Mid-Infrared Spectrometer and Camera (MISC) for the Origins Space Telescope (OST)

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ABSTRACT

The Mid-infrared Imager, Spectrometer, Coronagraph (MISC) is one of the instruments studied both for the Origins Space Telescope (OST) Mission Concept 1 and 2. The highest ever spectro-photometric stability achieved by MISC transit spectrometer module (MISC TRA) enables to detect bio-signatures (e.g., ozone, water, and methane) in habitable worlds in both primary and secondary transits of exoplanets and makes the OST a powerful tool to bring a revolutionary progress in exoplanet sciences. Combined with the spectroscopic capability in the FIR provided by other OST instruments, the MISC widens the wavelength coverage of OST down to 4μm, which makes the OST a powerful tool to diagnose the physical and chemical condition of the ISM using dust features, molecules lines and atomic and ionic lines. The MISC also provides the OST with a focal plane guiding function for the other OST science instruments as well as its own use.

Keywords: Origins Space Telescope (OST), mid-infrared

1. INTRODUCTION

The Origins Space Telescope (OST; Meixner et al. 2018; Leisawitz et al. 2018) is one of the four mission concept studies for the 2020 Astronomy and Astrophysics Decadal survey. The OST has two mission concepts; Mission concept 1 is composed of a cryogenically cooled 9.1 m off-axis telescope and five instruments covering wavelengths from 5 to 660μm, while Mission Concept 2 of a cryogenically cooled 5.9 m on-axis telescope with JWST-sized collecting area and four instruments covering wavelengths from 5 to 660μm. The Mid-infrared Imager, Spectrometer, Coronagraph (MISC) is one of the instruments studied both for the Origins Space Telescope (OST) Mission Concept 1 and 2 (cf., OSS, Bradford et al. 2018; FIP, Staguhn et al. 2018; HERO, Wiedner al. 2018). The MISC instrument will observe at the shortest wavelengths of any of these OST instruments, covering from 5 to 38 μm for the Mission Concept 1 and from 4 to 28 μm for the Mission Concept 2. In this proceedings paper, the results of the studies of MISC for Mission Concept 1 are described in Section 2 and that for Mission Concept 2 are described in Section 3.

2. MISC FOR THE OST MISSION CONCEPT 1

The MISC instrument for the OST Mission Concept 1 consists of three modules; the MISC Imager and Spectrometer module (MISC I&S), the MISC Coronagraph module (MISC COR; Fujishiro et al. 2018) and the MISC Transit spectrometer module (MISC TRA; Matsuo et al. 2018). The MISC TRA provides OST with the capability to search for biosignatures in the atmospheres of exoplanets via ultra-stable spectro-photometric observations of primary and secondary transits. The MISC COR will directly image and characterize Saturn and Jupiter analogs, as well as ice giant planets at ice-melting temperatures at ~300K, in extrasolar planetary systems. The imaging capability of the MISC I&S will be used to study episodic accretion in circumstellar debris disks, and to support the biosignature observations. The spectroscopic capability with resolving power ranging from ~10^2 to 10^4 of the MISC I&S will support prioritized observing campaigns in all of OST's science themes (Margaret et al. 2018). The MISC I&S also serves as the focal plane pointing and guiding for the observatory.

2.1 Imager and Spectrometer Module of the MISC for the OST Mission Concept 1

The MISC I&S is designed to offer (1) wide field imaging and low-resolution spectroscopic capability with filters and grisms covering from 6 to 38 μm (hereafter WFI-S and WFI-L), (2) medium-resolution (R~1,000) Integral Field Unit (IFU) spectroscopic capability covering from 5 to 38 microns (hereafter MRS-S, MRS-M and MRS-L) and (3) high-resolution (R~25,000) slit spectroscopic capability covering from 12 to 18 μm and from 25 to 36 μm (hereafter HRS-S and HRS-L). The diffraction-limited image quality over the 3 arcmin by 3 arcmin field-of-view (FOV) is achieved at any wavelength from 6 to 38 μm with the help of a deformable mirror and a tip tilt mirror in the fore optics of the MISC I&S. The slit mirror changer for MISC I&S has four ø4-inch positions for slit mirrors. It is used to switch the observing modes of MISC I&S among WFI-S/L, MRS-S/M/L, HRS-S/L and a blind mask for the dark measurement. The filter wheel assemblies used in each of the MISC I&S WFI-S and WFI-L has triple wheels. Each wheel has six ø3-inch positions for band-pass filters and/or grisms for low-resolution spectroscopy. The 3D solid model of MISC I&S is shown in Figure 1.

