E-ELT PROGRAMME

MICADO Phase A
Executive Summary

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TABLE OF CONTENTS

ABBREVIATIONS AND ACRONYMS

AO	adaptive optics
CAD	computer aided design
CAE	computer aided engineering
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 APPLICABLE AND REFERENCE DOCUMENTS

1.1 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

AD5 'Executive Summary' Document for the E-ELT Instrument and Pre-Focal Adaptive Optics Module Studies, memo circulated by S. D'Odorico on 3 June 09

1.2 Reference Documents

RD1 MICADO Instrument Development and Management Plan, E-PLA-MCD-561-0020, v1.0

RD2 MICADO Scientific Analysis Report, E-TRE-MCD-561-0007, v2.0

RD3 MICADO System Overview, E-TRE-MCD-561-0009, v2.0

RD4 MICADO Design Trade-Off and Risk Assessment, E-TRE-MCD-561-0010, v2.0

RD5 MICADO Opto-Mechanics Design and Analysis, E-TRE-MCD-561-0011, v5.0

RD6 MICADO Control Electronics Design, E-TRE-MCD-561-0013, v1.0

RD7 MICADO Top Level Instrument Software User Requirements, E-TRE-MCD-561-0013, v1.0

RD8 MICADO Top Level Data Reduction User Requirements, E-TRE-MCD-561-0024, v1.0

RD9 High Precision Astrometry with MICADO at the E-ELT, Trippe et al., MNRAS submitted

RD10 MICADO Photometric Study, E-TRE-MCD-561-0023, v1.0

RD11 MICADO Single Conjugate Adaptive Optics Module, E-TRE-MCD-561-0022, v1.0

RD12 MICADO Compliance Matrix, E-TRE-MCD-561-0008, v2.0

RD13 MICADO-MAORY Interface Specification, E-SPE-MCD-561-0014, v1.0

RD14 MICADO-EELT Interface Information and Requests, E-SPE-MCD-561-0015, v1.0

RD15 MICADO MAIT Plan, E-TRE-MCD-561-0025, v1.0

2 SCOPE

This document provides an overview of the MICADO instrument. The contents address all the points raised in AD5. It includes a summary of the consortium, science drivers, instrument design, operational concept, performance, work breakdown, cost, and schedule.

3 INTRODUCTION

MICADO is the Multi-AO Imaging Camera for Deep Observations, which is being designed to work with adaptive optics on the E-ELT. The instrument has been optimised for the multi-conjugate adaptive optics module MAORY; but it is also able to work with other adaptive optics systems, and includes a separate module to provide a single conjugate adaptive optics capability using natural guide stars during the early operational phase.

The instrument is compact and is supported underneath the AO systems so that it rotates in a gravity invariant orientation. It is able to image, through a large number of selected wide and narrow-band near infrared filters, a large 53” field of view at the diffraction limit of the E-ELT. MICADO has two arms. The primary arm is a high throughput imaging camera with a single 3mas pixel scale. This arm is designed with fixed mirrors for superior stability, thus optimizing astrometric precision. In addition, MICADO will have an auxiliary arm to provide an increased degree of flexibility. In the current design, this arm provides (i) a finer 1.5mas pixel scale over a smaller field, and (ii) a 4mas pixel scale for a simple, medium resolution, long-slit spectroscopic capability. However, in principle the auxiliary arm also opens the door to many other options, including a ‘dual imager’ based on a Fabry-Perot etalon to image separate emission line and continuum wavelengths simultaneously, or a high time resolution detector.

Early in the project, the consortium highlighted several key capabilities that exemplify the unique features of the E-ELT at which MICADO will excel in comparison to other facilities. These are at the root of the science cases and have driven the design of the camera: sensitivity and resolution, precision astrometry, and high throughput spectroscopy. By both promoting and exploiting these capabilities with a simple and robust design, the consortium believes that MICADO can be considered for an E-ELT first light instrument.

4 CONSORTIUM

The MICADO consortium comprises the following six partners:

- MPE: Max-Planck-Institut für extraterrestrische Physik
- MPIA: Max-Planck-Institut für Astronomie
- USM: Universitäts-Sternwarte München
- NOVA: Nederlande Onderzoekschool voor Astronomie
  specifically including: University of Leiden, University of Groningen, NOVA optical/IR instrumentation group
- OAPD: Osservatorio Astronomico di Padova, INAF
- LESIA: Laboratoire d'Etudes Spatiales et Instrumentations pour l'Astrophysique, Paris Observatory

All partners have a strong tradition of working together to design and build world-class optical/infrared instrumentation; and have the appropriate facilities and scientific and engineering expertise available for the project. The combined expertise of the partners covers all areas required for the MICADO instrument.

5 KEY CAPABILITIES

The consortium has highlighted the following 3 capabilities that lie at the root of the science cases and that should drive the design of the instrument:

- Sensitivity and Resolution
- Precision Astrometry
- High Throughput Spectroscopy

The superior sensitivity of MICADO@E-ELT will allow discovery and study of new or unexplored phenomena. The high angular resolution, and the astrometric and spectroscopic capabilities of MICADO will yield new insights into the structure and physics of cosmic objects. With the superb astrometric precision achieved by MICADO many astronomical objects/phenomena will no longer be static but become dynamic. Many historical examples demonstrate that attaining this additional capability often leads to dramatic new insights into the three dimensional structure and evolution.

The MICADO design to achieve these capabilities is simple, compact and robust, which minimizes risks on cost and schedule. The consortium has also identified a

- Phased Approach

as an important option. While MICADO achieves superb wide-field performance with the MCAO module MAORY, in its first phase MICADO will be combined with an internal SCAO module. As this simple on-axis, natural guide star mode sets low requirements on the telescope and AO performance (no lasers), MICADO+SCAO thus is an optimum choice for demonstrating the scientific capabilities of the E-ELT at first light.

5.1 Sensitivity and Resolution

MICADO is optimised for imaging at the diffraction limit, and will fully sample the 6–10mas FWHM in the J–K bands. With a throughput exceeding 60% its sensitivity at 1–2μm will, for the AO performance predicted by MAORY, be comparable to, or surpass, JWST even for isolated point sources, and be clearly superior to JWST in crowded regions. MICADO thus will realise the full power and most unique features of a 42m-AO telescope in its first light capabilities. Following the end of Phase A, the consortium will pursue a project to develop OH suppressing filters that could further improve the sensitivity by a significant factor. MICADO's superior resolution means that it will be able to probe the detailed structure of objects that are unresolved by JWST. In addition, its field of view of nearly 1 arcmin yields a significant multiplex advantage compared to other ground-based cameras such as IRIS on the TMT. Together, these characteristics make MICADO a powerful tool for many science cases, from studies of faint high redshift galaxies to performing photometry in crowded fields. In important issue in this respect is the availability of tools to extract and measure point sources, and so the consortium has initiated a study to assess the suitability and future requirements of photometry packages.

