# Mid-InfRAred Camera w/o LEns (MIRACLE) for SPICA

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## ABSTRACT

Mid-InfRAred Camera w/o LEns (MIRACLE) is a focal plane instrument for the future JAXA/ESA infrared astronomical mission, SPICA. MIRACLE is designed for wide field imaging ($5' \times 5'$) and low-resolution spectroscopic observations (R$\sim$100) over a wide spectral range in the mid-infrared wavelengths (5–38$\mu$m). Thanks to the SPICA's large aperture (3-m class) and cold (<6K) telescope, MIRACLE has a better sensitivity than JWST/MIRI at the wavelength over 20$\mu$m (3.5 $\mu$Jy at 20$\mu$m, R=5, S/N=5, 3600 seconds) and its wider field of view (FOV) provides a faster mapping speed in its full spectral range for point sources. Confocal off-axis reflective imaging system provides a wide FOV with diffraction limited image quality over wide spectral range. MIRACLE consists of two channels: MIRACLE-S and MIRACLE-L, which are optimized for 5-26$\mu$m and 20-38$\mu$m, respectively. Each of them consists of a fore-optics and a rear-optics, each of which has a pupil position equipped with a filter wheel and a grating wheel, respectively. A field stop wheel, which provides optimal slits in the spectroscopic mode and a wide FOV in the imaging mode, is installed at the focal plane of the fore-optics. A large format array detector (Si:As 2Kx2K for MIRACLE-S and Si:Sb 1Kx1K for MIRACLE-L) is installed at the focal plane of the rear-optics in order to achieve Nyquist sampling of the point spread function. Contiguous wavelength coverage is considered in choice of the filter bands from the experiences in the Spitzer and AKARI observations. We will present the results of conceptual design study including sensitivity analysis.

**Keywords:** infrared astronomy, infrared instrumentation, space mission, SPICA

## 1. INTRODUCTION

As it is clearly demonstrated in the AKARI/IRC[1] and Spitzer/IRAC[2] and MIPS[3] observations, mid-infrared wavelength is the key wavelength to study the physical condition of solid state interstellar medium and the evolution and the formation of galaxy/star/planet in the dusty universe. Multi-band imaging with contiguous wavelength coverage and low-resolution spectroscopy are important in this spectral range because broad emission and absorption lines of PAH and Silicate are dominant spectral features in this wavelength region, and useful to determine physical information by SED fitting technique such as redshift and star formation rate (Figure 1). Wide field of view is also critical for large area survey and study of variation of star formation activity in galaxies along the clustering scale (Figure 2). In order to make a merit of the state-of-art large format array detector, wide field of view is also desirable.

We are proposing a focal plane instrument, Mid-InfRAred Camera w/wo LEns (MIRACLE) for the future JAXA/ESA infrared astronomical mission, SPICA.[4] MIRACLE is designed for wide field imaging and low-resolution spectroscopy with contiguous wavelength coverage in 5-38$\mu$m. The wavelength region of 26-38$\mu$m is the new window which MIRACLE explores. In section 2, we discuss the scientific objectives which MIRACLE are designed for, and resolve instrument specifications resuired. In section 3, we present the result of the conceptual design study.

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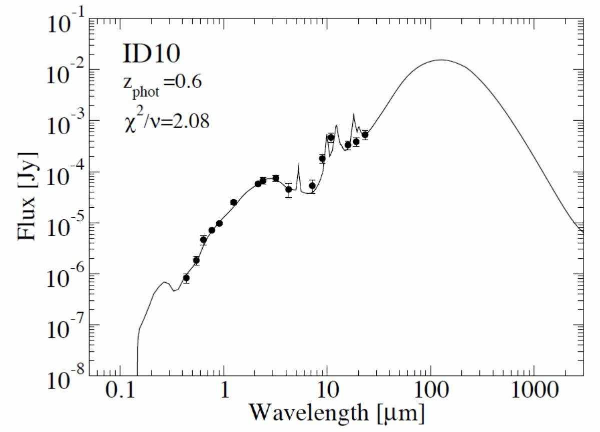


