MIDIR/T-OWL: the thermal/mid-IR Instrument for the E-ELT

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ABSTRACT

MIDIR is a combined thermal/mid-infrared imager and spectrograph for the European Extremely Large Telescope (E-ELT). It will operate in the infrared L, M, N, and Q-band to 20\,\mu m with a goal to extend the wavelength coverage to 27\,\mu m if the atmospheric properties of the site are sufficiently good. MIDIR will offer imaging and spectroscopic modes over a wide range in spectral resolution. MIDIR will be designed for diffraction limited performance, requiring an optimized, cryogenic adaptive optics (AO) system. The conceptual study of MIDIR is part of a suite of eight ELT instrument “small studies” partly funded by the EU [1]. The study is being performed by an international consortium of Leiden Observatory, Astron, MPIA, UK-ATC, and ESO. The high level instrument requirements for MIDIR have been directly derived from numerous important science cases. In this paper we discuss the science case for MIDIR, provide a summary of the technical specifications, discuss the requirements on the AO system, and estimate the sensitivity in various observing modes. More technical details on the instrument are given in a parallel paper at this conference [2].

Keywords: ELT, mid-infrared, imaging, spectroscopy, adaptive optics, MIDIR

1. SCIENCE CASE

1.1 Overview

The combination of a large 30 – 60m telescope aperture with a good telescope site, and low-noise, large-format mid-IR array detectors will open up completely new perspectives for mid-IR astronomy from the ground, way beyond the areas of classical mid-IR astronomy. The high point source sensitivity will allow studies of objects at very high redshifts, and high-resolution spectroscopy can be used for morphological and kinematical studies in unsurpassed details.

In general, cooled space based observatories are considerably more sensitive in the mid-IR to faint surface brightness objects than ground-based observatories. Space-based observatories, however, because of their restricted aperture size (85cm for Spitzer, up to 6.5m for JWST), are rather limited in terms of angular resolution compared to a ground-based ELT. Consequently, most MIDIR science cases from the ground focus on high angular resolution and compact objects, rather than the study of faint surface brightness features. Specifically, exciting science cases for MIDIR focus on:

- highest angular resolution
- very high spectral resolution
- quick response times (< 1 day)

In the following sections we discuss several example science cases. However, it is important to note that the MIDIR capabilities are by no means limited to these topics.

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1.2 Conditions in the early Solar System

Comets are considered to represent the most primordial bodies in our solar system accessible to Earth-based observations to date. The structure and composition of cometary ices are key to understanding the formation and evolution of matter within the early solar system. Ices are particularly sensitive to temperature and radiation processing. Comets likely formed at diverse distances from the sun and outside the ‘frost line’ in the solar nebula (~5AU) out to the Kuiper Belt (40-50AU). Depending on the temperature – thus the distance – of the formation region, dust alteration from amorphous to crystalline forms may have occurred. Thus, the composition of a comet in its icy and dusty components contains the signatures from the formation period. Today, icy and dusty planetesimals reside in two reservoirs: the Oort cloud contains the long-periodic and ‘dynamically new’ comets, the Kuiper Belt is the main source for the short-periodic comets.

Sensitive mid-IR spectroscopy provides the most important tool to understand the “weathering” cometary nuclei have undergone since their formation. In principle, the spin statistics of protons in H\(_2\)O and NH\(_3\) in the gaseous outflows are considered a reliable thermometer to probe the temperature history over the past 10\(^6\) years – but only if the spin statistics has not been altered by the solar radiation, once the molecules were released from the comet nucleus. The high spatial resolution which can be achieved with MIDIR will probe the unaltered gas within seconds after it has left the surface. The richest wavelength domain for volatile studies is the thermal IR between 3 and 5\(\mu\)m, and for the dust the 7 to 23\(\mu\)m range. Using high-dispersion spectroscopy in the former case a number of parent gas species from cometary ices (H\(_2\)O, CO, NH\(_3\), CH\(_4\), C\(_2\)H\(_2\), C\(_2\)H\(_6\), CH\(_3\)OH, HCN) can be measured. The constitutional structure and composition of the dust is revealed by low and medium resolution spectroscopy. Both techniques have been used at 8m-class telescopes, but their application is limited to the very brightest comets. A comprehensive map of the formation regions and conditions in the early solar system can only be obtained from 30-50m-class telescopes.

