirror design from Phase 1, which addressed the problem of field dependent pupil position. In the first of these, shown in Figure 1, the smaller pupil was possible due to the greater power in the mirrors, which resulted in a more compact design. The second of the 3-mirror designs, shown in Figure 2, has a nominal size pupil (i.e. approximately 100mm). However, this leads to a larger design.

The next 2 designs, shown in Figure 3 and Figure 4, are based around 4 mirrors. In these designs, the first mirror creates the pupil in a collimated beam, which is then imaged by a 3-mirror system.

The final design, in Figure 5, is for the more classical approach of a catadioptric design. We note that

(i) with a strongly curved input field, there is no 'ideal' design: the output focal plane must also be curved, and field dependent changes in pupil shape/size/location cannot be eliminated.

(ii) the design appears more compact in the figure because it is already folded; however, the unfolded camera is long. Perhaps the biggest advantages of this design are the abilities to include spectroscopy and change the pixel scale. This is an important issue that is addressed separately in detail in Section 5.2.

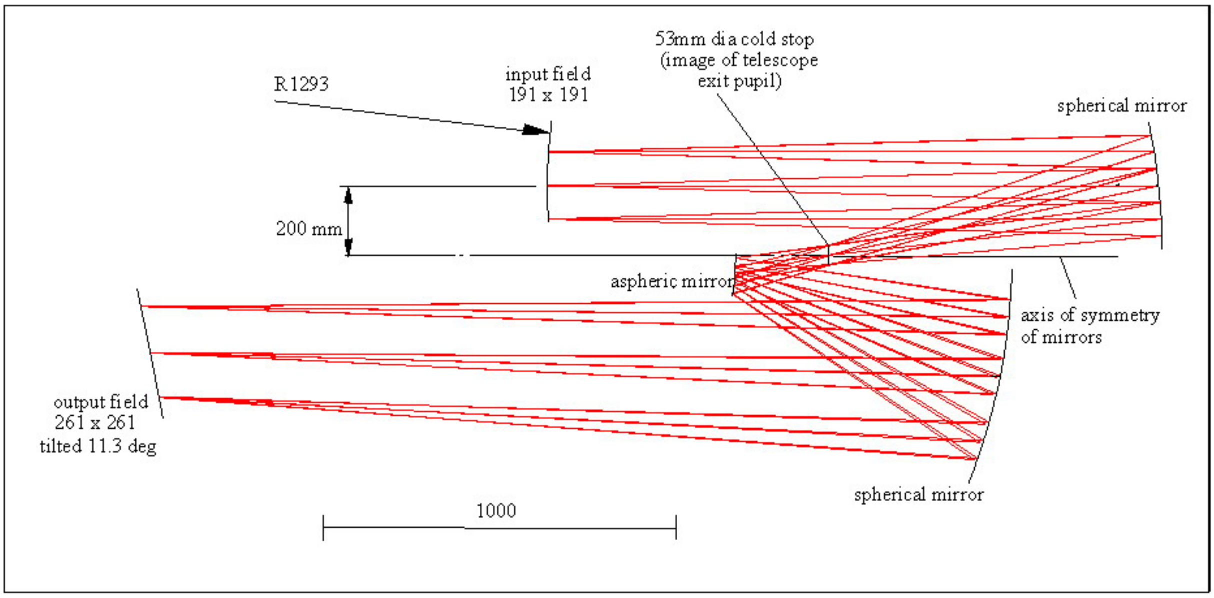

Figure 1: 3-mirror optical design with a small 53mm pupil.

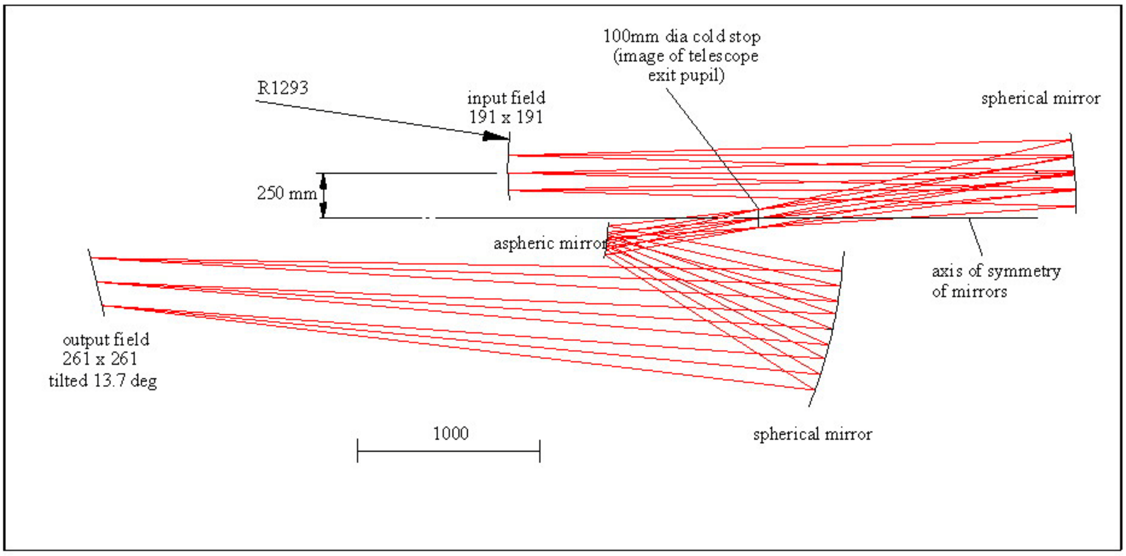

Figure 2: 3-mirror optical design with a nominal (100mm) pupil size.