5.2 Precision Astrometry

The primary imaging field of MICADO employs a catoptric design using only fixed mirrors. Together with the gravity invariant rotation and the baseline to use HAWAII-4RG detectors (developed to meet the stringent requirements of space astrometry missions), this makes MICADO an ideal instrument for astrometry. A robust pipeline, based on software already available in the AstroWISE system, will bring precision astrometry into the mainstream. An analysis of the statistical and systematic effects shows that proper motions of 40μas/yr in a single epoch of observations should be achievable; and after only 3-4 years it will be possible to reach 10μas/yr, equivalent to 5km/s at 100kpc. At this level, many novel science cases become feasible, including proper motions of stars in the centre of the Galaxy and other nearby galaxies, mass determinations of intermediate mass black holes, proper motions of globular clusters, and testing cold dark matter structure formation using internal kinematics of dwarf spheroidals.

5.3 High Throughput Spectroscopy

The obvious, but powerful, complement to pure imaging is spectroscopy, and this capability is mandatory if MICADO is to be considered as a first light instrument. We have implemented a simple slit spectrometer with a high throughput that is ideal for obtaining spectra of compact objects. The resolution of R~3000 is sufficient to probe between the near infrared OH lines. This simple addition will enhance many science cases, for example: deriving stellar types and 3D orbits in the Galactic Center; using velocities of stars in nearby galaxies to probe central black hole masses and extended mass distributions; measuring absorption lines in galaxies at $z = 2–3$ and emission lines in galaxies at $z = 4–6$ to derive their ages, metallicities, and star forming histories; and obtaining spectra of the first supernovae at $z=1-6$.

5.4 Phased Approach

In order to be a viable first-light instrument, the MICADO consortium has decided to implement a phased approach whereby the instrument is operated first with a more simple form of adaptive optics, SCAO, and only later upgraded to work with full MCAO. In this way the camera will be able to produce diffraction limited images leading to high quality scientific results from the very beginning. Since the E-ELT baseline is that SCAO wavefront sensing capability is not provided to the instruments by the telescope, the consortium has included the study of such a module. The optical relay and support structure have been designed so that the interface between MICADO and the SCAO module is the same as that with MAORY. Furthermore, they can in principle also be used to interface MICADO to other AO systems such as ATLAS. There are technical and fiscal benefits to this phased approach:

(i) MICADO is able to make use of adaptive optics at a level of sophistication that increases as more complex AO systems are commissioned.

(ii) The high capital cost of the detectors required to image the large field corrected by MCAO is spread over a longer time period.

6 PRIMARY SCIENCE DRIVERS

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 accurate 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.

The Galactic Centre is a unique laboratory for exploring strong gravity around the closest massive black hole. The fundamental goal is to measure the gravitational potential in the relativistic regime very close to the central black hole via stellar motions, using very faint stars that are likely present but cannot be detected nor studied with any other facility prior to the E-ELT. These motions may also reveal the theoretically predicted extended mass distribution from stellar black holes that should dominate the inner region, as well as test for a distributed component of dark matter. Similar studies of the nearby Arches and Quintuplet clusters also raise the intriguing possibility of kinematically detecting intermediate mass black holes.

Globular Clusters, among the oldest known components of the Milky Way, may also host intermediate mass black holes, the presence and masses of which would be derived from measurements of the cluster internal kinematics. Deriving the clusters' orbits would enable one to address questions about the formation and evolution of the Galaxy. The internal kinematics of Dwarf Spheroidal Galaxies will also shed light on this issue, by revealing the amount and distribution of dark matter in these objects; and hence testing models of structure formation, with respect to the clumps (sub-haloes) in which the dwarf spheroidals reside.

An alternative way to probe a galaxy's evolution is through its star formation history, which can be assessed using colour-magnitude diagrams that trace the fossil record of the star formation. Spatially resolving the stellar populations in this way is a crucial ability, since integrated luminosities are dominated by only the youngest and brightest population. MICADO will extend the sample volume from the Local Group out to the Virgo Cluster and, through its capability to perform photometry in crowded fields, push the analysis of the stellar populations deeper into the centres of these galaxies.

The excellent performance of MICADO in crowded fields and its large field of view are also key to understanding star formation itself, whether in nearby galaxies or galactic star clusters. Deep multi-colour images will provide a detailed census of stellar types and ages in a variety of star forming environments, yielding important results about the form of the initial mass function.

Galaxy evolution and formation is the primary science driver at high redshift. Continuum and emission line mapping of high redshift galaxies will enable us to address questions concerning their assembly, and subsequent evolution in terms of mergers, internal secular instabilities and bulge growth. The resolution of better than 100pc, equivalent to 1arcsec imaging of Virgo Cluster galaxies, will resolve the individual star-forming complexes and clusters, which is the key to understanding the processes that drive their evolution.

One of the outstanding questions in galaxy evolution concerns the cores and cusps in galactic nuclei, the role of central supermassive black holes, the mechanisms of mass transport into these central regions, and the influence of the galaxy-scale and larger environment. AGN feedback is also a crucial issue that appears to be responsible for quenching star formation and turning massive star-forming galaxies into passive spheroids. In the local Universe MICADO will fully exploit the much higher angular resolution of the E-ELT for studying massive black holes and the nuclear stars and gas at the low mass end, and at larger distances (and thus, effectively also at the higher mass end). Studies of large samples of QSOs at high redshift are complementary to the more detailed studies of the nuclei of nearer galaxies. At high-redshifts the resolution and sensitivity of MICADO will, for the first time be sufficient to spatially resolve the nuclear regions and study the growth of black holes and bulges in the ‘epoch of galaxy formation’.

At the other extreme of the distance scale, MICADO’s large field of view is well matched to the angular sizes of planets such as Venus, Jupiter, and Saturn. Time resolved observations at high spatial resolution are an important part of understanding their weather systems; and using appropriate narrow band filters allows one to probe to different depths in their atmospheres.

The summary above demonstrates that the combination of high spatial resolution and wide field provided by MICADO, together with MAORY, have applications across a broad range of science and will enable us to make important contributions to a number of the key topics identified by the E-ELT Science Working Group.

6.1 Science Requirements

The science trade-off and the detailed science cases described in the Science Analysis document (RD2) have led to the baseline requirements given in Table 1.

Table 1: summary of baseline science requirements for the instrument design

Requirement	*Baseline Design*	*Comment*
Field of View	Greater than 30”, closer to 60” preferred	For multiplex advantage in studies of resolved stellar populations and high-z galaxies
Spatial Sampling	3mas	Fixed pixel scale in primary arm to maximise stability
Total Wavelength Coverage	0.8-2.4μm	Some science cases would benefit from 0.6μm, but AO performance is insufficient
Throughput	>60%	This is used to characterize sensitivity, which is strongly affected by AO performance and thermal background over which MICADO has no control
Instrumental Distortions	stable	The degree of distortion is less important that the stability over time
Number of Filters	20	To allow flexibility without needing to open the cryostat; each arm has this many filters
Image Quality	70% Strehl at 1μm	This is the metric used to estimate the tolerances
Photometric Accuracy	0.03mag	The accuracy is dominated by the PSF fitting
Astrometric	50μas	Relative accuracy across the full field of a single carefully

Accuracy		calibrated exposure
Spectroscopy	R~3000	Resolution is high enough to probe between OH lines

6.2 MICADO in the context of other Facilities

MICADO will be operating both in synergy and in competition with a few other comparable facilities. The basic characteristics of these are summarised in Table 2.