1.3 The Formation and Evolution of Proto-Planetary Disks

Circumstellar disks are a natural by-product of the star formation process. The material in these disks comprises the building blocks for future planetary systems (e.g., Lissauer 1993, Beckwith et al. 2000). Virtually all of the planets detected to date are gaseous Jupiter-like planets, which are thought to form in disks within 1–10 Myr after the formation of the parent star (Pollack et al. 1996). Over time, the gas in the disk will dissipate and the small grains will coagulate or be blown away. In particular Herbig Ae/Be stars (t = 1–5 Myr) in the later stages of their evolution are the immediate progenitors of classical debris disks like Vega (A0V, t ~100 Myr), β-Pic (A5V, 20 Myr) or Fomalhaut (A3V, 100 Myr). After ~20 Myr, disks become optically thin at UV and IR wavelengths, and are called debris disks. The dust grains in the debris disks are of secondary origin, replenished by collisions of larger objects. This implies the presence of asteroid-sized bodies, the so-called planetesimals. In the core-accretion model, rocky planets with masses comparable to those of the Moon or Earth form by gradual accretion of planetesimals, and only the heaviest of these cores, with masses of 10–20 Earth masses, can attract gas to form a gas-rich planet.

The transition phase from gas-rich to gas-poor disks is clearly a pivotal period in planet formation and direct observations of the gas content and composition are key to constrain the processes and time-scales involved. In particular, the bulk of the disk mass is in the gas, not in the dust. The following discussion lists the main diagnostics for studies of proto-planetary disks.

- **Evolution of Dust Grains.** The N-band contains the resonance of the Si-O stretching mode, characteristic of silicate dust grains, which can be found in pre-main sequence stars with circum-stellar disks or solar-system comets. The evolution of dust grains is illustrated in Figure 1-1. Currently, resolved imaging spectroscopy can only be done for a very small number of nearby disks. Nevertheless, the spatially resolved spectroscopy of silicate and PAH has opened the completely new field of mineralogy inside circum-stellar disks (van Boekel et al. 2004a, 2004b; Okamoto et al. 2004; Habart et al. 2004). Okamoto et al. (2004) performed this for the large disk around β-Pictoris using COMICS at the SUBARU telescope. Resolving the locations of dust replenishment reveals indirectly the location and process of planet formation. MIDIR, unlike VLTI/MIDI, will be sensitive enough to observe a statistically relevant sample of disks. For this case, instantaneous spectral N-band coverage at low spectral resolution is the preferred observing mode.
Figure 1-1 Continuum-subtracted 10µm silicate emission bands observed toward a selected sample of isolated Herbig Ae stars with ISO-SWS. The silicate bands of interstellar medium dust and comet C/1995 O1 Hale-Bopp are included for reference. The dotted vertical line indicates the position of the 9.8µm amorphous silicate band observed in the interstellar medium. The red solid line indicates the best-fit models using a mixture of amorphous and crystalline material with different grain sizes. The sharp 11.3µm feature is evidence for crystallization, the shift toward longer wavelengths hints grain growth (Bouwman et al. 2001).

- **H₂ pure rotational lines in the MIR.** H₂ is the main gaseous reservoir in disks, and an essential ingredient for building gas giant planets. The pure-rotational mid-IR lines are the lowest possible transitions to search for, but they are extremely difficult to detect because they are intrinsically very weak and always superposed on a strong continuum. For a typical sensitivity of $10^{16}$ erg s⁻¹ cm⁻² at 17µm (10σ, 1hr), MIDIR can detect ~10 M_⊕ of H₂ gas in a disk at 150 pc. For a disk at the distance of the TW Hya association (56 pc), models predict S(1) and S(2) fluxes around 2x10^{15} erg s⁻¹ cm⁻² if the star has excess UV radiation (Nomura & Millar 2005), readily detectable with MIDIR. A MIDIR key program would be a survey in the S(1) 17µm and S(2) 12µm lines in a large set of disks of various evolutionary stages, taken from samples defined, e.g., by Spitzer. An integral field unit would be crucial for these studies. MIDIR’s resolution is well matched to the size of disks (10 AU = 0.07″ at typical distances of 150 pc for T Tauri stars in Oph, Cha, or Lupus).