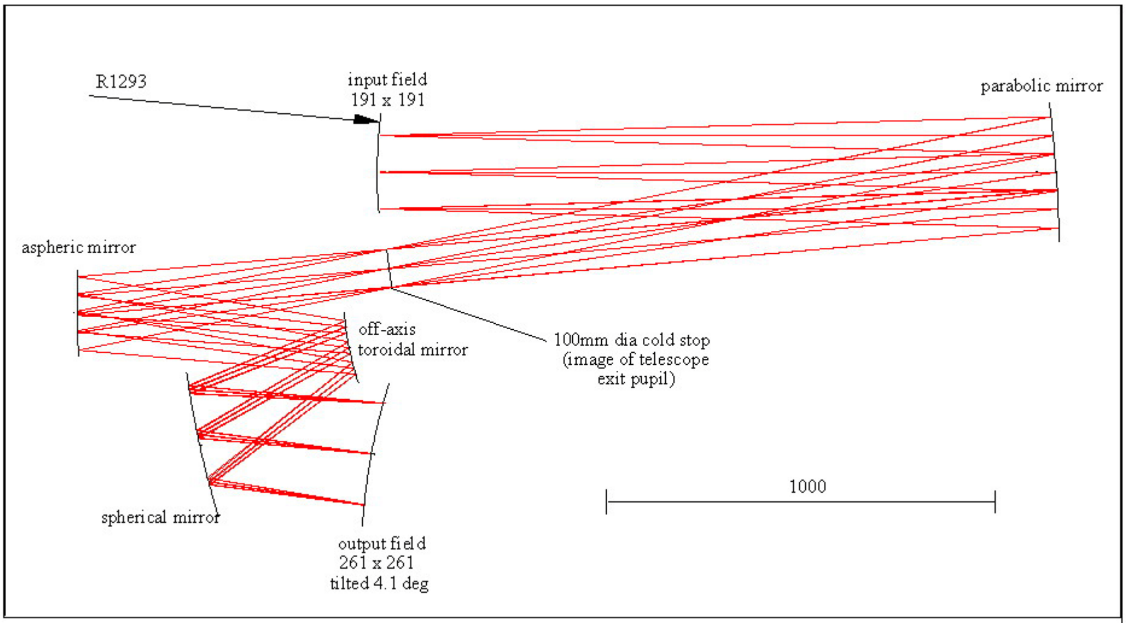

Figure 3: 4-mirror design with a 100mm pupil collimated by an off-axis parabola.

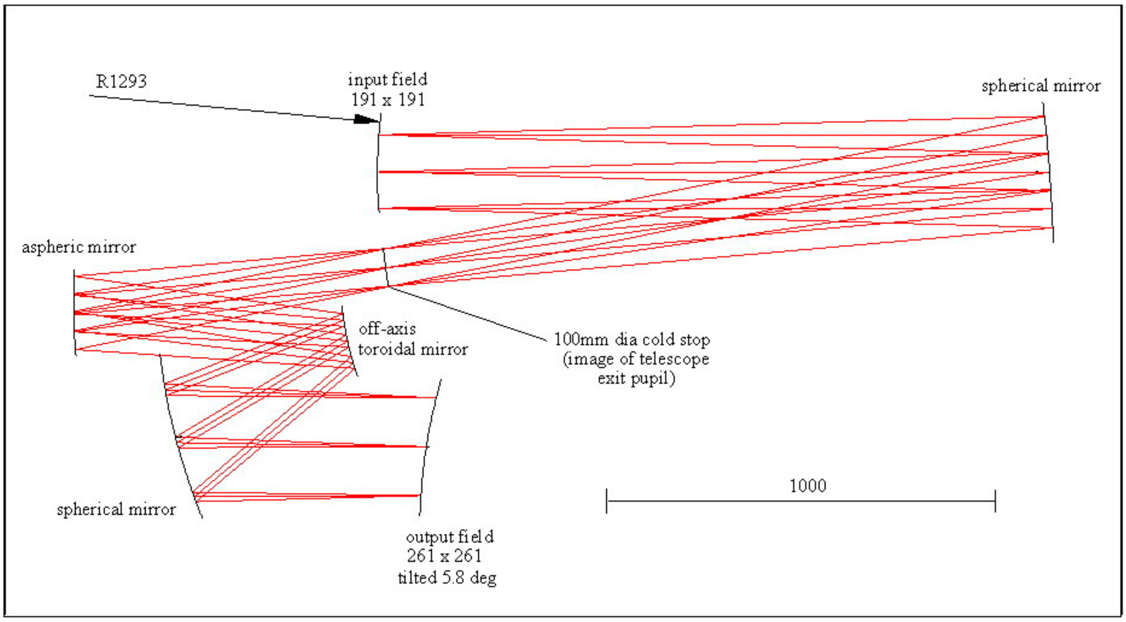

Figure 4: 4-mirror design with a 100mm pupil collimated by a spherical mirror.