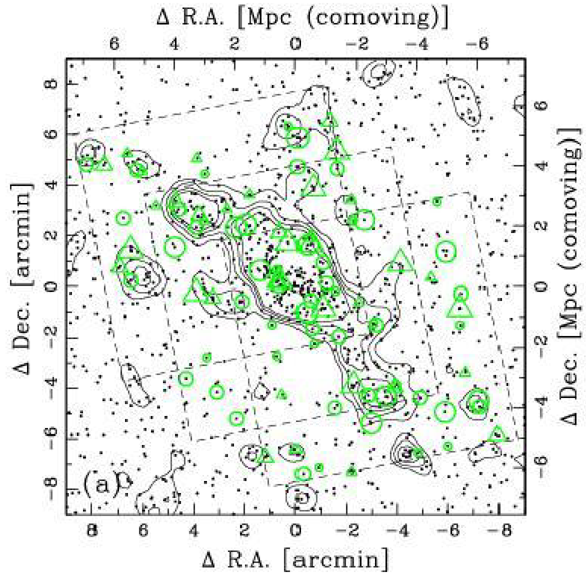




Figure 1. (left) A example of MIR SED fitting for a galaxy obtained by AKARI/IRC MIR multi-band imaging observation. The SED is well fit by a dusty star forming galaxy at z=0.6. The board emission lines by PAH at the MIR provide a good diagnostic for redshift and star formation.[5]

Figure 2. (right) A example of MIR observation for a distant cluster of galaxies (z=0.81). Dots and contours are distribution and density of photo-z member galaxies. The dots marked with green triangle and circle are galaxies detected by AKARI/IRC 15$\mu$m survey and thought to be active star forming galaxies because PAH emission at rest-frame 8$\mu$m comes into 15$\mu$m band at this redshift. Clear enhancement of 15$\mu$m sources are found near over density regions, and FOV of 5'×5' are useful to map out these galaxy clustering regions.[6]

## 2. SCIENTIFIC OBJECTIVES AND REQUESTED INSTRUMENT SPECIFICATIONS

MIRACLE can be used for wide variety of observational study for astronomy and astrophysics, however, MIRACLE is mainly designed for the science related to two of three large SPICA's Scientific objectives: "Resolution of Birth and Evolution of Galaxies" and "Life Cycle of Interstellar Dust". In the former objective, we focus on "Cosmic Star-Formation and Mass Assembly History". In the latter objective, we focus on "Interstellar Medium in Nearby Galaxies". The detailed discussion on SPICA's Scientific objectives can be found in the proceedings of SPICA Science Workshops.[7,8]

### 2.1 Cosmic Star-Formation and Mass Assembly History

Main mission of MIRACLE in the objective, "Cosmic Star-Formation and Mass Assembly History", is to make wide field survey with multi-band imaging which is required to extract the physical informations; for example, redshift and star formation rate of distant active star-forming galaxies through the SED fitting technique.

The key feature for these study is the broad emissions of PAH in the mid-infrared wavelength because the PAH emission is a good tracer of the star-formation activity. Spectral features in the mid-infrared wavelength is important for study of star-forming galaxies which is usually heavy obscured by the dust because the effect of interstellar dust extinction is extremely smaller than that in the optical wavelength. The broadness these feature enables us to estimate the redshift of galaxies with relatively low spectral resolution, thus faster observation can be done with required signal-to-noise ratio.

In order to trace the Cosmic Star-Formation Rate (CSFR) with the rest-frame 8$\mu$m PAH emission in the redshift range of z=1-4, in which the CSFR shows a maximum, the instrument must cover wavelength of 5-40$\mu$m contiguously, with a spectral resolution of R=5-10. In order to avoid bias effect from cosmic variance, we must cover a volume of cluster size at redshift of z=1-4, and the instrument must cover a field of view of a few arc-min.

Model prediction of galaxy confusion limit shows a few arc-second resolution is required to make observation deep enough. In order to apply deconvolution technique to reduce the effect of confusion, the PSF must be fairly sampled compared to normal Nyquist sampling.

### 2.2 Interstellar Medium in Nearby Galaxies

Main mission of MIRACLE in the objective, "Interstellar Medium in Nearby Galaxies", is to make high resolution imaging and low resolution spectral mapping observations in the mid-infrared wavelength.

In the mid-infrared wavelength, there are plenty of broad band features of dust and molecules, such as PAH emission, Silicate absorption, emission from VSG, water ice features, vibration mode molecular gas features, etc. Comparing multi-band mid-infrared imaging (spectral resolution of R=5) with models enables us investigation of global distribution of those interstellar medium as well as global variation of physical and chemical condition of interstellar medium in the galaxies, such as radiation field strength, dust density, chemical composition (PAH abundance for example), etc.[9]

Long-slit low resolution spectroscopy is also powerful tool to investigate spatial variation of these broad spectral features. For example the shape of PAH emission has dependence of chemical composition (number of carbon atoms in each molecule for example), and charge state of each molecule. Multi-slit is desirable to improve observational efficiency.

In order to maximize the merit of these broad band features of dust and molecules, whole wavelength range of mid-infrared wavelength must be covered, from 3.3um (PAH C-H stretching mode) to 44um (Water ice features).