- **CO fundamental band at 4.7µm.** The CO v=1-0 fundamental vibration-rotation transitions at 4.7µm have been detected toward more than a dozen Herbig Ae and T Tauri stars (Brittain et al. 2003, Najita et al. 2003, Rettig et al. 2004, Blake & Boogert 2004). The lines often show a double-peaked profile whose width varies from 5–10 km/s to more than 100 km/s and correlates with the inclination angle (see Figure 1-2). Thus, a spectral resolving power of R~50000 is needed to resolve these lines. The kinematical information provides constraints on the location of the emitting gas in the disk. Both collisional excitation in the inner dense warm gas (<1 AU) and resonance fluorescence in the outer disk play a role in the CO excitation, and extended CO has been detected out to radial distances of ~20 AU (0.3″ Ø at 150 pc).

- **H₃⁺ emission at 3.9µm.** H₂, CO and H₃⁺ are the three molecules most fundamental and abundant in the interstellar medium. They often control the chemistry and physics whatever their environment. H₃⁺ is 10,000 times less abundant than molecular hydrogen in dense molecular clouds, and 10⁷ times less in diffuse clouds. However, H₃⁺ is a universal protonator that works with almost any atom or molecule. Despite its significance, the ion molecules is not yet well understood itself. The H₃⁺ ion has strong emission bands at 3.9µm. These lines have been detected in the polar regions of Jupiter in our own solar system, and may be prominent as well in exo-planetary atmospheres. A possible detection of H₃⁺ lines in the HD 141569 transitional disk has been claimed by Brittain & Rettig (2002), but has not been confirmed by subsequent searches (Goto et al. 2005).
• **Gas-phase molecules.** Molecules such as CH$_4$ (7.7µm), C$_2$H$_2$ (13.7µm) and HCN (14.0µm) are key species in the organic chemistry that occurs in the inner (<20 AU) planet-forming zones of disks. At the high temperatures in these regions, even more complex organic molecules can be formed (Markwick & Charnley 2004), which could be detected via their C-H stretching vibration in the 3–4 µm region. Indeed, this wavelength range is the fingerprint region for different hybridized bonds of sp$^3$ (e.g. CH$_4$), sp$^2$ (e.g. C$_2$H$_2$) and sp (C$_2$H$_2$) type. O-H and N-H bonds also have signatures in this range. Note that ALMA cannot see symmetric molecules without a dipole moment, such as CH$_4$ and C$_2$H$_2$, which are the main building blocks of organics.

• **Ices.** At low temperatures (<90 K), the organic molecules will be frozen out as icy mantles on the grain cores where they can also be studied through infrared spectroscopy. Examples are solid H$_2$O (3µm), HDO (4µm), CO (4.67µm), OCN$^-$ (4.62µm), CH$_4$ (7.67µm), NH$_3$ (9.0µm) and CH$_3$OH (3.5, 9.7µm) bands, which can be observed from the ground. The line of sight through edge-on disks can also intercept the cold outer layers of the disk where these molecules are frozen out. An example is the edge-on disk CRBR2422.8-3423 whose spectrum shows very deep ice absorptions (Thi et al. 2002, Pontoppidan et al. 2005). A spectral resolving power of at least R~3000 is needed to properly sample the line profiles, which vary from source to source and contain interesting information on the ice environment and temperature history.

• **PAHs.** Polycyclic aromatic hydrocarbons are the largest organic molecules that can be observed in disks. Their strong emission features completely dominate the structure of the MIR spectrum. PAHs are not only interesting for the disk chemistry, but are also excellent diagnostics of the UV radiation incident on the disk surface, and thus its flat or flaring geometry (Acke & van den Ancker 2004). Moreover, they are important in heating the gas to temperatures higher than that of the dust through photo-ionization (Jonkheid et al. 2004). In contrast to the thermal dust emission, the PAH features are known to be extended to radii of at least 30 AU, as demonstrated by spatially-resolved spectroscopy on 8-m class telescopes (Habart et al. 2004, Geers et al. 2004). The spatial extent is expected to vary from feature to feature; for example, the 3.3µm feature is predicted to be more compact than the 11.3µm feature. These models can be directly tested by spatially resolved spectroscopy with MIDIR.