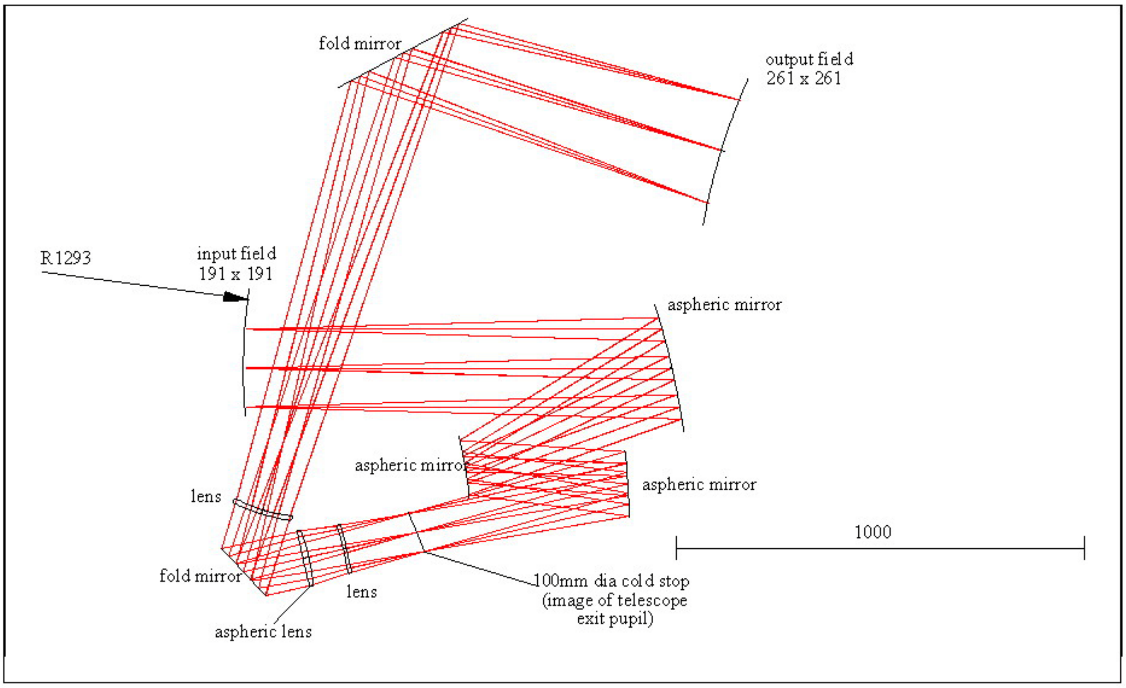

Figure 5: classical catadioptric design with a 3-mirror anastigmat to collimate the pupil and a 3-lens camera for re-imaging. The design is already folded.

5.1.2 Trade-off Table

For this trade-off, the only criteria considered were directly related to only the efficancy of the optical design to image at a fixed pixel scale. Each design was scored for each metric, and these are denoted by the colours (on a scale of 1-4 from red, through orange and yellow, to green). The purpose was to select the design with the minimum score.

Design	**3 mirror (small pupil)**	**3 mirror**	**4 mirror, parabolic collimator**	**4 mirror, spherical collimator**	**Classical catadioptric design**
Cold Stop diameter	53mm	98mm	99mm	98mm	98mm
Pupil area undersize (dependent on field position)	6.5% – 6.9%	1.2% – 2.4%	0.1% – 1.4%	0.8% – 1.8%	3.6% – 5.4%
Convergence at pupil (impact on narrow band filters)	1.33deg about chief ray; chief ray angles to 8.1deg	1.26deg about chief ray; chief ray angles to 4.4deg	Collimated; chief ray angles to 4.4deg	Collimated; chief ray angles to 4.4deg	Collimated; chief ray angles to 4.4deg
Imaging quality (Strehl) at 780nm	0.93 – 0.97	0.91 – 0.98	0.90 – 0.96	0.90 – 0.98	0.84 – 0.98

Detector plane	Flat. Tilted by 11.3deg	Flat. Tilted by 13.7deg	Convex (1500mm radius). Tilted by 4.1deg	Convex (1500mm radius). Tilted by 5.8deg	Convex (1500mm radius).
Output Field: Width mm Height mm	267.1 – 260.8 262.4 – 263.5	265.2 – 260.4 264.1 – 264.9	261.2 – 266.1 268.5 – 269.2	255.0 – 253.0 257.1 – 257.2	265.8 – 270.0 265.1 – 266.1
Size	Design is moderately long, so needs folding.	Design is very long so needs folding (hard)	Collimator long. Otherwise design is compact.	Collimator long. Otherwise design is compact.	Camera is very long so needs folding (straightforward)
Detector Mount	Flat	Flat	Detectors must be mounted optimally (relative tilts by up to 5.4deg) to minimize focal mismatch & keep strehl in range 0.88 – 0.94.	Detectors must be mounted optimally (relative tilts by up to 5.4deg) to minimize focal mismatch & keep strehl in range 0.88 – 0.98.	Detectors must be mounted optimally (relative tilts by up to 5.4deg), to minimize focal mismatch & keep strehl in range 0.88 – 0.98
Number, size, and complexity of optical components	Only 1 simple aspheric. 1 mirror is large (0.6m)	Only 1 simple aspheric. 1 mirror is very large (0.9m)	3 aspheric mirrors. 2nd mirror very off-axis. 3rd mirror has complex shape	2 aspheric mirrors. 2nd mirror very off-axis. 3rd mirror has complex shape	3 aspheric mirrors, 3 lenses (~15cm diameter; 1 aspheric). Active area of 2 mirrors has complex shape. Lens transmission low at 2320nm.