From this comparison, it is immediately clear that, for the ELTs, MICADO has by far the largest field of view sampled at the diffraction limit. This gives it an enormous multiplex advantage (a factor 10 wrt IRIS and a factor 16 wrt HRCAM) which is particularly important for studies of resolved stellar populations and high redshift galaxies. These are 2 of the key science cases identified by the Science Working Group and, as indicated in the Science Trade-Off, both require large fields to be effectively and efficiently executed. A wide field of view is also crucial for a number of astrometric studies, where field stars or background galaxies are used to establish the calibration and reference frame. We consider MICADO's wide field capability to be the primary advantage of MICADO over the other ELT imaging cameras; and it argues for as rapid as realistically possible upgrade from the initial SCAO mode to full MCAO.

Table 2: Basic specifications for MICADO and its competitors

Instrument & telescope	MICADO / E-ELT	NIRCam (short arm) / JWST	IRIS / TMT	HRCAM / GMT
First light date	2018	Launch 2014	2018	2018
Wavelength	0.8-2.5µm	0.6-2.3µm	0.8-2.5µm	1.0-2.5µm
Field & sampling	53"×53" @ 3mas + 6"×6" @ 1.5mas	130"×260" @ 31.7mas	17"×17" @ 4mas	13"×13" @ 3mas, 40" ×40" @ 10mas
Resolution wrt MICADO	×1 (10mas @ 2.1µm)	×6.5	×1.4	×1.7
Number of filters	20 primary arm, 20 auxiliary arm	14 (of which 4 are narrow)	unspecified	unspecified
Additional modes	Slit spectroscopy (options: dual imager, high time resolution)	Long arm to 5µm	Integral field spectroscopy	Integral field spectroscopy

Of particular importance is the synergy between the JWST and the E-ELT. JWST will be launched about 4 years in advance of the E-ELT's first light. The absence of sky background for NIRCam means that it will be as sensitive as MICADO, but with a wider field of view. As such, JWST will excel in detecting and defining large samples of targets. What NIRCam has discovered and detected can then be explored and studied in terms of structure and physical processes with the superior resolution of MICADO@E-ELT. An example of this unique synergy between these facilities is the investigation of a high-z galaxy, shown in Figure 1. The detection of spectral line emission from typical galaxies up to z~3 is also one of the key science drivers for ALMA; and, with a spatial resolution of ~30mas (down to only a few mas at the highest frequencies), it will be scientifically highly complementary to MICADO. For high redshift galaxies on which ALMA has provided spatially resolved distributions of the molecular gas and dust continuum, MICADO will add detailed images of the stellar continuum and, with appropriate filters, the ionised gas.

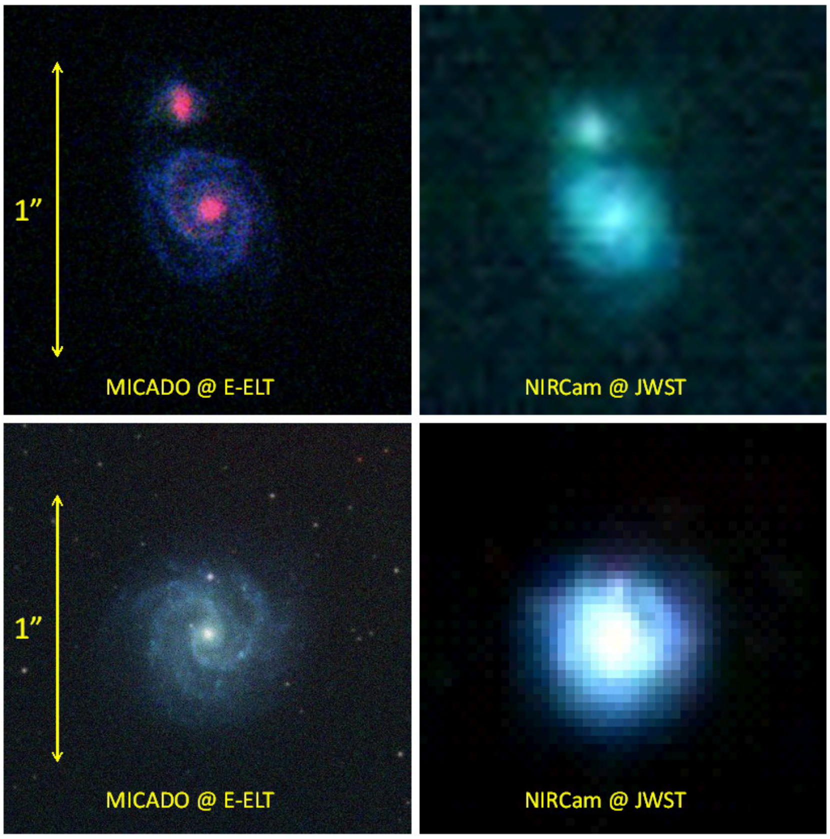

Figure 1: Comparisons of how MICADO and NIRCam might view high redshift galaxies in true-colour images made by combining J, H, and K band observations. Local templates (B, V, and R band) were used to model a galaxy at z=2 (top) and z=1 (bottom) with R_{eff}=0.5" and M_V=-21. It was 'observed' by both instruments in the J, H, and K bands, each with 5hrs integration.

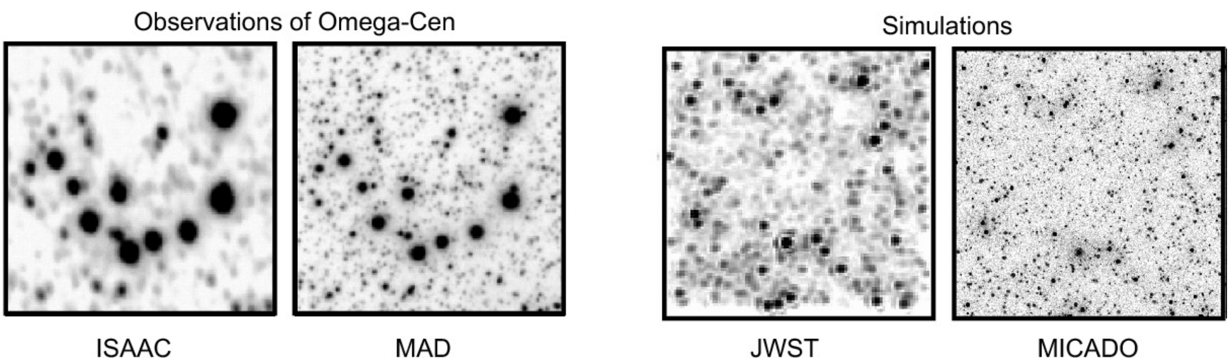

Figure 2: Comparison of ISAAC and MAD observations of Omega-Cen (left) show that a factor 6 improvement in resolution leads to 3mag deeper observations in crowded fields. The difference in resolution between MICADO and JWST is comparable, and simulations of a crowded field (right) suggest we can expect similar gains in depth.

A second example of how the superior resolution of MICADO will enable synergies is in studies of spatially resolved stellar populations. In crowded fields, spatial resolution is equivalent to depth, a fact that is well demonstrated by the comparison show in Figure 2. What this makes clear is that, while both NIRCam and MICADO will be able to study stellar populations out to the Virgo Cluster, NIRCam will be limited to probing the fringes of the galaxies at radii of 3-4R_{eff} while MICADO will be able to work in the central regions at 1-2R_{eff}. This is a fundamental advantage since it enables one to study the bulk of the stellar mass and hence gain important and significant information about the global star formation history.