### 1.4 The Galactic Center

The Galactic Center region is of great interest not only as the center of our galaxy but also as the environment of the closest (quiescent) super-massive black hole. Largely enshrouded by gas and dust, it can be best explored at radio, sub-
millimeter, infrared, X-ray and γ-ray wavelengths. All constituents of the inner few parsecs, the super-massive black hole (SMBH), surrounding star clusters, streamers of ionized gas, molecular dust ring and a supernova remnant have been studied extensively during the last years. (See Melia & Falcke 2001 for an overview).

There are numerous topics of great scientific importance in this complex region, including the stellar dynamics around the SMBH and its associated radio source Sgr A* and the location of massive young clusters in the region. Here we focus on just one issue – the accretion and emission mechanisms of the SMBH. The intrinsic size of Sgr A* has remained unresolved at centimeter and longer wavelengths because radio waves from Sgr A* are scattered by the turbulent interstellar plasma along the line of sight. The scattering increases with wavelength as $\lambda^2$, pushing observations to shorter and shorter wavelengths. ALMA is expected to be a powerful tool for such observations, and MIR observations at the highest spatial resolution will enormously contribute to this exciting puzzle. Recent broad band observations give upper limits of factors of 2 – 10 above the theoretically expected SED for Sgr A*, based on a variety of accretion- and jet models.

In the context of MIDIR it is important to note that the detectivity of Sgr A* is not limited by the atmospheric background but by the diffuse emission of the surrounding gas and dust. Thus, studies from space are severely limited by the low spatial resolution and the high surface brightness. MIDIR on the E-ELT will be able to detect Sgr A* and distinguish between different accretion models by measuring the broad band fluxes coming from the central $\leq 17$ Schwarzschild radii at the most critical wavelengths between L and N band (Figure 1-3 right).

![Colour Composite of the Galactic Centre (VLT/MidiPac + VISIR)](image)

Figure 1-3 **Left:** The 33″×33″ of the Galactic Center region observed with VLT/VISIR at 8.6µm (blue), 12.8µm (green) and 19.5µm (red), with total integration times of 300, 160 and 300s, respectively. **Right:** Broad band spectrum of Sgr A* produced by a jet model, with a power-law (PL) and a relativistic Maxwellian (MW) electron distribution, compared to radio and IR observations (Melia & Falcke 2001).

### 1.5 The Luminous Centers of Nearby Galaxies

The most extreme starbursts are found in mergers of gas-rich galaxies, where the dissipative gas components quickly sink to the center of the potential well, resulting in an intense burst of star formation. So-called ultra-luminous infrared galaxies (ULIRGs) are a manifestation of this phenomenon, and approach quasar-like luminosities, which are, however, almost entirely (re)radiated at mid- and far-infrared wavelengths. Although locally rare, at high redshifts ULIRGs are responsible for a large fraction of the integrated sub-millimeter background and the overall star formation budget. If ULIRGs are the progenitors of present-day elliptical galaxies the origin of the relation between spheroid mass and nuclear black hole mass would be related to the ULIRG phase. Many of the most luminous ULIRGs also contain an active galactic nucleus (AGN). Does the occurrence of an extreme starburst trigger the AGN activity? How does it depend on the parameters of the starburst?
The MIR wavelengths do not only penetrate dust but also provide numerous important diagnostics: the ionic lines of [Ne II], [S IV], [Ar III], [S III] and others probe the photo-ionized gas, emission features of PAHs trace massive, young OB stars, the H$_2$ lines probe the warm molecular gas, and the broad 9.8 and 18\mu m silicate features contain information on the absorbing material along the line of sight. Altogether, these diagnostics can be used to separate the contributions from starburst and AGN to the total infrared luminosity. At the wavelength covered by MIDIR, the heating source of the dust is probed directly, providing the link between the power source and the far-IR emission.

Observational studies of these important objects require imaging spectroscopy in the mid-IR at very high angular resolution and medium sensitivity. In the nearest ULIRGs, like Arp 220 (Figure 1-4), the resolution provided by MIDIR will allow to spatially resolve the individual components of AGN, supernova remnants, super star clusters and HII regions, and other IR-luminous components. Most importantly, IFU spectroscopy will permit the spectral classification and relative velocities of these components. It is important to note that due to the extreme extinction these studies cannot be done at NIR wavelengths.