Table 4 Technical trade-off between optical design

5.1.3 Conclusion

The trade-off table shows that there are no show-stoppers for any of the designs, but that the 4-mirror designs are slightly favoured. We have therefore selected the 4-mirror design with a parabolic collimator.

5.2 Inclusion of Auxiliary Arm

The heart of this important issue can be posed as the following question:

Should the ability to change the pixel scale and perform spectroscopy, as required by the science cases, be incorporated into the design of the main imaging field or be included in a separate auxiliary arm?

5.2.1 Trade-off Issues

The main points addressing this are summarised in the following table:

Astrometry & pixel scale changes	Astrometry has been identified as one of the key capabilities for MICADO. This is one of the reasons why the instrument is designed to have gravity invariant rotation – to minimize flexure. For the same reason, there is a strong preference for all the optics in the main imaging field to be fixed. To a large extent, this negates the principal advantage of the catadioptric design, which would otherwise have provided the best way to change pixel scales by a complete exchange of the camera optics. The need to change pixel scales is driven by performing astrometry in extremely crowded fields, and so only a small field (a few arcsec) need be imaged at the finer scale. For the 4-mirror design, it is possible to insert a set of optical elements to provide a 1.5mas scale across a single detector (see Figure 6). Alternatively, the capability is provided by the auxiliary arm. There is little to choose between these two options.
Spectroscopy	Spectroscopy would be performed best by the catadioptric design; but for the reasons in Section 5.1 and also above, this design has not been selected. The designs of the main imaging field and auxiliary arm are very similar, and the spectroscopic performance in both is similar. Although a longer slit is, in principle, possible in the main field, there is no requirement for this. The science requirement is for spectroscopy of compact sources; and operationally, nodding is limited to very small distances. As such there is no need to have a slit longer than ~10arcsec. A minor advantage of the auxiliary arm is that it allows the spatial pixel scale to be optimised to the slitwidth: for the 12mas slit width, we have increased the pixel scale to 4mas to avoid greatly oversampling.
Performance & flexibility	The 4-mirror design is able to offer similar performance (spectral coverage; and for imaging, FoV at 1.5mas) to the auxiliary arm, but not more. In this respect the two options are equal. One important advantage of the auxiliary arm is the flexibility it affords. Depending on requirements, one could redesign it independently of the main imaging field – for example to provide better spectroscopic capability; or to

	include additional capabilities such as - basic polarimetry; - simultaneous dual-wavelength imaging (e.g. on-line and off-line for emission line imaging); - high time resolution astronomy. This latter option could conceivably be provided simply by adding by an additional fold mirror that sends the light to a different detector.
Cost, Complexity, Robustness	As is apparent from the Opto-Mechanical Design Report (RD8), the auxiliary arm has little impact on cost and complexity. For example it is not driving the size of the cryostat nor adding large or complex optics. Indeed, although the option has not been studied, the cost and complexity (in terms of optics, motors, etc) of providing the same capability in the main arm is likely to be comparable. The requirement that the main field be as robust as possible would argue for a separate auxiliary arm. In the current design, only one additional optic moves in/out of the optical path for this field. In a design where the capabilities of the auxiliary arm were included in it, there would be at least 2-3 additional moving optics, adding risk to this primary capability.

Table 5 Trade-off for auxiliary arm

5.2.1.1 Note on Changing Pixel Scale in the Main Imaging Field

The options available for changing the pixel scale in the 4-mirror design have been assessed by David Freeman. The assumptions are that one needs to change the pixel scale from 3mas to 1.5mas across one $4k^2$ detector. The full report is available on request, but the summary conclusions are as follows:

1. unacceptable performance is given by any of the following:
    a. replacing the collimator
    b. adding optics near the cold stop
    c. adding optics that do not increase the optical path length
    d. using powered mirrors
2. using lenses to increase the path length between the input field and collimator can give excellent performance but is quite complex (minimum 4 lenses and 3 plane mirrors); but this solution works for any part of the field
3. using lenses to increase the path length between the last mirror and the detectors can give good performance; one needs 2 lenses (negative power achromatic doublet) and 2 plane mirrors as a minimum (alternative solutions exist with more mirrors); the performance may be field dependent.