7 INSTRUMENT OVERVIEW

The design of MICADO has been developed by combining the results and conclusions from parallel scientific and technical trade-off studies (see the Design Trade-Off and Risk Assessment, RD4). These have resulted in a concept for the camera comprising purely reflective optics that images a contiguous field, having a ~75arcsec diagonal size, onto a focal plane. The focal plane is tiled with detectors, and provides 16000×16000 pixels at a scale of 3mas/pixel. As a baseline we adopt the HAWAII-4RG (with a 15µm pixel size), which has been developed to meet the stringent requirements of space astrometry. The combination of fixed monolithic optics, a single fixed mount for the focal plane array, and a gravity invariant rotation will significantly enhance the astrometric stability of the camera compared to other designs, as well as simplifying the associated mechanics. The design allows for a large wheel with space for 20 filters, providing a high degree of flexibility for imaging projects. Both the filter wheels, as well as the focal plane mechanism, are supported and driven at their rim, lessening the torque requirements on the mechanisms.

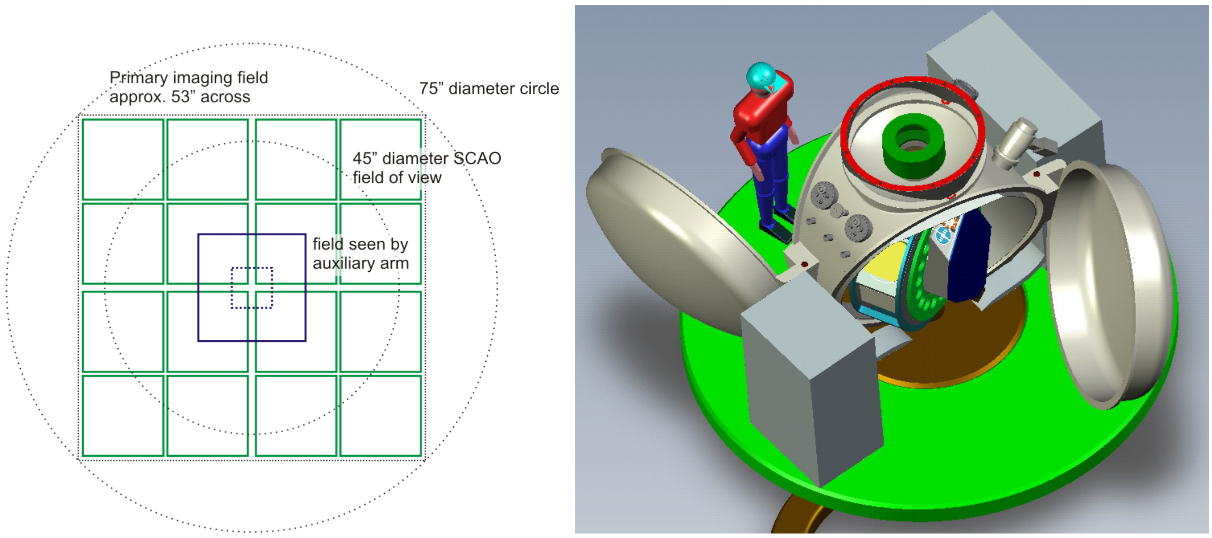

Figure 3: **LEFT** illustration of the focal plane division. The main imaging field is approximately 53"×53" and will be imaged at a scale of 3mas/pixel by an array of 4×4 HAWAII-4RG detectors. A selection mechanism enables one to pick off a smaller field for the auxiliary arm. **RIGHT** overview of MICADO. The mechanical interface to the AO systems is the red mounting ring at the top. Access to all key systems is provided through 2 large doors in the cryostat, facilitated by a rotational offset between the optics and the cryostat. The electronics are mounted on a co-rotating platform that rests on the Nasmyth floor and provides the cable-wrap for external supplies.

In addition to the primary imaging arm, MICADO has an auxiliary arm that can be selected by moving in a single mirror on a rotation stage. This arm has a separate filter wheel, providing space for an additional 20 filters, and requires only 1 additional HAWAII-4RG detector. In the current design, the auxiliary arm provides 2 important complementary capabilities: (i) a smaller 1.5mas pixel scale over a 6"x6" field of view, which is crucial for accurate astrometry in the most extremely crowded fields; (ii) a 4mas pixel scale for slit spectroscopy using R~3000-5000 grisms. The slit mask is located in the input focal plane mask.

7.1 Optics

The optical design of MICADO is very simple, and for each of the arms there are relatively few working mirrors, although additional fold mirrors are required to keep the instrument compact.

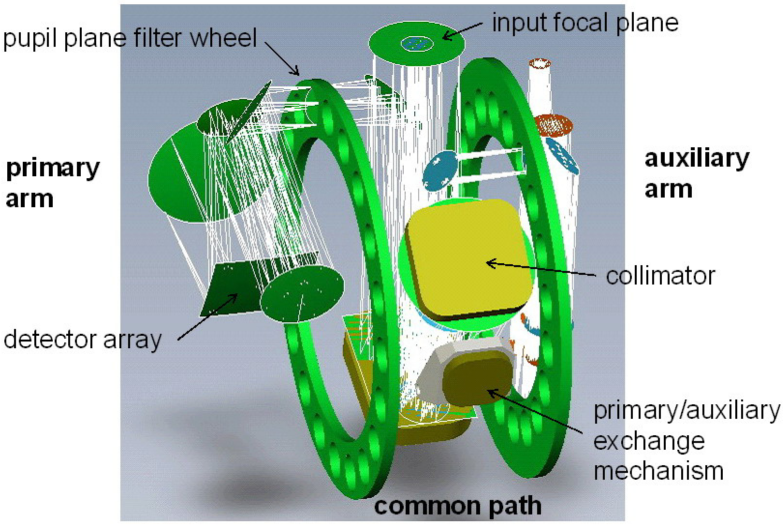

Figure 4: Overview of MICADO optics, which comprises the common path (ADC (not shown) and collimator) in the centre, the primary arm, and the auxiliary arm.

For the primary arm, all the mirrors are fixed, providing excellent stability. To use the auxiliary arm, an alternative collimator is rotated into position, and the light is directed outwards to the opposite side. An additional selection mechanism enables one to switch pixel scales. In both cases, there is large filter wheel at the pupil. The focal plane mechanism, which has space for 6 masks as well as a large access space, surrounds all the cold optics in the common path.

7.2 Mechanics

The mechanical design has been driven by the limited space under MAORY. To keep torques small and to maintain optical alignment during cool-down, the centre of gravity is close to the optical axis which itself is close to the centre of shrinkage. In order to minimize cable lengths and to limit the mass mounted on the derotator, the electronics racks are mounted on a co-rotating platform on the Nasmyth floor which also houses the cable-wrap for external supplies. Service and maintenance are key aspects of the design, leading to a design in which the core instrument and optics structure are rotated by 25° with respect to the cryostat. This provides better access through the cryostat doors to the detector arrays, the primary/auxiliary arm selection and focal plane mechanisms, the filter wheels, and the core optics.