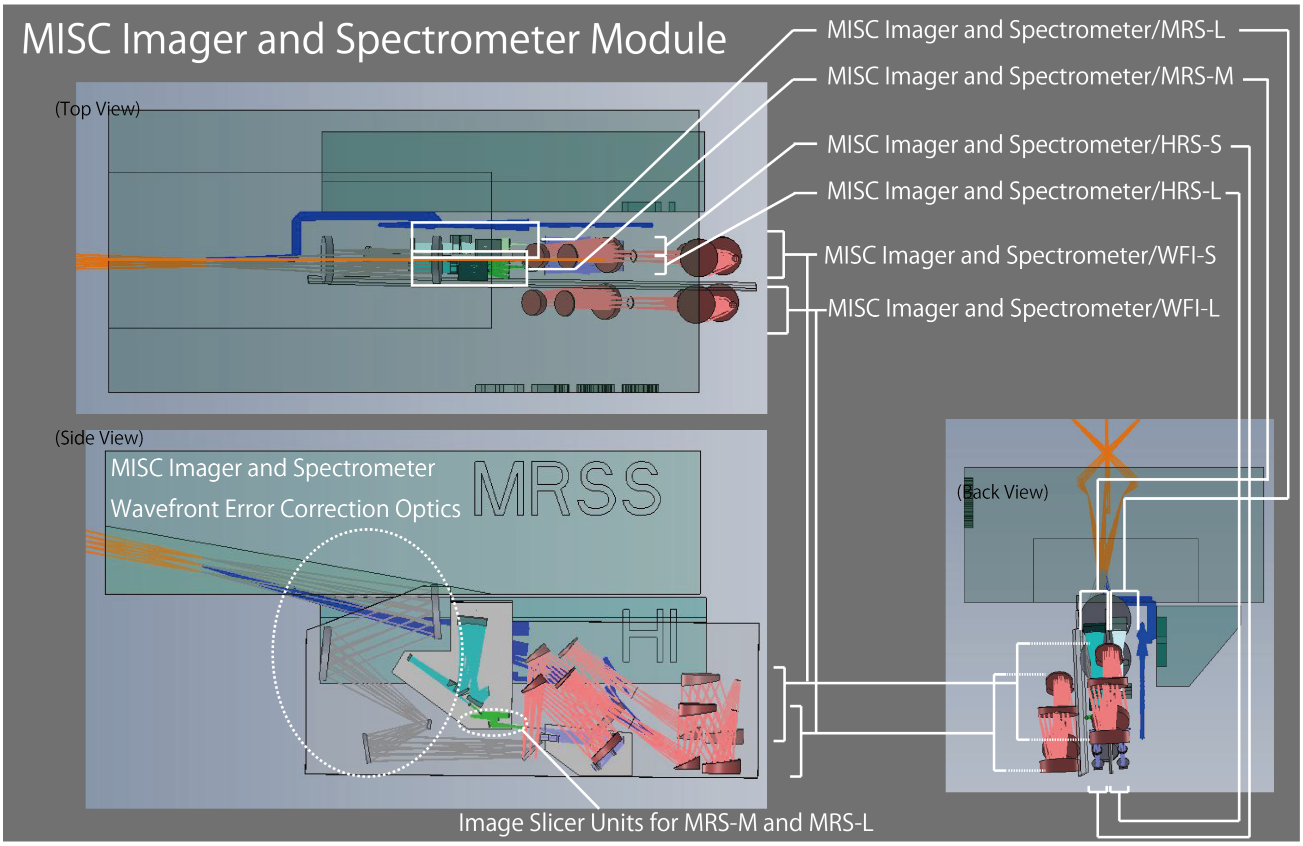

Figure 1. The optical and structural model of the MISC Imager and Spectrometer Module