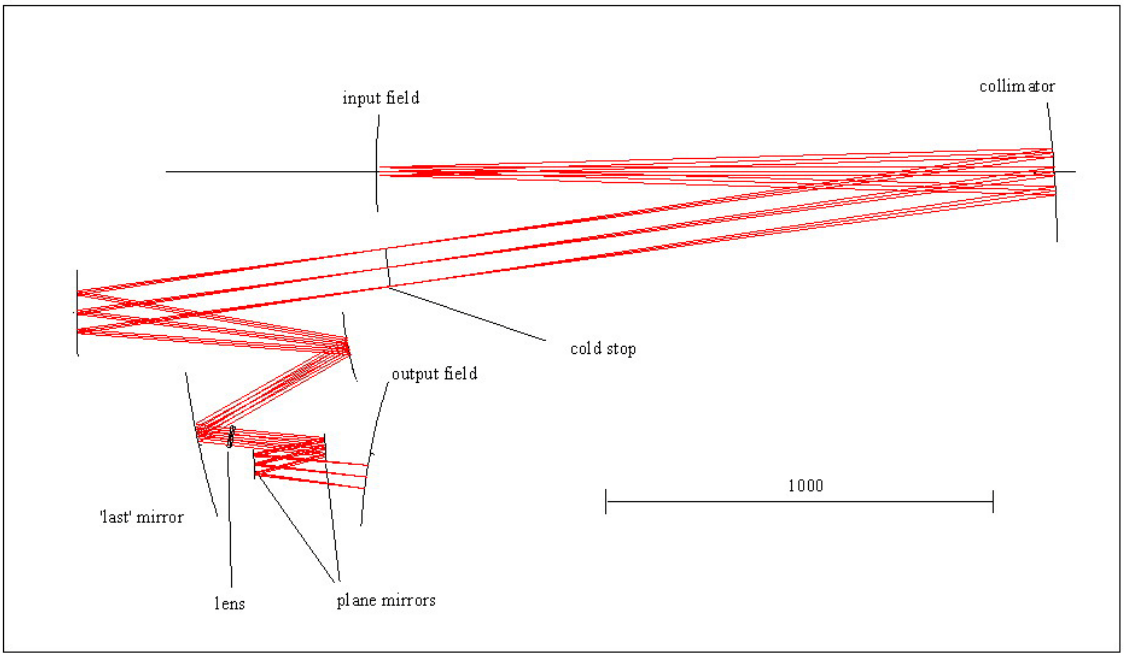

Figure 6: One illustration of how, by inserting lenses and mirrors in front of the detector array, one might change the pixel scale for a part of the main imaging field.

5.2.2 Conclusion

The conclusion is that there is little to choose between including the capabilities of the auxiliary arm in a separate arm or incorporating them into the main arm. Our preference is to keep a separate arm, since this provides (i) better stability and hence astrometric performance in the primary arm, and (ii) the flexibility during Phase B to include other capabilities that might be wanted by the community.

5.3 Mechanical Design Trade-off

5.3.1 Mechanical Design Options

Based on the chosen optical design concept, two mechanical design options have been developed and presented to the consortium:

1. Vertical cryostat
2. Horizontal cryostat

5.3.1.1 Vertical cryostat

The vertical cryostat concept is shown in Figure 7. For this concept the cryostat dimensions are Ø1500x1900mm, but the rotation would be around an off-center axis, resulting in a rotating diameter of Ø2300mm.

The vertical concept allows highly merged optical models, main and auxiliary are sharing one filter wheel, and selection of the arm would be done by inserting a folding flat.

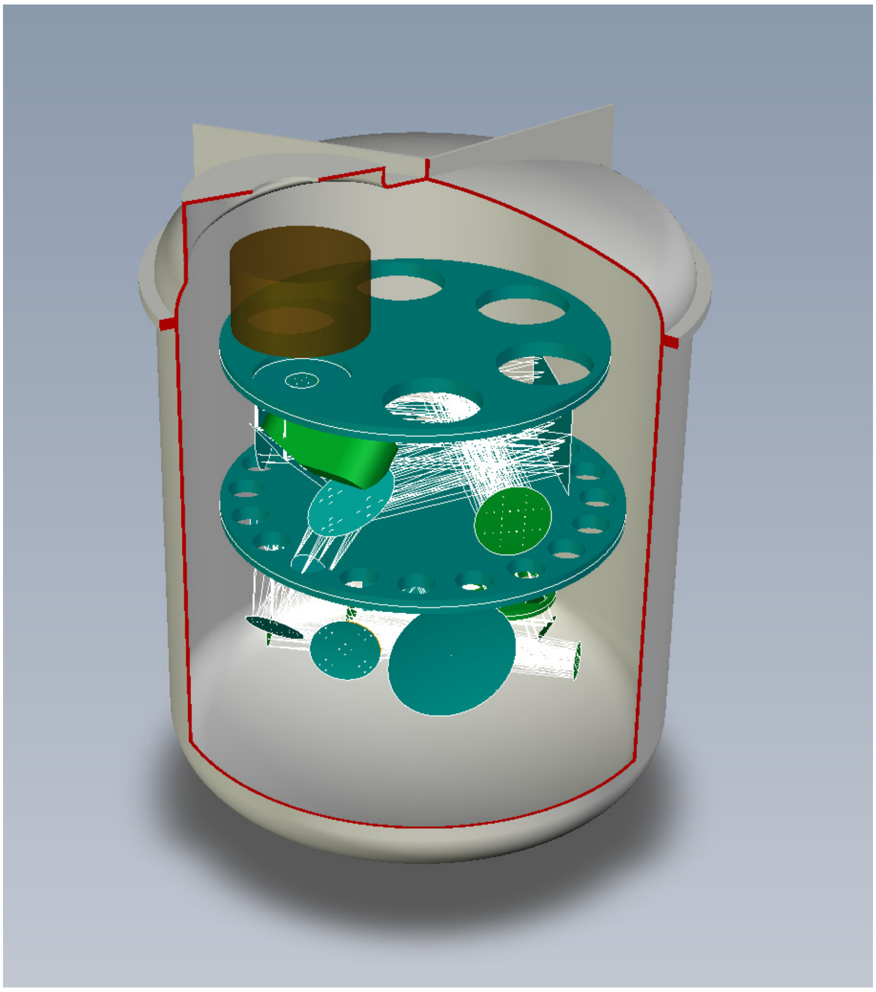

Figure 7: Vertical cryostat

5.3.1.2 Horizontal cryostat

In the horizontal cryostat concept (see Figure 8) the two arms are folded of in opposite direction. The dimensions of the horizontal cryostat are Ø1700x1600mm, overall height 1900mm. The rotating diameter is Ø2200mm, the CoG is nearly on the rotation axis

This concept allows partly merged optical models, it requires separate filter wheels for the main and auxiliary arm and a movable parabola for selection of the arm.