MICADO is surrounded by a cryostat that has a tapered part that provides space for all the through-ports, and 2 large doors. The total mass of the cryostat and instrument supported by the derorator is 3000kg; an additional 2800kg are supported on the Nasmyth floor, and 500kg in a calibration unit located in the AO system. The instrument inside the cryostat comprises 3 main structures: primary arm, auxiliary arm, and core sub-assembly. The design approach for each of these housings is to assemble them from plate material to keep part complexity and accuracy low, and ensure a rigid boxed structure. The instrument core is supported by the cryostat via 3 V-rods and a transfer structure, which has been designed to accommodate the rotating focal plane mechanism and acts as a bridge to the stiff support structure of the core sub-assembly.

7.3 Cryogenics

In order to avoid the use of cryo-coolers, the vibrations from which would have a strong adverse effect on the AO performance, MICADO will be cooled by continuous flow liquid nitrogen (LN2) during cool-down/warm-up cycles as well as steady state phases (63L/day). Cooling pads are located at strategic points in the cryostat, and connected so that during a cool-down cycle the heat shield is cooled first, followed by the optical bench and finally the detectors. During steady state the sequence is reversed so that the detectors have the lowest possible temperature. In this concept, the same circuit can be used in both phases by reversing the direction flow. Variations of this concept would allow the system to be closed so that LN2 can be pumped round the instrument multiple times, reducing the LN2 source flow required.

7.4 Telescope & AO Interfaces

MICADO does not have a direct optical or mechanical interface to the telescope. Instead it is mounted under various AO systems. A detailed study of all the interfaces (optical, mechanical, communication, operational, etc.) between MICADO and MAORY has been performed by the two consortia and is given in RD13. There are no major outstanding issues or discrepancies. The support structure and optical relay of the MICADO SCAO module has been designed in such a way that the interfaces here are also exactly the same. If MICADO were to be used with LTAO (e.g. ATLAS), then in principle the same relay and support structure could also be used for that. This greatly simplifies the whole issue of interfaces.

The information requested by ESO about the interface to the E-ELT is given in RD14. The only non-standard requirement is that there are science cases for which MICADO will need to offset to sky fields that are up to 15arcmin from the science field. Given the 53” field of view of MICADO, the 60” maximum sky offset indicated in the observatory top level requirements is insufficient.

7.5 Adaptive Optics Modes

MICADO has been optimised for use with the MAORY MCAO system. However it provides good optical quality over a smaller (~30”) field when used with SCAO even though the optical interface is significantly different. The consortium considers SCAO to be an important adaptive optics mode in the early operational phases of the E-ELT, since it is simple, well understood and robust. SCAO can operate with minimum requirements on the telescope and facility performance (no lasers). MICADO+SCAO thus is an optimum choice for demonstrating the scientific capabilities of the E-ELT at first light. A conceptual design of such an SCAO module appropriate for MICADO has been developed. This includes the WFS system as well as the necessary optical relay and support structure for MICADO, providing the same mechanical and operational interface as to MAORY. MICADO provides high image quality over the field corrected by SCAO (central 2×2 detectors, approximately 27”×27”) even though the optical interface (field curvature) is different. An illustration of how MICADO might look with its own SCAO module is shown in Figure 5, and with MAORY in Figure 6.

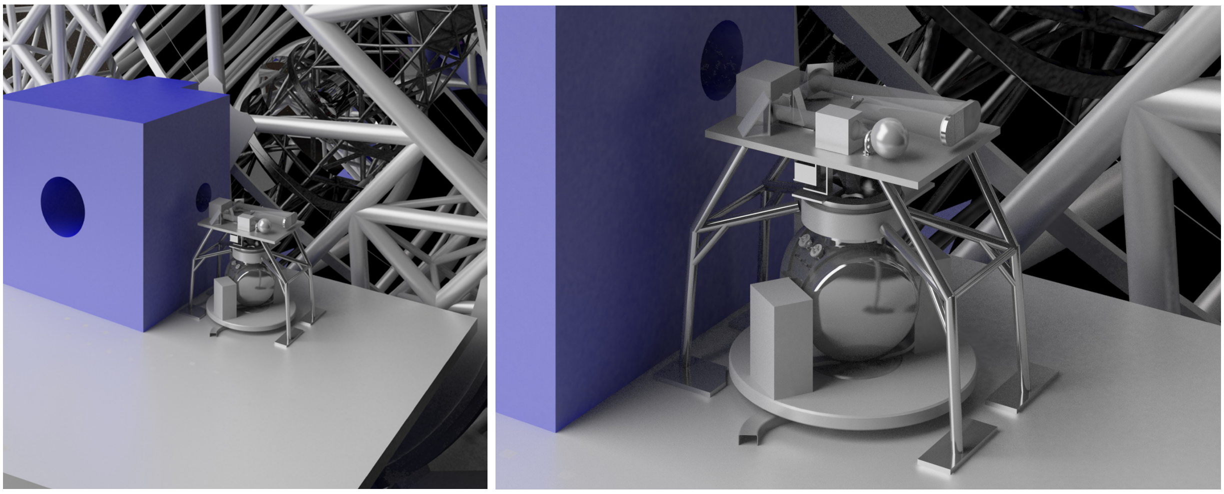

Figure 5: illustration of MICADO mounted under its own SCAO module during initial operations (the relay and calibration optics on the bench will be covered).

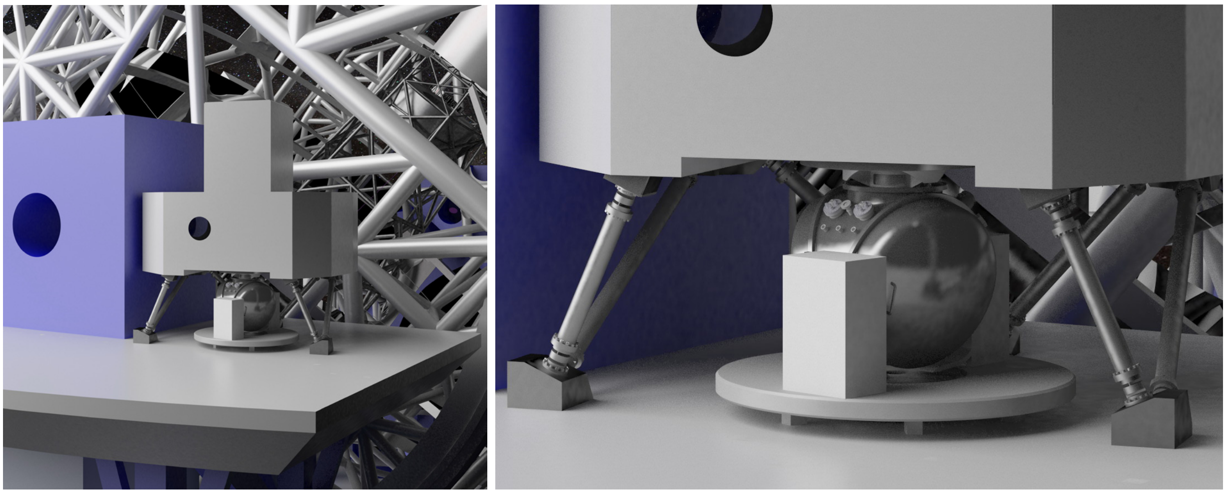

Figure 6: illustration of MICADO in its final location mounted under MAORY

We therefore foresee the adaptive optics modes for MICADO as:

Baseline AO modes:

SCAO: to be used initially, since this is a simple & robust AO mode, and will provide diffraction limited data right form the start. There will be enough science targets for 2-3 years of operation using NGS with SCAO.