A few arc-second spatial resolution is necessary for resolving basic structure of nearby galaxies such as Giant Molecular cloud and inter-arm structures (typical size of GMC, 500pc, at 10Mpc correspond to 10 arc second). A few arc-minutes field of view is appropriate in order to cover nearby galaxies (10kpc at 10Mpc correspond to 3.4 arc-minutes).

### 2.3 summary of required specifications to the instrument

The instrument must satisfy the following specification in order to meet above scientific requirement.

- Wavelength coverage of 5–38um. Extension to 3.3um PAH emission and 44um water ice feature is highly recommended.
- Wide field of view (4–6 arc-minutes)
- Diffraction limited spatial resolution
- Fair sampling of the PSF for deconvolution technique
- Contiguous wavelength coverage
- broad band filters (R=5–10)
- Low resolution spectroscopic capability (R=100)
- long/multi slit mode for spectroscopic mapping survey.
- narrow band filters (R=50) for line emission survey.

## 3. RESULT OF CONCEPTUAL DESIGN STUDY

According to the specification required for the science objectives, we have conducted a conceptual design study for MIRACLE. The specifications of MIRACLE are summarized in Table 1.

### 3.1 optical design

MIRACLE consists of two channels: MIRACLE-S and MIRACLE-L, which covers spectral range of 5-26$\mu$m and 20-38$\mu$m (goal -50$\mu$m), respectively. Figure 3 shows the conceptual design of the MIRACLE optics. Each MIRACLE optics consists of two part, fore-optics and rear-optics. Fore-optics is used as a rely optics and re-imaging the telescope focal plane. In order to realize both slit spectroscopy and wide-field imaging with a single instrument, we will install a field-mask wheel at the re-imaging focal plane. Filter wheel will be installed at the fore-optics pupil and wheel for dispersion elements will be installed at the rear-optics pupil. The detector will

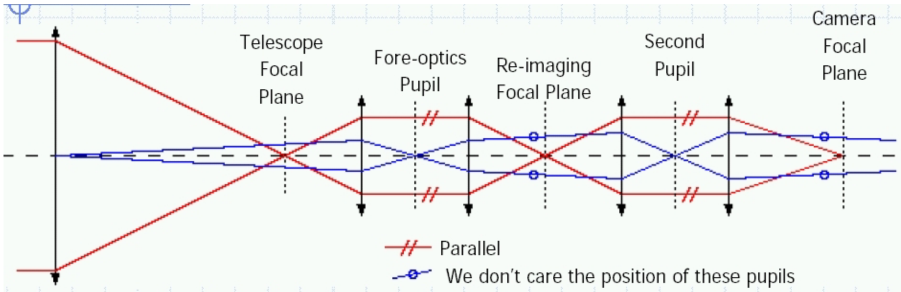



Figure 3. Design concept of MIRACLE optics.[10] A filter wheel is installed at the fore-optics pupil. A slit wheel is installed at the focus of fore-optics in order to impliment both wide field imaging and slit spectroscopy. A grating/mirror wheel is installed at the rear-optics pupil.

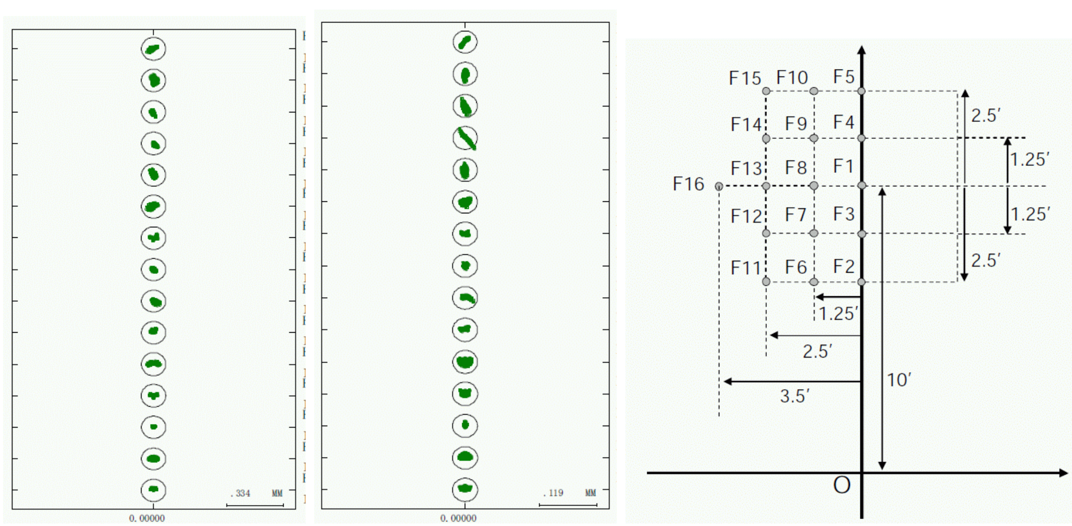



Figure 4. Spot diagram of MIRACLE-S and -L optics. The circles show the size of airy disc at the wavelength of $5\mu$m. The top spot diagram shows that at the position of F1 and the bottom shows that of F15.