2.2 Coronagraph Module of the MISC for the OST Mission Concept 1

The PIAA coronagraph has been chosen as the baseline concept for the MISC COR as a result of a trade-off study on coronagraphy methods among a PIAA coronagraph (Guyon et al. 2014), a 4QPM coronagraph (e.g., Lajoie et al. 2014), a 8OPM coronagraph (Murakami et al. 2016), a Vortex coronagraph (Mawat et al. 2011) and a binary pupil mask (BPM) coronagraph (Enya et al. 2010). Although the PIAA coronagraph method requires its own independent module within the MISC instrument, it achieves the highest contrast at a small inner working angles with the highest throughput among the various types of coronagraphy methods. The 4QPM and 8OPM methods have the advantage that they do not necessarily require an independent module and that they can add a coronagraphic capability to MISC I&S module with a relatively minor impact on its optical and mechanical design. However, as is the case for Vortex coronagraph, they require very stringent pointing accuracy and pointing stability requirements (i.e., a pointing jitter of $0.04\times\lambda/D$ generates a 10^{-7}-level leak at $2\times\lambda/D$ and, therefore, a pointing accuracy and pointing stability better than 4 mas is requested) and, above all, the fabrication of the phase masks that achieve a homogeneous capability in a wide mid-infrared wavelength range requires further technical development. The MISC COR includes a DM and a TTM in its fore-optics to correct for the telescope's wave front errors. The DM assembly with 32×32 actuators is used to exclude the speckles in regions up to $16\times\lambda/D$ from the PSF peak (Takahashi et al. 2017). The filter wheel assemblies used in each of the MISC COR-S and COR-L has double wheels. Each wheel has six ø1-inch positions for band-pass filters and/or grisms for low-resolution spectroscopy. The slit wheel used for each of the MISC COR-S and COR-L has a single wheel with six ø0.5-inch positions for slit masks for low-resolution spectroscopy. The 3D solid model of MISC COR is shown in Figure 2.

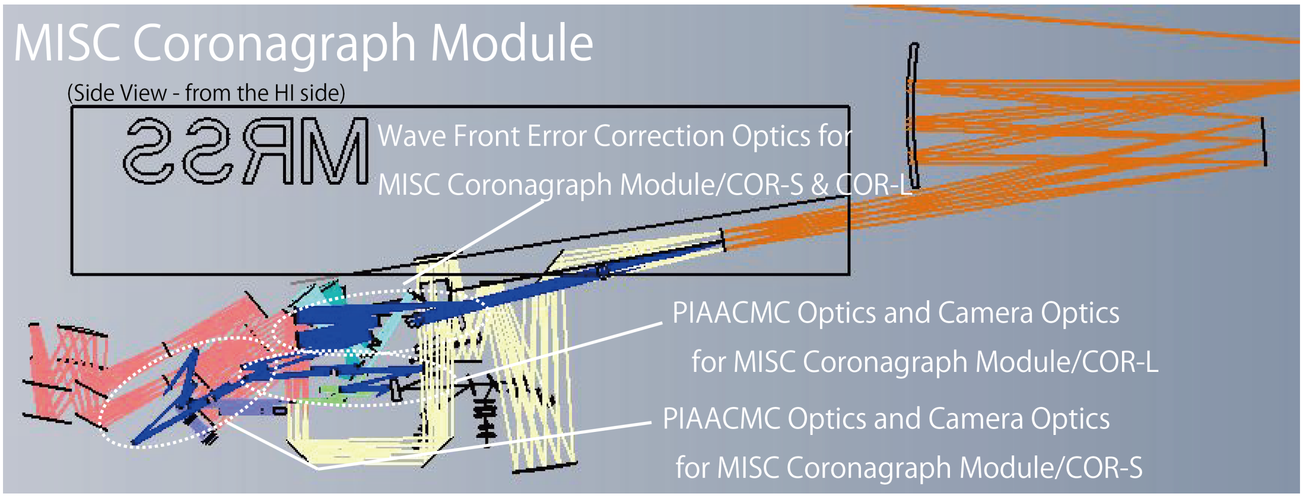

Figure 2. The optical and structural model of the MISC Coronagraph Module

2.3 Transit Spectrometer Module of the MISC for the OST Mission Concept 1

A densified pupil spectroscopy is a newly studied method for transit spectroscopy (Matsuo et al. 2016). This method will greatly improve spectro-photometric accuracy performance against optical disturbances. The science image is not disturbed by minor telescope pointing jitter or deformation of primary mirror. A large number of science pixels minimizes intra- and inter-pixel sensitivity variations. A number of reference pixels are also employed for calibration of potential detector gain fluctuations with a cold photon shield mask. An optimal calibration technique using the reference pixels will be developed using a test bed of a prototype system during development (Matsuo et al. 2018). The 3D solid model of MISC COR is shown in Figure 3.