Figure 1-4  Zooming into the center of Arp 220, the nearest ULIRG.

Figure 1-5 shows the velocity map of the center of the Seyfert galaxy NGC 7582 in the [Ne II]12.8\mu m line, taken with VLT/VISIR in high resolution mode. From the comparison to models an upper limit on the black hole mass of 5\times10^7M_\odot could be derived. To appreciate the need for angular resolution we note that the nearest ULIRG, Arp220, is at a distance of 75 Mpc. Even for a modest sample of ULIRGs one must already reach out to distances of ~200 Mpc. At that distance, a 42m E-ELT will provide a maximum resolution of about 100 pc at N-band – still sufficient to reveal the large scale structures of the nuclear regions, but not feasible from smaller space-based telescopes like JWST.

The only other facility comparable to MIDIR in terms of resolution for this application will be ALMA in its widest configuration at high frequency. MIDIR will provide the necessary information at the Wien side of the Planck curve, probing the thermal and non-thermal processes directly associated with the starburst and the central AGN. ALMA will probe the cooler bulk material at the Rayleigh-Jeans side. Hence, MIDIR will be a perfect complement to ALMA.
1.6 AGN at high Redshifts

Coronal lines are collisionally excited, forbidden transitions of ionic species with an ionization potential of 100 – 400 eV. These lines can only form in extreme energetic environments such as AGN, and are therefore considered good discriminants between AGN and starburst-dominated environments (Penston et al. 1984; Marconi et al. 1994; Prieto & Viegas 2000; Rodriguez-Ardila et al. 2002; Reunanen et al. 2003). The strongest coronal lines can be observed in the 1 – 40 µm range: [Si VI] … [Si IX], [Ne V], [Ne VI], [Mg VII], [Ca VII], etc., and their strengths are comparable to that of lower ionization atomic or molecular lines in this spectral range.

Coronal lines typically have asymmetric profiles and line widths of $\geq 1000$ km/s, broader than those measured in the narrow line region but narrower than those of the broad line region. They are likely to originate from a region very close to the nucleus but still outside the broad line region (e.g. Penston et al. 1984; Reunanen et al. 2003; Siebenmorgen et al. 2005: Yan et al. 2005), and remain mostly unresolved even at E-ELT resolution. Their strength and exclusive ubiquity in AGN together with their low susceptibility to dust extinction makes them ideal tracers of AGN activity, in particular in optical obscured AGN at high redshift. Figure 1-6 illustrates the accessibility of coronal lines for a given redshift. At redshifts $3 \leq z \leq 6$ and $2 \leq z \leq 4.5$ the strong [Si VI]1.6µm and [Si VII]2.4µm lines, respectively, fall into the N-band. Their expected line flux is about $10^{-14} – 10^{-15}$ erg cm$^{-2}$s$^{-1}$ at $z = 0$, which corresponds to a line peak of about $10^{-21}$ erg cm$^{-2}$s$^{-1}$Å$^{-1}$ at $z \sim 5$. MIDIR will be able to detect these lines at the 3σ-detection within one night.
1.7 Gamma-Ray Bursts at high Redshift

Since their published discovery in 1973 gamma-ray bursts (GRBs) have been one of the most exciting areas of extragalactic astronomy. Besides being extremely interesting events in their own, they can be used to probe the ionization state and metal content of the intergalactic medium (IGM) at high redshifts. For a short period of time they are the brightest and most energetic events in the distant Universe, and are – even on E-ELT scales – point sources. At $z \sim 10$ an observed K-band wavelength corresponds to rest frame UV light which may be strongly affected by extinction. All these points make MIDIR the ideal instrument for GRB observations at high-$z$.

Figure 1-7 (left) shows the predicted flux densities from GRBs as a function of redshift. GRBs observed after one day have 10$\mu$m flux densities of $\sim 0.01$mJy, which can be easily detected. Within the first hours, GRBs out to $z \sim 15$ have typical flux densities of 0.1mJy, which is even within the capabilities of the MIDIR spectrograph. At that flux level (or higher) one would expect a rate of $10^{-4}$ GRBs per square degree (Figure 1-7, right). MIDIR spectroscopy may also be used to determine the redshift via the Pa-$\alpha$ (1.87$\mu$m) line ($3.0 < z < 6.2$) or the Pa-$\beta$ (1.28$\mu$m) line ($4.8 < z < 9.5$).