Table 1. Specification of MIRACLE.

| | Short channel | Long channel |
|---|---|---|
| Core wavelength | 5-20$\mu$m$^{:1}$ | 20-38$\mu$m$^{:2}$ |
| Spectral resolution | 5-200 | 5-200 |
| FOV | 5'×5' | 5'×5' |
| Image Quality | telescope diffraction limited | |
| Noise | background limited (zodiacal light) | |
| Observational mode | broad/narrow band imaging<br>slit-less and slit spectroscopy | |
| Number of filters | 18 $^{:3}$ | 18 |
| Detector | Si:As 2Kx2K<br>Si:Sb 1Kx1K (backup) | Si:Sb 1Kx1K<br>Si:X 128x128 (for 38-50$\mu$m) |

1: Wavelength down to 3$\mu$m can be covered by Si:As detector with Nyquist sampling of the PSF.
2: Wavelength up to 50$\mu$m can be covered by Si:X detector with a limited FOV.
3: Wavelength of 5-26$\mu$m can be covered by 17 filters with a spectral resolution of R=10.

be installed at the final focal plane. Current design shares the same design of fore-optics in order to reduce the cost of fabrication and verification.

Reflective optical system without lens have been designed in order to cover wide wavelength range (5-38$\mu$m) with only two channels.[10–12] The trial design with lens needs four channels because of limitation of the lens material.

The current design has achieved diffraction limited performance (Strehl ratio is 0.9 or more) both for short (at 5$\mu$m) and long (at 20$\mu$m) channel in entire $5' \times 5'$ FOV (Figure 4). The physical dimension is approximately $40 \times 95 \times 15$ cm for each channel and meets the current system requirement. Optimization for volume and mass will be done subsequently.

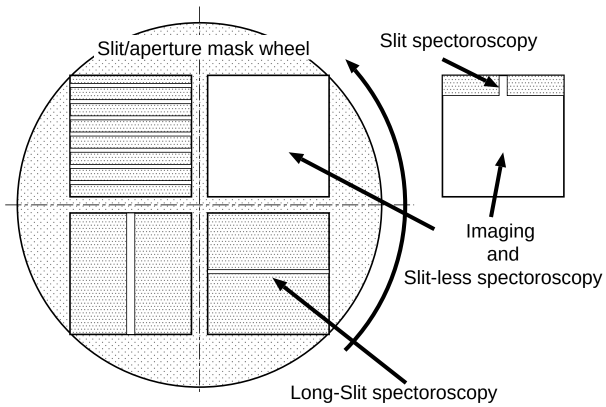
The current size of fore-optics pupil is 25mm which is designed to be meet a filter with diameter of 30mm. The size of pupil (the size of filter, the size of filter wheel, and the number of filter) is anti-correlated with the size of FOV. If pupil size of 30mm (filters with diameter of 1.5 inch) is allowed, FOV of $6' \times 6'$ can be achieved. The size of FOV also affects the amount of distortion. Further discussion on scientific merit have to be done for a trade-off between the size of FOV and number of filter, and also between with the size of FOV and the amount of distortion.

In order to achieve high efficiency in low resolution spectroscopic observations, we are planning to install a field-mask/slit wheel at the focal plane of fore-optics. AKARI/IRC and JWST/MIRI used a fixed short slit at the edge of the field mask for low resolution slit spectroscopy. In case of AKARI/IRC, however, slit spectroscopic observations often suffer from electrical (MUX bleeding and/or column pull down) and optical (ghost) artificial effect cause by bright objects in the same field of view (Figure 6). In order to avoid these defects, a long-slit installed at the field-mask/slit wheel is used. Longer slit helps to maximize the observational efficiency for spectroscopic mapping of nearby galaxies and blank field survey.

### 3.2 detector

We are planed to use Raytheon's 2K×2K Si:As IBC detector array for short channel (5-26$\mu$m) and DRS's 1K×1K Si:Sb BIB detector array for long channel (20-38$\mu$m). We summaries the expected performance of MIRACLE arrays estimated by the existing proto-types in Table 2.