MCAO: the final, optimal, AO mode for MICADO, and for which it has been optimised. This mode provides very significant scientific advantages over other contemporary facilities.

Optional AO mode:

LTAO: this AO mode is intermediate in both complexity and science return (i.e.sky coverage and corrected field). Depending on the timescale for implementation of MCAO, LTAO is an important option to consider. The same optical relay and support structure designed for SCAO could be used here also.

7.6 Operational Concept

The basic operational scenario for MICADO is very similar to other imaging cameras and spectrometers such as ISAAC and NACO. For imaging, the sky background will be derived either by combining dithered exposures or, when necessary, by offsetting to sky. For spectroscopy, the source will be nodded back and forth along the slit. Typical exposure times will be a few seconds (broad band filters) up to tens of seconds (narrow band filters). For the shortest exposure times, several exposures will be made at the same pointing before dithering.

The main issue is the size of the dithers, which must be optimised for science while minimizing the AO and telescope overheads. Table 3 summarises the definition of dithers and offsets for MICADO.

Table 3: expected magnitude and frequency of dithers & offsets (to reduce AO and telescope overheads)

Small dither	Offset of up to ±0.3” (goal ±0.5”) from the initial pointing in each of X- and Y-directions, with an accuracy of <2mas. AO loops remain closed. Cadence: 10-30sec
Large dither	Offset of up to ±10” from the initial pointing. AO loops open during the offset and telescope is involved. Cadence: a few minutes
Sky Offset	Offset of up to 15’ (when background cannot be recovered by dithering). AO loops do not need to close in the offset position; telescope may need to preset to reach required offset, and it is likely that pupil quality should be maintained and that the telescope GLAO loops should be closed. Note: sky offsets of ‘up to 60arcsec’ as per the Observatory TLR make no sense in the context of MICADO, which has a 53” field of view. Cadence: 20-30 minutes (depends on overhead)

Most of the calibrations can be performed internally during the day while the dome lights are on: flatfields, wavelength calibration, darks. Additional twilight flats will be required in order to correct illumination gradients in the internal flats. The only non-standard calibration required is that to correct instrument distortions in the AO system and MICADO. This will also be possible during the day with the dome lights on, and will be achieved by inserting a special calibration mask into the focal plane in front of the AO system. The only standard nighttime calibration is to observe standard stars for flux calibration.

7.7 Performance

The broadband imaging performance for the MICADO primary field is show in Figure 6. This has been calculated for isolated point sources using PSFs provided by the MAORY consortium and for standard broadband filters similar to those in HAWK-I. It shows that the 5σ sensitivity will be better than a few nano-Jy (30mag AB) for the I, J, and H bands in only 1-2 hours. The K-band performance depends strongly on the thermal background and hence the ambient temperature, but is likely to be about 1mag less.

Advanced filters – including high throughput broad band filters and OH suppressing filters – will have a very significant impact on MICADO sensitivity. The prototype J-band filter pair that we have developed together with the Laser Zentrum Hannover increases the sensitivity in a given integration time by 0.3mag (see RD5). More advanced design optimisation techniques could lead to a 0.5mag sensitivity gain in this band, and comparable gains may be expected for the I-band and H-band.

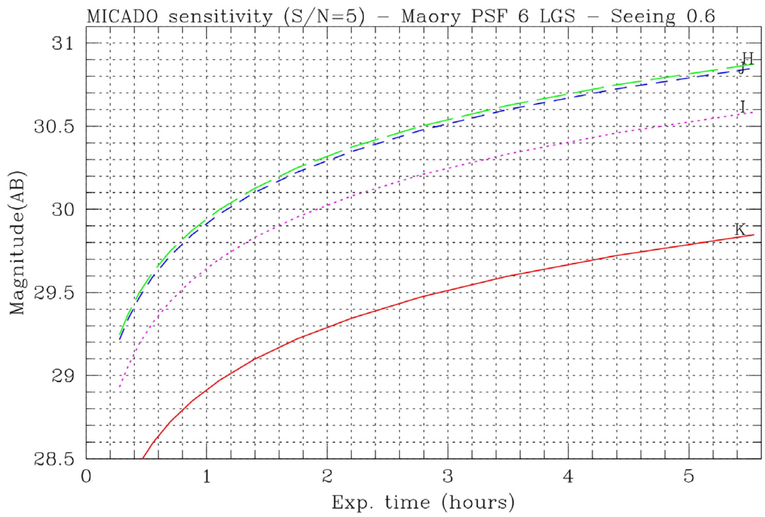

Figure 7: Broad-band imaging sensitivity of MICADO, calculated using PSFs provided by the MAORY consortium. The lines are for standard I, J, H, and K filters, and show the 5σ magnitude limit reached in a given integration time.

The spectroscopic performance has also been calculated for isolated point sources, taking into account all slit losses (including diffraction effects, which are important in the K-band). The resulting sensitivities are to reach J_{AB}=26.7mag to 5σ in a 5 hour integration; and similarly to K_{AB}=25.7mag (again about 1 mag less primarily due to the thermal background).

Both imaging and spectroscopic sensitivities are summarised in Table 4.

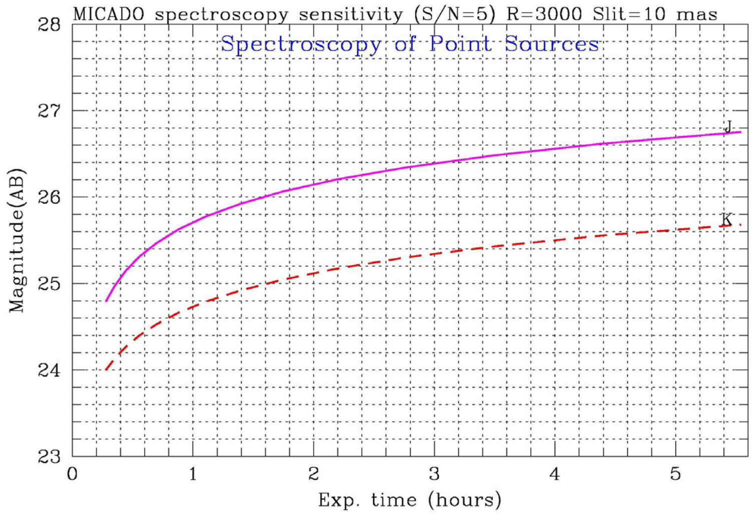

Figure 8: Spectroscopic sensitivity of MICADO, calculated using PSFs provided by the MAORY consortium. The lines are for standard J and K filters, and show the 5σ magnitude limit reached in a given integration time through a 10mas slit (all slit losses, including diffraction effects, are included).

Table 4: predicted point source sensitivities to 5σ in a 5hr integration.