With its rather small field of view MIDIR is not well suited to discover GRBs – this task has to be done by a dedicated survey satellite like SWIFT. However, once a high-$z$ GRB candidate has been identified, MIDIR would be able to observe the target much quicker than JWST/MIRI.

1.8 Summary

An E-ELT aperture of about 42m would provide a spatial resolution 6.5$\times$ higher than what will be achieved with JWST/MIRI at competitive point-source sensitivities. MIDIR’s capabilities improve significantly on basically all areas of “traditional” MIR science, but also open up MIR astronomy to areas which have traditionally been in the optical/NIR regime. From the science cases we derive the following requirements:

- Due to the huge thermal background, the large gain in sensitivity provided by an E-ELT will only be achieved for unresolved sources. Hence, the science case is strongly biased toward compact sources and small-scale structures (small in angular units).
- In most cases the required field of view is in the order of arcseconds rather than arcminutes. Since the distribution of MIR sources across the sky (within the isoplanatic angle) is sparse a multi-object capability is not required.
- High-resolution spectroscopy (R$\sim$50,000 or 6 km/s) is strongly desired for several reasons. First, to separate close spectral features (R$\sim$30,000 is needed to discern disk emission from ambient nebular lines). Second, at R$\sim$50,000...
the Earths orbital velocity can Doppler-shift lines in and out of opaque, narrow windows. Third, higher spectral resolution means better sensitivity to unresolved emission and absorption lines. Besides, \( R \geq 50,000 \) will not be offered by any IR space observatory in the foreseeable future.

- For the spectrograph an integral field unit (IFU) is required for scientific and practical reasons.
- The wavelength coverage needs to include the thermal L and M bands, and the mid-IR N and Q bands out to at least 20\( \mu \)m. The usefulness of the Q band beyond 20\( \mu \)m depends strongly on the atmospheric characteristics of the telescope site. If the water vapor content is low the spectral coverage should be extended to 27\( \mu \)m.

In summary, MIDIR will offer broad- and narrow-band imaging over at least 20\( '' \times 20'' \), low resolution long slit spectroscopy, medium resolution (\( R \sim 3000 \)) IFU spectroscopy with wide instantaneous spectral coverage, and high resolution (\( R \sim 50000 \)) spectroscopy.

### 2. INSTRUMENT OVERVIEW

From the science case we derived the high-level instrument requirement on (quasi) diffraction limited performance at LM, N and (at least part of the) Q bands with the following instrument modes:

- broad- and narrow-band imaging over about a 20''\times20'' FOV
- low-resolution (\( R \sim \text{a few hundred} \)), long-slit spectroscopy
- medium resolution (\( R \sim 3000 \)), integral field (IFU) spectroscopy over a 1''\times2'' FOV.
- high resolution (\( R \sim 50000 \)), IFU Echelle spectroscopy

After completion of the various studies not all of these options may be recommended for all wavebands. A careful trade-off study between scientific importance and instrument complexity is ongoing. The need for and feasibility of polarimetry is under study. The field of view can be kept relatively small, given the scientific focus on compact objects and the relatively smaller space density of IR sources. Part of the requirement on the field size of about one arcminute comes also from the possible need for chopping. For more technical specs and details on the optical set-up of MIDIR see [2]

In contrast to some other proposed E-ELT instruments, MIDIR does not require developments of fundamentally new technologies, but extends certain technologies beyond the current state-of-art. Critical items which require future attention include:

- design and testing of cryogenic AO systems
- development and implementation of a suitable chopping scheme
- characterization of the strength and impact of water vapor fluctuations
- specific requirements on the telescope design and performance
- requirements on the internal metrology system
- fabrication of large format Echelle gratings.