We will use 2K×2K Si:As array based on existing 1024x1024 version of SB-375 array which is already developed and evaluated for JWST/MIRI detector.[13] The 2K×2K Si:As array is, however, in R&D phase. If development of 2K×2K Si:As arrays is not ready in time, we will use existing 1K×1K Si:As arrays. In this case, Nyquist sampling of the PSF is only achieved over 10$\mu$m in the short channel.



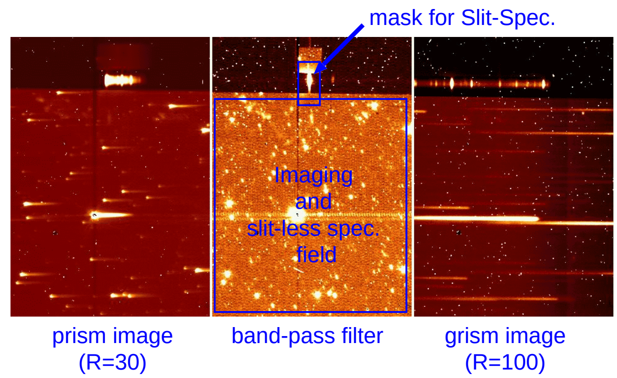




Figure 5. (left) Schematic of field mask/slit wheel.
Figure 6. (right) Example of slit-less and slit spectroscopy by AKARI/IRC.
Table 2. Expected performance of MIRACLE arrays

| Supplier | Raytheon | DRS |
|---|---|---|
| Format | 2048x2048 | 1024x1024 |
| Detector | Si:As IBC | Si:Sb BIB |
| wavelength | 1-26$\mu$m | 1-38$\mu$m |
| Q.E. | 0.5 | 0.5 |
| Readnoise[*1] | 20 e | 100 e |
| Dark current | 0.1 e/s | 2 e/s [*2] |
| Pixel size | 30 $\mu$m | 18 $\mu$m |
| Operating temperature | 6 K | 3 K |

1: Noise in CDS readout. The noise will be reduced up to 1/4 in Fowler-16 sampling.
2: Including emission from ROIC (Read-Out Integrated Circuit) near the side edge. 0.2 e/s excluding the side edges.

We will use 1K$\times$1K Si:Sb arrays based on existing detector for Spitzer (128x128 Si:Sb for IRS)[14] and ROIC for WISE (1024x1024 Si:As).[15] No larger than 1K$\times$1K format is required for long channel, because 1K$\times$1K format detector already satisfy Nyquist sampling at 10$\mu$m even for the goal of FOV (5'$\times$5').

We are also studying 128$\times$128 Si BIB detector which is sensitive up to wavelength of 50$\mu$m with DRS in order to cover 44$\mu$m ice feature and rest-frame 8um PAH emission at the redshift. We will use highly doped Si BIB wafer in order to extend cutoff wavelength up to 50$\mu$m[16] and will use existing 128x128 ROIC for Spitzer array.

## 3.3 optical element

### 3.3.1 mirror

Current optical system requires curved surface with 4th order polynomial function. In order to fabricate such a complicated mirror, we will use "5-axis nano machine" by a Japanese company (FANAC LTD.). The specification of that machine shows surface roughness is less than 10nm (RMS), and surface accuracy is better than 0.2$\mu$m over 200m length with work area of 280$\times$150$\times$40mm, which is good enough for all mirror surface required for MIRACLE optical system.

Fabrication of mirror by machining has merit so that we can fabricate optical and mechanical interface points at the same time with same precision. This simplifies the optical alignment procedure so much.

In order to simplify optical test, we will use same material (Aluminum alloy) both for mirror and supporting structure, so that room temperature optical alignment is also effective for cryogenic temperature.

#### 3.3.2 filter

Filters which cover wavelength region up-to 28um has been well developed by industry for JWST/MIRI mission.[17] Filter technology covering wavelength region from 30 to 50$\mu$m is not mature and need development. We have already confirmed by experiment that Silicon has a good optical transparency at these wavelength and can be used for substrate material. We are developing multi-layer interference filters with several technique.

We are currently assuming the size of filter as 30mm in diameter, so that we can use filters with diameter of 30mm or 1.25 inch, which is easy in fabrication and handling. If we can use 1.5 inch filter, and with expense of distortion, we can increase the size of FOV from the current 5'$\times$5' to 6'$\times$6'.

#### 3.3.3 disperser

**grating** We will use the same technique to fabricate grating as we use for mirror fabrication. The specification is good enough for our gratings.

**prism** Prism is required for multi-slit spectroscopy. Grating is not adequate for multi-slit spectroscopy because higher or lower order light will contaminate the light from the other slit.

In the wavelength of 5-10$\mu$m, there is a example of prism (JWST/MIRI). Study for longer wavelength is underway. Using CsI or KRS-5 is a solution, but these materials are fragile to thermal cycle and humidity, and special care must be taken for space application like SPICA.