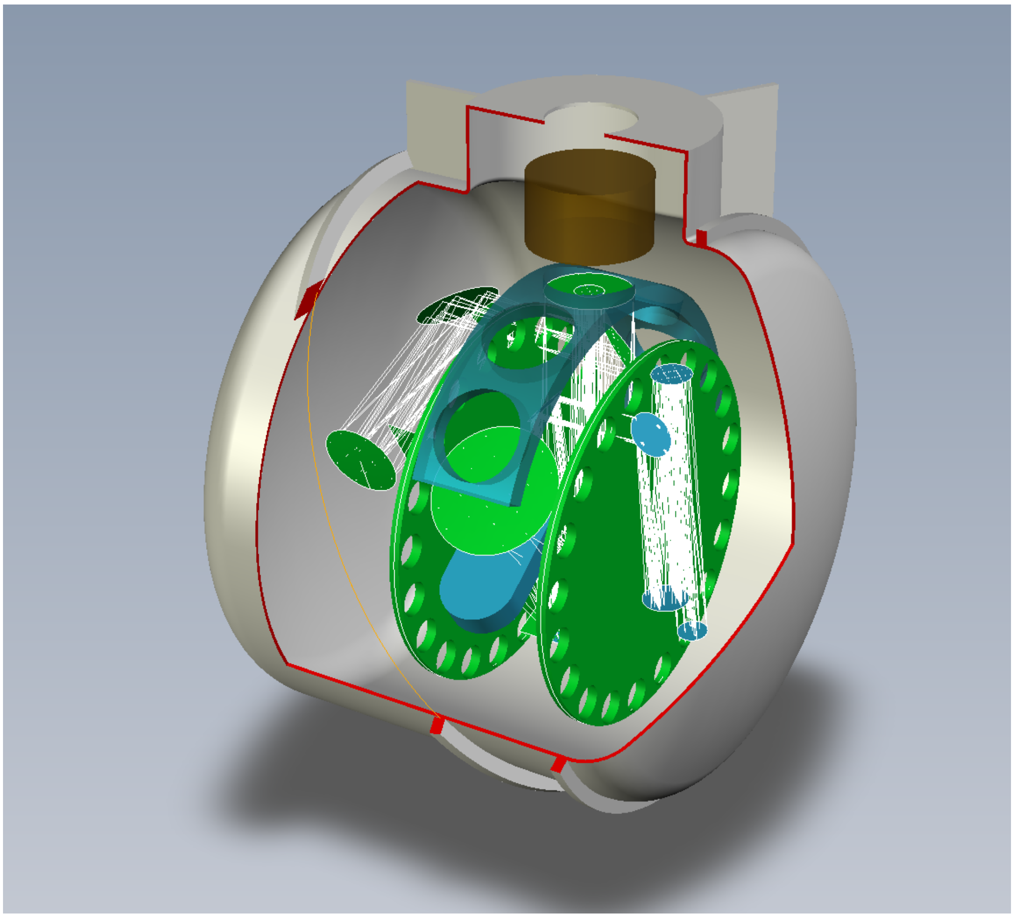

Figure 8: Horizontal cryostat. Note that this image shows the first concept for a horizontal cryostat as considered during the design trade-off, not the state of design at the end of Phase A

5.3.2 Trade-off Table

For the trade-off, each design was again scored on a scale from 1 (ideal) to 4 (show-stopper), indicated by colours from green, through yellow and orange, to red. The purpose was to select the design with the minimum score.

	Vertical cryostat	**Horizontal cryostat**
Astrometry	Imager has only fixed mirrors; rotation is gravity invariant	Imager has only fixed mirrors; rotation is gravity invariant
Take out auxiliary arm	No impact IM, shorter, CoG same but off-axis	No impact IM, volume same, CoG minor change, on-axis
Overall dimensions/Weight	Ø1.5x1.9m Rot 2.3m	Ø1.7x1.6m Height 1.9m Rot 2.2m

Shape/stability (during cool-down)	Shrinkage is on axis but optical beam is not	Optics on-axis, so alignment is naturally maintained during cooldown
Mirror mounting	No problems	No problems
No. and accommodation of cryogenic mechanisms	4 Very limited space for selection mechanism (main / auxiliary arm), difficult to realize	5 Parabolic selection mechanism for auxiliary arm
Focal plane selection wheel	Standard wheel mechanism (circular plate)	Cylindrical focal plane wheel (slightly more complex)
Filter / grism wheels	One shared filter wheel (less HW but requires optical paths to cross at same angle, & less flexibility in filter choice)	Two filter wheels, focal plane selection mechanism wheel more complex design
Location detector unit	Very long (>2m) cable to outside, since fixed part of cryostat is at top	Fixed part of cryostat is all around, so only short cables needed.
Number of added folding mirrors	Main arm: 4 (one double pass); Auxiliary arm: 4	Main arm: 3 (one double pass); Auxiliary arm: 3 (one double pass)
Cryostat aspects/cooling circuit	Space for pumps cabling etc. is very limited (needs to be at top of cryostat)	Sufficient space on fixed section of cryostat
Service aspects (at telescope location)	Not possible when installed at the telescope	Both ends of cryostat can be removed at the telescope, providing good access to all key components
Cable wrap and de-rotation concept	Only top is possible unless cables are lengthened and brought down the outside of the cryostat	Top and floor entrance/exit to cryostat; so cable wrap can be mounted on the Nasmyth platform

Table 6 Trade-off between vertical and horizontal cryostat design

The result from this trade-off study is very clear: In most relevant aspects the horizontal design is either equal or superior to the horizontal design. In particular for the two high ranking criteria

- structural stability,
- access for service,

the horizontal cryostat concept excels over the vertical, and has thus been chosen to be pursued in the next project phases.