	J_{AB}	H_{AB}	K_{AB}
Imaging	30.8	30.8	29.8
Imaging with advanced filters (see Section 7.8); estimated	31.3	31.3	30.1
spectroscopy	26.7	26.7	25.7

7.8 Technological Developments and Risks

MICADO is a simple camera and has been designed to have few risks. Indeed, the preliminary Risk Register given in RD4 contains no technical or programmatic risks above a 'low' level. Those that do exist at this level are common risks associated with all (cryogenic) instruments, and not specific to MICADO. The highest risks, at the C3 level (on a scale of A-E indicating the chance of occurance and 1-5 indicating severity) or equivalent are:

Table 5: summary of highest level risks from preliminary risk register in RD4

Risk scenario	*Grade*	*Mitigation measures*
Flexure of main structure due to thermal distortions	C3, low	Calculation of thermal distortions based on preliminary design
Required tolerances for optical surfaces not met (0.05mm 0.01deg)	C3, low	Follow-up during design phase; apply milling in assembly
Functionality of large cryogenic mechanisms	C3, low	Follow-up during design phase; use proven

		actuators, bearings; perform tests
Reliability of cryogenic mechanisms	C3, low	Follow-up during design phase; determine MTBF by analysis & test
Required positioning accuracy for optical surfaces not met	C3, low	Follow-up during design phase; apply indent method successfully used in MIDI
Access for installation & removal of instrument	C3, low	Proceed with design of support equipment; coordinate with MAORY & E-ELT
Detector price might not go down to predicted level of 0.02€/pixel	C3, low	Follow-up; negotiate with supplier
Increase in cost and/or workpower due to changes in E-ELT schedule	C3, low	Maintain close co-operation with E-ELT team at ESO; adapt mid- and long-term staff planning
Increase in cost and/or workpower if future E-ELT control standards differ from those proposed by MICADO	C3, low	Maintain close co-operation with E-ELT team at ESO, adapt mid- and long-term budget and staff planning
Loss of key personnel during project implementation	C3, low	Ensure availability of competent staff by proper mid- and long-term staff planning

There are several future developments that we will pursue during the preparatory phase (i.e. until the beginning of the preliminary design phase). None of these is required for the successful and functioning of MICADO. However, they would each increase the competitiveness of MICADO with respect to other facilities. The developments include:

Advanced filters: The broad-band sensitivity of ground-based telescopes in the near-infrared is strongly limited by OH sky line emission. Substantial gains in sensitivity and speed can be attained by sky line suppression or avoidance. We have begun a research project with Laser Zentrum Hannover to develop both (i) high throughput broad band filters, and (ii) OH suppressing interference filters. The initial work, which is now under way, is to design and make a prototype for the J-band. This comprises low-pass and high-pass filters coating opposite sides of a substrate which together make a broad-band filter with ~99% throughput. The OH suppression is achieved by transmitting several narrow bandpasses within this range where the background is sufficiently low. The current design would allow one to reach the same signal-to-noise in the J-band in only 60% of the observing time. During the next 2 years we expect to improve on this. Development will focus on the extension to other bands and address (a) optimisation of the filter profile, (b) process qualification, (c) coating homogeneity, (d) coating stress, (e) coating characterisation.

Dual Imager: The science team have identified a ‘dual imager’ as a desirable addition to the auxiliary arm. This would be complementary to integral field spectroscopy, but provide higher quality images of individual emission lines. It would be based on Fabry-Perot technology, and enable simultaneous imaging of both the emission line and continuum wavelengths. The company FRACTAL in Spain (General Manager Dr M. Garcia-Vargas) has indicated a strong interest to develop a concept for such a dual imager. Many members of FRACTAL were involved in development of the Spanish 10-m GTC, and the company has experience in instrument development including cryogenic tunable Fabry-Perot filters.

High Time Resolution: A simple complement to the auxiliary arm would be detectors able to perform high time resolution astronomy. The science that could be addressed by such a capability includes the stochastic behaviour of accretion disks (e.g. around neutron stars and white dwarfs) and pulsar magnetospheres, follow-up and time resolved observations of gamma-ray and X-ray transients and anomalous repeaters. Detector technology is available now in the range 0.8-1.2μm using APDs and pnCCDs. There is every expectation that electron multiplication systems will extend towards 2μm over the next two years. An High Time Resolution Astronomy instrument is essentially a simple imaging device with a fast detector, and such an instrument suitable for inclusion within the MICADO Auxiliary Arm could be constructed today with a limited wavelength range (0.8-1.2μm) and within 2 years up to 2μm. If the detectors are able to operate using the pixel scales already provided, there would be very little additional opto-mechanical development required. There is a strong interest for such a capability from the National University of Ireland in Galway (Dr. A. Shearer).

8 Management Plan

8.1 Management Structure

The MICADO project will be lead by the Principal Investigator, who is responsible to the Board of Directors, and ensures the instrument will meet its scientific capabilities. The PI liaises both with ESO and also with the Project Office, which comprises the Project Manager and Systems Engineer. They provide overall coordination and management of all aspects of the project. They in turn, work together with the Responsible Partners, who provide local management. The routes of communication between these roles are summarised in Figure 8.

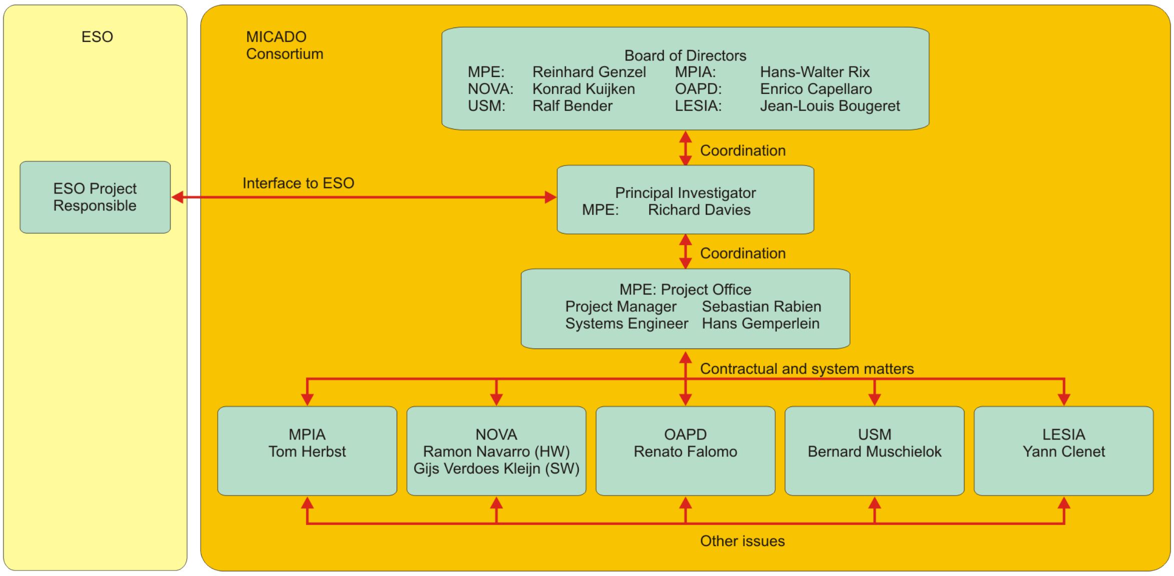

Figure 9: Structural organization of the MICADO project.