### 3.4 wheel design

MIRACLE uses three types of wheels, filter wheel (FW), slit wheel (SW), and grating/beam switching wheel(GW).

All three types of wheels are designed based on heritage of previous JAXA's space infrared camera instruments, AKARI/IRC and AKATSUKI/IR camera. Current design parameter is summarized in table 3.

We, currently, assume 40mm diameter of filter, which is over sized compared to required size (31.7mm) from current optical design with FOV 5'$\times$5'. We have choice to increase FOV up to 6'$\times$6' or increase number of filter from 18 up to 22. We summarize the relationship between FOV and number of filters in the filter wheel in table 4.

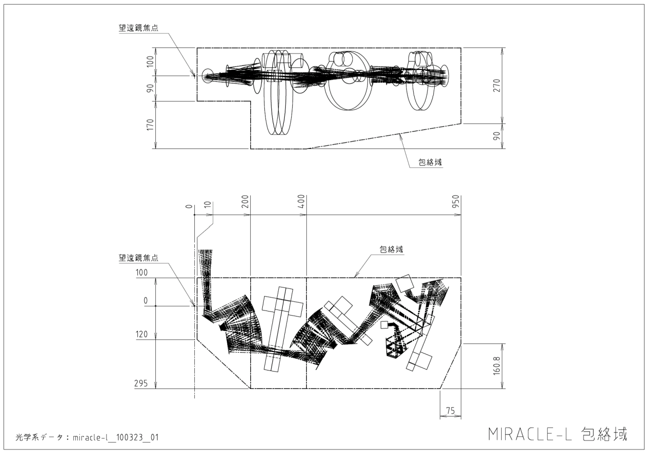
Table 3. Specification of MIRACLE wheels

| | diameter | thickness | diameter of element | number of position |
|---|---|---|---|---|
| FW | 300mm | 25$\times$2 mm | 40mm | 10 x 2 |
| SW | 200mm | 25mm | 40mm | 5 |
| GW | 200mm | 25mm | 40mm | 5 |

Table 4. Relation between number of filter and FOV

| pupil diameter | filter diameter | number of position per wheel | total number of filters | FOV |
|---|---|---|---|---|
| 30mm | 40 mm | 10 | 18 | 6$\times$ 6 |
| 25mm | 31.7mm | 12 | 22 | 5$\times$ 5 |
| 20mm | 25.4mm | 14 | 26 | 4$\times$ 4 |

note FOV is also sensitive to distortion.



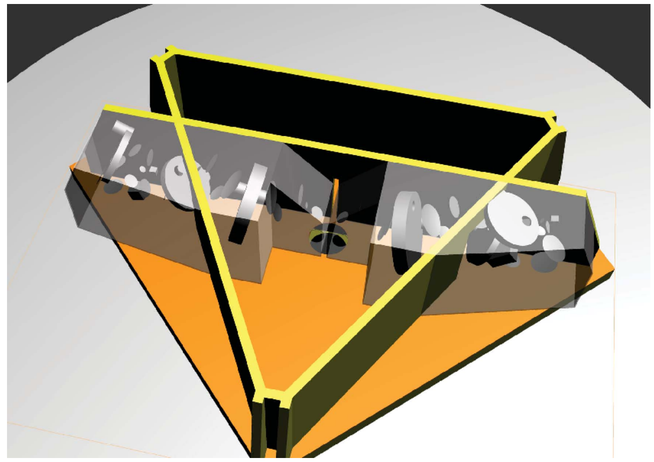



Figure 7. (left) Result of raytrace and Physical configuration of each optical and mechanical elements in MIRACLE-L. Both length and height are within system requirement size (1000mm and 400mm).
Figure 8. (right) MIRACLE on the IOB. MIRACLE optical elements are supported by an alignment panel. The alignment panels are mechanically connected to a triangle shape wall, the support rim of the IOB (Instrument Optical Bench). The alignment panels of MIRACLE-S and -L are connected near the telescope focus in order to increase the characteristic frequency of the IOB above the launch environmental requirement . Instrument rather than MIRACLE and the top panel of the IOB are not shown because of visibility. Right hand is MIRACLE-S and left is MIRACLE-L, and MIRHES and MIRMES is equipped on the other side of the alignment panel, respectively.

### 3.5 Structural design

Figure 7 shows the physical configurations of MIRACLEs. All MIRACLE elements, including optical and mechanical components, and the array detectors are placed on each alignment panel which is vertically placed onto the IOB (Instrument Optical Bench). The alignment panel also support the elements of MIRMES and MIRHES on the other side. Figure 8 shows MIRACLEs placed on the IOB. The alignment panels of MIRACLE-S and MIRACLE-L are mechanically connected each other near telescope focal plane in order to increase the stiffness of IOB. The panel is also mechanically connected the triangle rim of the IOB. The total mass of MIRACLE including MIRMES, MIRHES is 54.3kg without margin (Table 5).