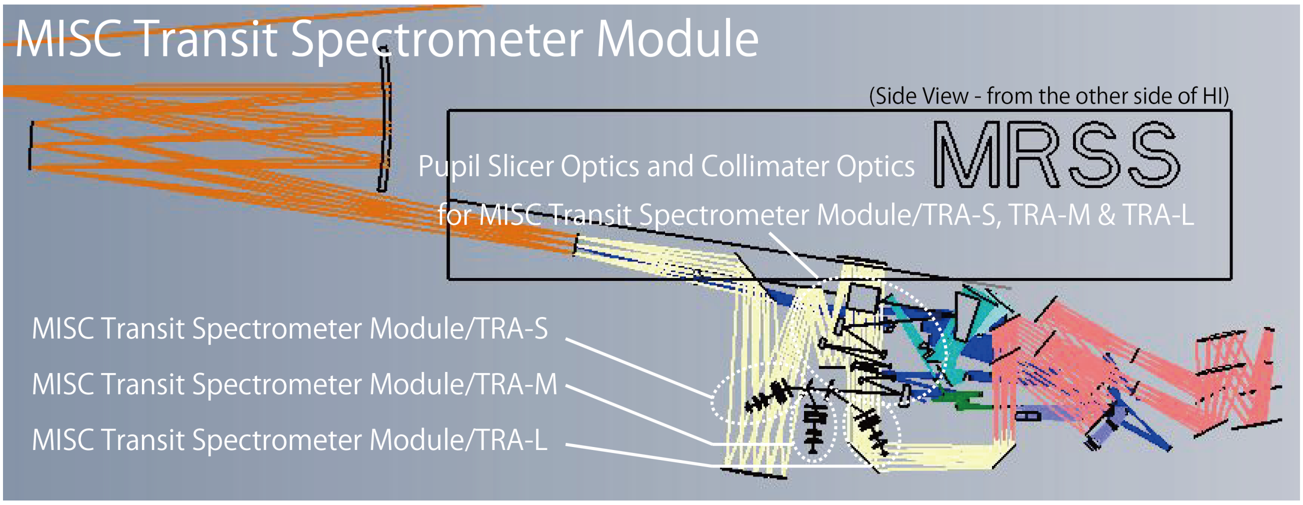

Figure 3. The optical and structural model of the MISC Transit Spectrometer Module

2.4 A Fact Sheet of the MISC for the OST Mission Concept 1

The basic measurement capabilities of MISC for the OST Mission Concept 1 are summarized in Table 1.