8.2 Workbreakdown Structure

A list of the workpackages and the partners who will lead the work is given in Table 6.

Table 6: List of Workpackages and Responsible Partners

WP #	*Sub-WP #*	*Name*	*Lead Partner*
1	Management		MPE
	1.1	Management	MPE
	1.2	Systems Engineering	MPE
2	Science		OAPD
	2.1	Science cases	OAPD (+all)
	2.2	Operations, Calibration, Maintenance	MPIA
3	Cryostat		NOVA
	3.1	Cryostat & Cryogenics	NOVA
	3.2	Handling Equipment	NOVA
	3.3	MICADO Test Facility	MPE
4	Cable-Wrap		NOVA
5	Opto-Mechanics		MPE
	5.1	Common path	OAPD (optics), NOVA (mechanics)
	5.2	Primary Arm	MPE (optics), NOVA (mechanics)
	5.3	Auxiliary Arm	OAPD (optics), NOVA (mechanics)
	5.4	Calibration Unit	MPE (optics), NOVA (mechanics)
6	Detectors		MPIA
	6.1	Detectors	ESO
	6.2	Focal Plane Array	MPIA
7	Electronics		USM
	7.1	Instrument Control	USM
	7.2	Housekeeping	USM
8	Instrument Software		USM
9	Data Processing		NOVA
10	SCAO		LESIA
	10.1	Support Structure	LESIA
	10.2	Optical Relay	LESIA
	10.3	Wavefront Sensing	LESIA
	10.4	SCAO Test Facility	LESIA

8.3 Schedule

The schedule for MICADO has been developed on the assumption that it should be ready and available for the E-ELT first light. It comprises the following phases, which are summarised on a timeline in Figure 9 and leads to the milestones and reviews listed in Table 7.

Preparatory phase: from the end of Phase A to the Instrument Kick-Off at the start of Phase B preliminary design. During this phase the consortium will work with ESO on development and definition of software framework and electronics standards; pursue the technological developments outlined in section 7.8, and improve simulations. In this way, the consortium will be in a good position at the start of Phase B.

Phase B-C: each of the preliminary and final design phases lasts for 1.5 years. During this time the design will be consolidated. Each of these phases finishes with a design review.

Phase D: lasting 3 years, this will include manufacturing, assembly, integration and testing. This phase is completed with Preliminary Acceptance in Europe.

Phase E1: commissioning will first be with the SCAO module, thus providing diffraction limited image quality at the very start of E-ELT operations. This phase finished with the Preliminary Acceptance at the Observatory.

Phase E2: a further commissioning phase is foreseen for each additional AO system with which MICADO should work. In the baseline this is MCAO, but could also include LTAO.

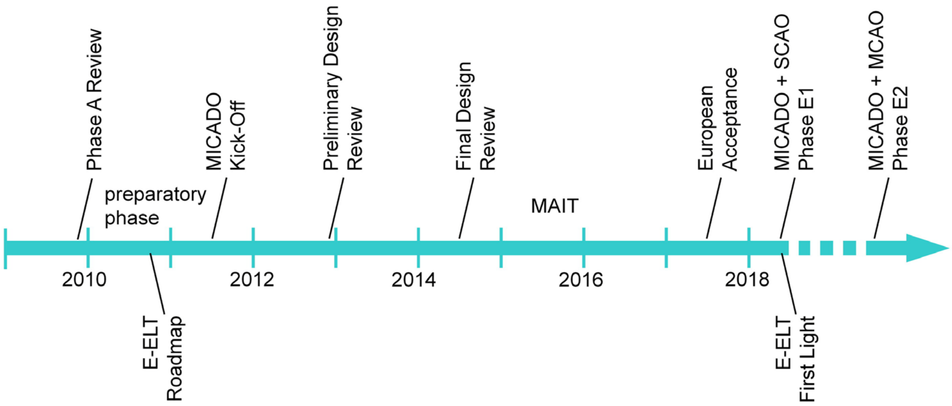

Figure 10: Illustration of the MICADO instrument schedule from the end of Phase A, through Kick-Off in 2011 to European Acceptance in 2017 and a first light matching that of the E-ELT to avoid delay in the start of science operations.

Table 7: Summary of the key milestones in the MICADO project

Instrument Kick-Off	June 2011
Preliminary Design Review	December 2012
Final Design Review	June 2014
Preliminary Acceptance in Europe	June 2017
Preliminary Acceptance at the Observatory	2018, matching first/early light at the E-ELT

8.4 Cost Summary

A summary of the cost and workpower required to design, manufacture, and commission MICADO is given for each workpackage in Table 8 and overall in Table 9.

Table 8: Summary of the cost and workpower estimates without contingency, given by Workpackage

WP #	WP name	total for initial phase		upgrade for MCAO	
		cost k€	FTE	cost k€	FTE
1	Management	56	10.60	8	0.85
2	Science	60	7.35	9	0.85
3	Cryostat	538	12.58	8	0.30
4	Cable-Wrap	160	3.85	1	0.10
5	Opto-Mechanics	1135	23.98	4	0.42
6	Detectors	2405	3.10	5023	0.80
7	Electronics	471	30.00	18	0.50
8	Instrument Software	264	26.63	6	0.62
9	Data Processing	60	15.00	14	1.50
10	SCAO module	574	18.77		

Table 9: Total cost & workpower, both without and with 20% contingency

	without contingency		with 20% contingency	
	cost k€	FTE	cost k€	FTE
MICADO	5149	133.09	6178	159.71
SCAO module	574	18.77	689	22.52
upgrade for MCAO	5091	5.94	6109	7.13
grand total	10814	157.80	12976	189.36

9 MICADO DOCUMENTS

More detailed descriptions of all aspects of the instrument can be found in the relevant Phase A documentation which is listed in Table 10.

Table 10: Phase A documentation for MICADO

	MICADO Executive Summary	E-TRE-MCD-561-0006
RD1	MICADO Instrument Development and Management Plan	E-PLA-MCD-561-0020
RD2	MICADO Scientific Analysis Report	E-TRE-MCD-561-0007
RD3	MICADO System Overview	E-TRE-MCD-561-0009
RD4	MICADO Design Trade-Off and Risk Assessment	E-TRE-MCD-561-0010
RD5	MICADO Optics, Mechanics, and Cryogenics Design and Analysis	E-TRE-MCD-561-0011
RD6	MICADO Control Electronics Design	E-TRE-MCD-561-0013
RD7	MICADO Top Level Instrument Software User Requirements	E-TRE-MCD-561-0021
RD8	MICADO Top Level Data Reduction User Requirements	E-TRE-MCD-561-0024
RD10	Photometry with MICADO	E-TRE-MCD-561-0023
RD11	MICADO Single Conjugate Adaptive Optics Module	E-TRE-MCD-561-0022
RD12	MICADO Compliance Matrix	E-TRE-MCD-561-0008
RD13	MICADO-MAORY Phase A Interface Specification	E-SPE-MCD-561-0014
RD14	MICADO-EELT Phase A Interface Information and Requests	E-SPE-MCD-561-0015
RD15	MICADO MAIT Plan	E-TRE-MCD-561-0024

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