Table 5. Mass of MIRACLE

| | MIRACLE-S | MIRACLE-L | MIRHES | MIRMES |
|---|---|---|---|---|
| optics | 2.8 kg | 2.8 kg | (4.4) kg | 4.4 kg |
| wheel filter | 5.0 kg | 5.0 kg | 0 kg | 0 kg |
| wheel slit | 1.8 kg | 1.8 kg | 0 kg | 0 kg |
| wheel grating | 1.8 kg | 1.8 kg | 0 kg | 0 kg |
| alignment panel | 16.7 kg | | | |
| cover | 6.0 kg | | | |
| total | 54.3 kg | | | |

### 3.6 thermal design

We will put the array detectors at 4 and 1.7K stage. We will also put the buffer amplifiers at 20 K stage, and put the warm electronics at 300K stage. Each stage are electronically connected by wiring's (66 wires per array).

The dominant power dissipation in cryogenic part of MIRACLE is that from the array detector and the buffer amplifiers. These power dissipation is only activated when the array detector is operated, and can be shut down by power off of the detector. We also calculate head conduction via the wiring's between the stage, which is parasitic and can't be stopped.

We summarize the heat load to each stage in tables 6, 7, 8. The heat load is within the system requirement.

Table 6. Heat load at 1.7K stage

| | unit | Parasitic | Active | Total |
|---|---|---|---|---|
| 1.7K stage | | | | |
| temperature | K | 3 | | |
| temperature stability | mK | 100 | | |
| Average lift | mW | 0.30 | 2 | 2.30 |

Table 7. Heat load at 4.5K stage

| | unit | Parasitic | Active | Total |
|---|---|---|---|---|
| 4.5K stage | | | | |
| temperature | K | 6 | | |
| temperature stability | mK | 100 | | |
| Average lift | mW | 0.30 | 3.4 | 3.70 |

Table 8. Heat load at 20K stage

| | unit | Parasitic | Active | Total |
|---|---|---|---|---|
| 20K stage | | | | |
| temperature | K | 20 | | |
| temperature stability | K | 1 | | |
| Average lift | mW | 6.6 | 11.2 | 17.8 |

#### 3.6.1 wheel operation

Heat generation by wheel operation has not estimated well, yet. According to AKARI/IRC experience, this is not significant compared with array power dissipation.

#### 3.6.2 annealing of array

Si:As and Si:Sb BIB detector are known to be subjected to memory effect after cosmic-ray hitting, bright light source, etc. In order to refresh, annealing operation, in which warm up the detectors up to 20K for a few minutes, is known to be effective. We are planning to anneal the detector frequently. Detailed of array operation is under study.

### 3.7 expected performance

Sensitivity for point sources is calculated using the following assumptions.

- Read noise of 20 electron.
- Dark current of 1 electron/pixel.
- Pixel scale of 0.36 arcsec/pixel.
- Optical efficiency of 0.35 including telescope.
- Detector efficiency of 0.50.
- Frame integration time of 617.3 seconds which is limited by cosmic ray event rate at the L2 environment.
- a background (Zodiacal light) of 261K black body spectrum normalized to 18MJy/str at 25um
- Total integration time of 3600 seconds.
- Aperture photometry with size of the first diffraction null ring.

Figure 9 shows the sensitivity for point sources compared with that of JWST/MIRI.[18] MIRACLE is more sensitive compared with JWST/MIRI over wavelengths of 20 $\mu$m because of SPICA's cooled aperture telescope. Figure 10 shows the mapping speed of MIRACLE compared with that of JWST/MIRI.[18] The wider FOV of MIRACLE provides a faster mapping speed in all JWST/MIRI bands. Figure 11 shows the line sensitivity of MIRACLE in case of narrow-band imaging and slit spectroscopy.