MIDIR would also be suitable as a first generation E-ELT instrument for various reasons:

- One of the biggest challenges for ELTs is arguably the diffraction-limited performance of the optical system, including the adaptive optics system. It is still uncertain whether a close-to-optimal performance can be achieved at optical/NIR wavelengths. Operating at longer wavelengths mitigates many of the difficulties.
- MIDIR can provide important additional information during the commissioning phase of the telescope on its structure and optical performance from the thermal point of view.
- The mid-IR imager and spectrograph would provide diffraction-limited, wide-field images at 10\( \mu \)m at roughly the same angular resolution as JWST in the NIR and HST in the optical. Hence, the combination of ancillary data with MIDIR N-band images of dusty systems would provide a significant PR value.
The cost of Mid-IR Imager and Spectrograph will be dominated by manpower and, on the hardware side, by MIR detectors. The cost estimates for MIDIR are well in line with independent estimates made for other ELT instruments.

### 3. ADAPTIVE OPTICS REQUIREMENTS

The large aperture size of the E-ELT requires adaptive optics to correct for atmospheric seeing even at thermal IR wavelengths. Figure 3-1 (left) illustrates the importance of atmospheric turbulence correction, which can yield an improvement of a factor of nine in angular resolution!

![Figure 3-1](image)

**Left:** Seeing and diffraction limits for various aperture sizes as a function of wavelength. Here we assume $r_0(0.5\mu m) = 12$ cm (0.8") and an E-ELT aperture of 42 m. The figure also shows why mid-IR instruments on current 8m-class telescopes do not need AO out to almost 20$\mu$m.

**Right:** Strehl ratios achieved with a MIDIR-specific AO system at various wavelengths (for details see main text). Figure courtesy of Miska LeLouarn/ESO.

The adaptive optics system for the thermal/mid-IR on a 42-m telescope has specific requirements that differ from the AO systems required for the NIR. While still challenging by today’s standards, it requires significantly reduced complexity compared to the NIR. However, to reduce the thermal background, the reflectivity needs to be optimized for the mid-IR, the surfaces need to be accessible for cleaning, and the entire system may have to be cooled significantly below room temperature. Although the AO system will be specifically designed for MIDIR, it is anticipated that the AO will be a stand-alone module.

Figure 3-1 (right) shows the expected performance of an AO system specifically designed to provide MIDIR with a diffraction limited PSF at N and Q-bands, and close to diffraction limited performance in the L and M bands. Here we assume 0.8” seeing, an outer scale of 25m, and a Paranal-like atmospheric turbulence profile, and a wavefront sensor operated at 500Hz at K-band with 6 electrons read noise. A system of 42×42 sub-apertures with a guide star of magnitude K=11.4 (corresponding to 130 photons/sub-aperture/frame) can achieve diffraction-limited performance [3] longward of 7$\mu$m and Strehl ratios greater than 40% at LM bands. The off-axis performance at 5" and 10" (indicated by the dashed lines in Figure 3-1) is not noticeably reduced due to the large isoplanatic angle at thermal/MIR wavelengths.

### 4. INSTRUMENT SENSITIVITY

In this section we estimate the instrument sensitivity, based on the following assumptions:

- Diffraction limited point source
- 42m E-ELT with an 8m central obscuration
• Site: Chajnantor, 5100m altitude, winter time, observations at zenith
• Telescope emissivity: 12.5% (unbaffled)
• Typical filter transmission, grating efficiencies, cold mirror reflectivities
• (Line) sampling: 2 pixels spatially and spectrally
• Detector DQE: 60%
• Pixel size: 30µm (AQUARIUS)
• Pixel f/#: 16.2 (LM), 6.7 (N), 3.3 (Q)
• IFU slice widths: 3.7µm (LM), 9.0µm (N), 18µm (Q)

The calculations are based on atmospheric transmission and emission spectra calculated with HITRAN-PC.

4.1 Imaging Sensitivity

Figure 4-1 shows MIDIR’s imaging sensitivity to a diffraction-limited point source within an hour, detected at 10-σ, for different telescope diameters.

![Figure 4-1](image)

Figure 4-1 10-σ point-source, broad-band imaging sensitivity for a 30m (blue), 42m (red) and 60m (green) ELT in 1hr integration time.

4.2 Spectroscopic Sensitivity

The sensitivity of the MIDIR spectrograph has been estimated at resolutions of R=3000 and R=50,000. The atmospheric spectra for L, M, N and Q bands were calculated by HITRAN-PC accordingly. Figure 4-2 shows the point-source continuum sensitivities for LM and N band at a resolution of R=3000.