6 RISK ASSESSMENT

6.1 Scope

In this section we present the risk management strategy chosen in the MICADO project and the current state of the risk register for the MICADO concept proposed at the end of Phase A2.

6.2 Risk management strategy

The MICADO project has introduced a systematic and iterative risk management system to identify and mitigate technical and programmatic risks. Risk management is carried out by managers and engineers at all project levels. The goal of risk management is to identify and assess the entire spectrum of risks, classify undesired events for their severity and likelihood of occurrence and perform trade-offs among different options for mitigating the risks in order to optimize the final project outcome, in terms of schedule, cost and performance.

6.3 Implementation of risk management process

Within the risk management process, available risk information is collected and classified in the MICADO Risk Register. The Risk Register lists all the risks identified since the start of the project, their grading in likelihood of occurring and seriousness of impact on the project as well as the plans for mitigating high level risks and the anticipated subsequent results.
The status and results of risk assessment and reduction are communicated within the project team for information and follow-up.

6.3.1 Risk management steps

The risk management process is including the following sequence of steps:

Step 1: Identify and assess the risks

- identification of risks and risk scenarios including causes and consequences, based on input from all project domains (technical, managerial, programmatic)
- determination of the magnitude of the individual risks (from ranking according to severity and likelihood of occurrence, see section 6.3.2).

Step 2: Decide and act

- analyse the acceptability of risks based on risk acceptance criteria
- for accepted risks proceed directly to Step 3

- for unacceptable risks, determine an appropriate risk reduction strategy, assess risk reduction potential of all mitigation measures/options and select the best risk reduction measures)
- verification of risk reduction, identification of risks that cannot be reduced to an acceptable level and presentation to the appropriate management level for disposition

Step 3: Monitor, communicate, and accept risks
- periodical assessment and review of all identified risks and updating of the results after each iteration of the risk management process in the risk register
- identification of changes to existing risks and initiation of new risk analysis needed in order to decrease uncertainties.
- verification of the performance and effect of corresponding risk reduction

6.3.2 Classification of risks

Classification of risks is performed according to likelihood of occurrence and severity as illustrated in Table 8 and Table 7:

E	Maximum	Certain to occur at least once or more times in a project
D	High	Will occur frequently (about 1 in 2 projects)
C	Medium	Will occur sometimes (about 1 in 10 projects)
B	Low	Will occur seldom (about 1 in 100 projects)
A	Minimum	Will almost never occur (about 1 in 1000 projects)

Table 7 Rating for likelihood of risks

5	Catastrophic	Leads to termination of the project
4	Critical	e.g. top-level functional requirement(s) not met, cost increase > 30%, delay of more than one year
3	Major	e.g. performance requirement(s) not met, cost increase > 20%, delay of more than six months
2	Significant	e.g. lower-level requirement(s) not met, cost increase > 10 %, delay of more than two months
1	Negligible	Minimal or no impact

Table 8 Rating for severity of risks

Table 9 shows a risk magnitude scheme combining the effects of severity and likelihood of risks, the required actions resulting form the rating of a risk are listed in Table 10.

		Severity				
		1	2	3	4	5
Likelihood	E	medium	medium	high	very high	very high
	D	low	low	medium	high	very high
	C	very low	low	low	medium	high
	B	very low	Very low	low	low	medium
	A	very low	Very low	very low	very low	low

Table 9 Risk magnitude scheme

Grade	Risk Actions
E4, E5, D5	Unacceptable risk: Actions to reduce the likelihood and seriousness mandatory. Implement new process or change baseline – seek project management attention at appropriate high management level
E3, D4, C5	Unacceptable risk: Actions to reduce the likelihood and seriousness to be identified and appropriate actions implemented during project execution.
E1, E2, D3, C4, B5	Actions to reduce the likelihood and seriousness to be identified and costed for possible action if funding permit. Consider alternative process or change of baseline.
D1, D2, C2, C3, B3, B4, A5	Acceptable risk: Control, monitor – seek responsible work package management attention. No further action is needed unless grading increases over time.
C1, B1, B2, A1, A2, A3, A4	Acceptable risk: No action is needed unless grading increases over time.

Table 10 Required actions for grades of risk

6.4 MICADO Risk Register

The MICADO Risk Register is considered as a living document which will be updated throughout all project phases. The risks included in the register have either been extracted from the Phase A reports (RD5 … RD15) or filed upon direct input the project partners. The current version of the Risk Register is given in Table 11:

No.	Risk scenario	Risk Source	Likelihood	Severity	Grade	Mitigation measures	Responsible	Due date	Status
Technical risks									
T-01	Instrument dimensions (e.g. height) not compatible with E-ELT / MAORY	Mechanical interface MICADO – MAORY (E-ELT)	A	3	very low	none (current baseline is compatible with MAORY and E-ELT)	-	-	closed
T-02	Instrument mass exceeds mass limit	Mechanical interface MICADO – MAORY (E-ELT)	B	3	low	Update and monitor instrument mass estimate based on preliminary design	Astron	PDR	open
T-03	Flexure of main structure / opto-mechanics due to changing gravity vector	E-ELT interface, gravity-variant mounting	A	3	very low	none (gravity invariant mounting is baseline)	-	-	closed
T-04	Flexure of main structure / opto-mechanics due to thermal distortions	Thermal control of cryogenic structure	C	3	low	Calculation of thermal distortions based on preliminary deign	Astron	PDR	open
T-05	Availability of large optical components for MICADO	Optical design, supplier of optical components	C	2	low	Proceed with market survey, get quotations based on specification	OAPD	PDR	open
T-06	Quality of large mirrors (parabolic)	Optical design, optics manufacturing	C	2	low	Proceed with market survey, get, use experienced suppliers, quotations based on specification	OAPD	PDR	open
T-07	Required tolerances for static positions of optical surfaces not met (±0.05mm on position and ±0.01deg)	Structure manufacture and assembly	C	3	low	Follow up during design phase, apply milling in assembly	Astron	PDR	open
T-08	Functionality of large cryogenic mechanisms	Opto-mechanical design, mechanisms	C	3	low	Follow up during design phase, use proven actuators and bearings, perform tests	Astron	PDR	open
T-09	Reliability of cryogenic mechanisms	Opto-mechanical design, mechanisms	C	3	low	Follow up during design phase, determine MTBF by analysis and test	Astron	PDR	open
T-10	Required (re)positioning accuracy for	Mechanisms accuracy	C	3	low	Follow up during design phase (apply indent method	Astron	PDR	open

No.	Risk scenario	Risk Source	Likelihood	Severity	Grade	Mitigation measures	Responsible	Due date	Status
	optical surfaces not met					successfully used in MIDI)			
T-11	Access for installation / removal of the instrument	Mechanical interface MICADO – MAORY (SCAO), support equipment	C	3	low	Proceed with design of support equipment, coordinate with MAORY and E-ELT	Astron, MAORY, ESO	PDR	open
T-12	Access for repair / maintenance	General instrument concept / setup	A	2	very low	none (baseline concept guarantees good access)	-	-	closed
T-13	Insufficient temperature stability of large FP array (main arm)	Detector mount thermal design, control concept	B	3	low	Follow up during design phase (analysis, design optimization)	Astron, USM	PDR	open
T-14	Manufacturing of (large) SCAO dichroic plate acc. to spec. (optical quality, transmission, reflection)	SCAO optical design, manufacturing	D	2	low	Feasibility study in detailed design phase, to be assessed with potential manufacturers	LESIA	PDR	open
T-15	Concept for tracking of pupil shifts	E-ELT, SCAO opto-mechanical design	C	2	low	Yet to be defined in detailed design phase	LESIA	PDR	open
T-16	Availability of visible detectors with specifications announced in RD16	Detector suppliers	C	2	low	Follow up during detailed design phase: To be further investigated and discussed with potential suppliers	ESO	PDR	open
T-17	New requirements on image data reduction for E-ELT with MCAO (actual needs difficult to determine)	Manpower, implementation of DR concept	D	2	low	Perform data reduction simulations with simulated E-ELT data to test various approaches in Phase B	NOVA	PDR	open
Programmatic risks									
P-01	Detector price might not go down to the predicted € 0.02 per pixel	Detector supplier	C	3	low	Follow up, negotiate with supplier	ESO (MPE)	FDR	open
P-02	Increase in cost / FTE's due to delay of E-ELT first light	E-ELT schedule	C	3	low	Maintain close co-operation with E-ELT team at ESO, adapt mid- and long-term staff planning	All	PAE / PAC	open

No.	Risk scenario	Risk Source	Likelihood	Severity	Grade	Mitigation measures	Responsible	Due date	Status
P-03	Increase of manpower and cost required for development of electronics in case future E-ELT control standards differ from standards proposed by MICADO	Cost, FTE's	C	3	low	Maintain close co-operation with E-ELT team at ESO, adapt mid- and long-term budget and staff planning	USM, ESO	PDR (FDR)	open
P-04	Loss of key personnel during project implementation	Personnel	C	3	low	Ensure availability of competent staff by proper mid- and long term staff planning	All	PAE / PAC	open

No.	Unique risk identifier.
Risk scenario	Identified managerial, programmatic, technical risk including potential consequences of occurrence
Risks associated	Technical risk(s) associated with the critical item (refer to the associated entry in the Risk Register).
Risk source	Description of the risk source (e.g. WP, event)
Severity	Classification of severity of risk (see Table 8)
Likelihood	Likelihood of risk (see Table 7)
Grade	Risk grade resulting from combination of effects from severity and likelihood (see Table 9)
Mitigation measures	Planned measures to reduce or control the risk and statement of verification of the control implementation (e.g. design and operational requirements, test, inspection and failure history).
Responsible	Name or title of team member / institution responsible for implementation of mitigation measures
Due date	Expected completion date of risk mitigation actions.
Status	Status of action: Open / Closed

Table 11 MICADO Risk Register

6.5 Summary- present state of risk assessment

As indicated by the green and yellow colours in Table 11 the risk grades of the identified risks are either very low or low. A major part of the technical and programmatic risks are common to most of the existing cryogenic instruments in this wavelength range. At the present time we could not identify any medium or even high risks related specifically to MICADO.

From this we conclude that, with the instrument concept for MICADO as presented at the end of Phase A, the MICADO consortium has indeed achieved the objectives introduced in section 4.1.2 to develop a simple and robust design, minimize complexity, and avoid uncontrollable risks.

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