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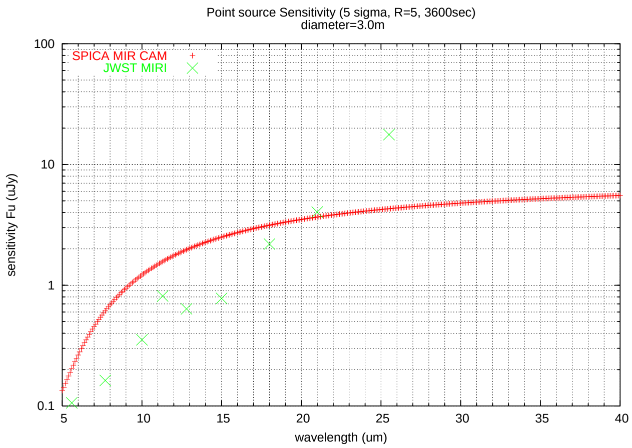


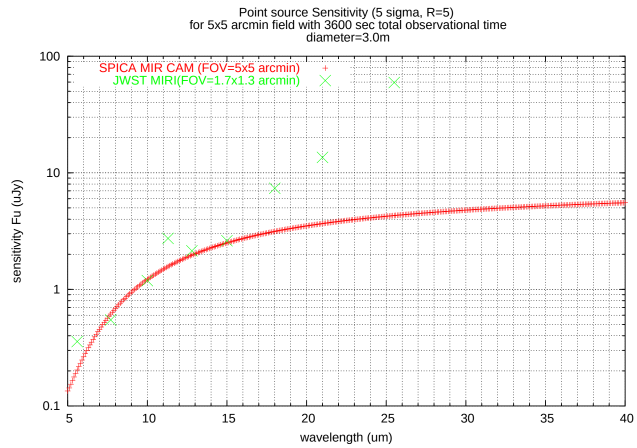
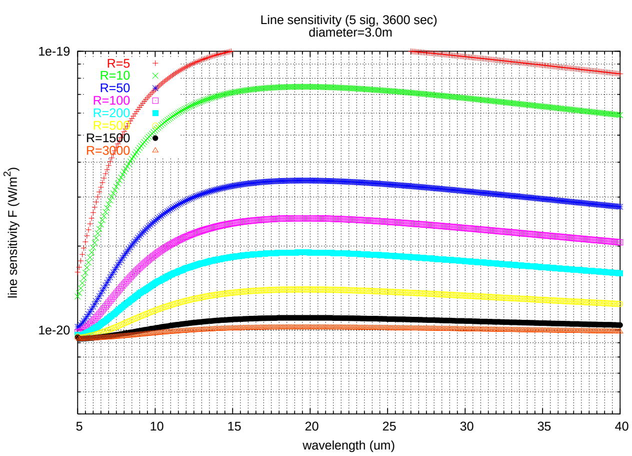




Figure 9. (left) Sensitivity of MIRACLE. Red plus signs show point source sensitivity (5 $\sigma$) of MIRACLE with one hour observing time in the imaging observations (spectral resolution R=5) as a function of wavelengths. Green crosses show point source sensitivity of JWST/MIRI with the same integration. MIRACLE has superior sensitivity compared with JWST/MIRI over wavelengths of 20$\mu$m because of SPICA's cooled aperture telescope.
Figure 10. (right) Mapping speed of MIRACLE. Red plus signs show point source sensitivity (5 $\sigma$) of MIRACLE with one hour observing time in the imaging observations (spectral resolution R=5) as a function of wavelengths. Green crosses show point source sensitivity of JWST/MIRI survey covering $5' \times 5'$ field with the same observing time. MIRACLE has superior mapping speed compared with JWST/MIRI over the entire MIRI wavelength coverage.



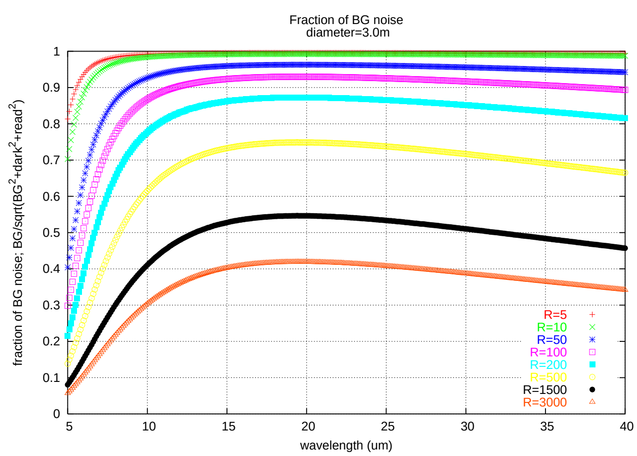




Figure 11. (left) Line Sensitivity of MIRACLE spectroscopy. Calculation is based on narrow band imaging case. In case of slit-spectroscopy, the sensitivity is slightly worse. Results of medium resolution spectroscopy are just for reference.
Figure 12. (right) Contribution of natural background photon noise to total noise as a function of wavelength is shown. Natural background (Zodiacal light) photon noise limited observations are achieved in wavelength over 10$\mu$m for low resolution spectroscopy. Read noise is dominant at wavelength close to 5$\mu$m.