At very high resolution the main interest is usually not in the continuum but in the sensitivity to narrow spectral features. Since R=50,000 is too high to be plotted for the entire band we show here the sensitivity to two representative lines, namely the H₂ S(3) line at 9.6649µm (N-band), and the [S III] line at 18.7130µm (Q-band). Figure 4-3 shows the 10-σ point-source sensitivities for these lines at a resolution of R=50,000 in units of [Wm⁻²].
Figure 4-2  **Left:** 10-σ, 1hr continuum sensitivity to a point source at R = 3000 in LM-band for DIT=10s.  **Right:** 10-σ, 1hr continuum sensitivity to a point source at R = 3000 in N-band for DIT=1s.

Figure 4-3  **Left:** 10-σ, 1hr point-source sensitivity to the unresolved H$_2$ (0,0) S(3) 9.6649µm line at R = 50000 and DIT=10s.  **Right:** 10-σ, 1hr point-source sensitivity to an unresolved [S III] 18.7130µm line at R = 50000 and DIT=1s.

Most of the future projects, both in space and on the ground, are rather complementary to MIDIR: SAFIR and ALMA will contribute the longer wavelengths ranges; JWST and WISE will have significantly lower spatial and spectral resolution than MIDIR; the VLTI will have higher spatial resolution but inferior sensitivity. The wavelength-sensitivity phase space coverage is illustrated in Figure 5-1. Taking also into account the high angular resolution provided by MIDIR and the very limited lifetime of cryogenic space missions, MIDIR would clearly fulfill the important niche of a sensitive and flexible MIR instrument providing high spatial resolution over a long time.

## 5. OTHER CONSIDERATIONS

The two main limiting factors on the performance of a ground-based mid-IR instrument are the thermal emission from the telescope and its surrounding structure and the transmission/emission of the atmosphere. In this section we will briefly address both factors.

### 5.1 Site

The feasibility of the above science case and the competitiveness of MIDIR with JWST/MIRI depends to a large extent on the properties of the atmosphere at the telescope site. At M and Q-band the performance is mainly limited by the atmospheric transmission, while at N-band the performance is mainly given by the temperature of atmosphere and
telescope, although the effective width of the N band depends on the transmission. The transmission properties of the atmosphere will determine if unique, important diagnostics (such as CO at 4.7µm or the H₂ line at 17.03µm) are accessible. At the long wavelength part of the M-band the sensitivity from a site like Chajnantor is about one order of magnitude better than from Paranal (Figure 5-2). A very significant factor is the amount of precipitable water vapor. The magnitude and timescales of its fluctuations require more study since fluctuations may become a strong component of the image degradation – despite AO correction – and may require wavefront/tip-tilt sensing at N-band. In any case, the amplitude of such an effect is expected to be much reduced at high altitudes.

Figure 5-1: Comparison of point source detectivity of contemporary IR and sub-millimeter instrumentations.

Figure 5-2: Comparison between a 42m telescope/MIDIR spectrograph on Chajnantor (blue) and Paranal (red). The better atmospheric transmission at the higher site will yield a gain in sensitivity of about one order of magnitude longward of 5µm.
5.2 Telescope emissivity

The performance of any Mid-IR Imager and Spectrograph will critically depend on the thermal background emission from telescope+AO system. Hence, a telescope with the minimum number of warm surfaces (2 or 3) is clearly preferred. The IR-optimized reflectivity of each surface – which includes both the initial surface coating and the dust-free preservation of the surface – is of crucial importance. Figure 5-3 shows that a 30 meter telescope with only two optimized mirrors (2% emissivity per surface) will yield the same sensitivity at N-band as a twice as large, 42m telescope with five “normal” mirrors (5% emissivity, each).

![Figure 5-3 Sensitivity comparison between an N-band spectrograph on an IR-optimized, two mirror, 30m telescope (blue), and a non-IR-optimized, 42m telescope with five mirrors (red). The performance in terms of sensitivity is essentially the same.](image)

ACKNOWLEDGEMENTS

This activity is supported by the European Community (Framework Programme 6, ELT Design Study, contract number 011863).

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