Table 1. The Fact Sheet of MISC for the OST Mission Concept 1

Module	MISC Imager & Spectrometer			MISC Transit Spectrometer	MISC Coronagraph
	Imager/Low-Res Spec.	Medium-Res Spec.	High-Res Spec.	(Densified Pupil Spec.)	(PIAA)
	WFI-S/-L	MRS-S/-M/-L*	HRS-S/-L	TRA-S/-M/-L	COR-S/-L
Bandpass (μm)	6--38	10--36 (goal: 5--36)	12--18, 25--38	5--26	6--38
Spectral Resolution	5-10 [Imager] 300 [Low-Res Spec.]	1000-1500	20,000-30,000	>100 (TRA-S, TRA-M) 300 (TRA-L)	300
Full FOV	3 arcmin x 3 arcmin [Imager]	3 arcsec x 5 arcsec [with IFU]		3 arcsec x 3 arcsec	5.5 arcsec x 5.5 arcsec
Slit for Spectroscopy	Length; 3 arcmin Width; 0.26 arcsec (WFI-SG1) 0.40 arcsec (WFI-SG2) 0.65 arcsec (WFI-LG1) 1.00 arcsec (WFI-LG2) [low-resolution Spec.]	Length; 3 arcsec (MRS-S/MRS-M/MRS-L) Width; 0.33 arcsec (MRS-S) 0.55 arcsec (MRS-M) 1.0 arcsec (MRS-L) # of Slices; 11 (MRS-S) 9 (MRS-M), 5 (MRS-L)	Length; 1.0 arcsec (HRS-S) 2.0 arcsec (HRS-L) Width; 0.5 arcsec (HRS-S) 1.0 arcsec (HRS-L)		Length; 1 arcmin Width; 0.26 arcsec (COR-SG1) 0.40 arcsec (COR-SG2) 0.65 arcsec (COR-LG1) 1.00 arcsec (COR-LG2)
Detectors	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:As (30um/pix) [M] 1kx1k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 1kx1k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:As (30μm/pix) [M] 2kx2k Si:As (30um/pix) [L]	2kx2k Si:As (30μm/pix) [S] 1kx1k Si:Sb (18μm/pix) [L]
pixel scale	0.088 arcsec/pix	0.0615 arcsec/pix (MRS-S) 0.10 arcsec/pix (MRS-M) 0.15 arcsec/pix (MRS-L)	0.17 arcsec/pix [S] 0.34 arcsec/pix [L]	0.1 arcsec/pix	0.05 arcsec/pix (COR-S) 0.10 arcsec/pix (COR-L)
Specification (Sensitivity/ Stability/ Contrast)	**Sensitivity [Imager] ;** *1-hour 5σ Continuum Sens . for a Point Source* 0.031μJy@5μm, 0.18μJy@10μm, 0.29μJy@15μm, 0.41μJy@20μm, 0.61μJy@25μm, 0.70μJy@30μm, 0.78μJy@35μm **Sensitivity [Low-Res Spec.];** *1-hour 5s Continuum Sens. for a Point Source* (R=300) 0.68μJy@5μm, 1.5μJy@10μm, 4.5μJy@15μm, 5.6μJy@20μm, 9.9μJy@25μm, 13.8μJy@30μm, 43μJy@35μm	**Sensitivity;** *1-hour 5s Continuum Sens. for a Point Source (R~1200)* 3.4μJy@7μm, 11μJy@15μm, 34μJy@24μm,114μJy@32μm *1-hour 5s Line Sens. for a Point Source* 1.1×10^{-21} W/m² @7μm, 2.3×10^{-21} W/m² @15μm, 3.4×10^{-21} W/m² @24μm, 1.1×10^{-20} W/m² @32μm	**Sensitivity;** *1-hour 5s Line Sens. for a Point Source* 1.2×10^{-21} W/m² @15μm, 3.6×10^{-21} W/m² @30μm	**Photometric stability;** 3-5 ppm on timescales of hours to days (excluding the fluctuation of detector gain)	**Average contrast;** 7×10^{-6} for 10% band 1×10^{-6} for 4% band in 0.88-3.6λ/D

3. MISC FOR THE OST MISSION CONCEPT 2

The MISC instrument for the OST Mission Concept 2 consists of two modules; the MISC Wide Field Imager module (MISC WFI) and the MISC Transit spectrometer module (MISC TRA; Matsuo et al. 2018). The MISC TRA provides OST with the capability to search for biosignatures in the atmospheres of exoplanets via ultra-stable spectro-photometric observations of primary and secondary transits. The imaging capability of the MISC WFI will be used for general science objectives. The spectroscopic capability with resolving power of a few hundreds of the MISC WFI will be used to measure the mid-infrared dust features and ionic lines at z up to ~1 in Rise of Metals and Balck Hole Feedback programs (Margaret et al. 2018). The MISC WFI also serves as the focal plane pointing and guiding for the observatory. No coronagraph module is studied in the MISC for the OST Mission Concept 2. Note that the Concept 2 instrument design parameters are subject to change before the end of our study.

3.1 Wide Field Imager of the MISC for the OST Mission Concept 2

The MISC WFI is designed to offer the wide-field imaging and low-resolution (R~300) spectroscopic capability with filters and grisms covering from 5 to 10 μm with WFI-S and from 9 to 28μm with WFI-L. Si:As detector is planned to be used for WFI-S and WFI-L. WFI-S and WFI-L share the same 3 arcmin × 3 arcmin field of view (FOV) by means of the beam splitter and the diffraction-limited image quality over the entire FOV is achieved at any wavelength from 6 to 28 μm with the help of a deformable mirror and a tip tilt mirror in the fore optics of the MISC WFI. The filter wheel assemblies used in each of the MISC WFI-S and WFI-L has triple wheels. Each wheel has six ø3-inch positions for band-pass filters and/or grisms for low-resolution spectroscopy. The slit mask changer used in MISC WFI-S has two ø4-inch slots (a slit mask and a hole) and that in MISC WFI-L has three ø4-inch slots (two slit masks and a hole). MISC WFI-S serves as the focal plane pointing and guiding for the observatory and has two redundant sets of 2k×2k Si:As detector arrays. The block diagram of the MISC WFI and the results of the optical design of the MISC WFI are shown in Figures 4 and 5, respectively.

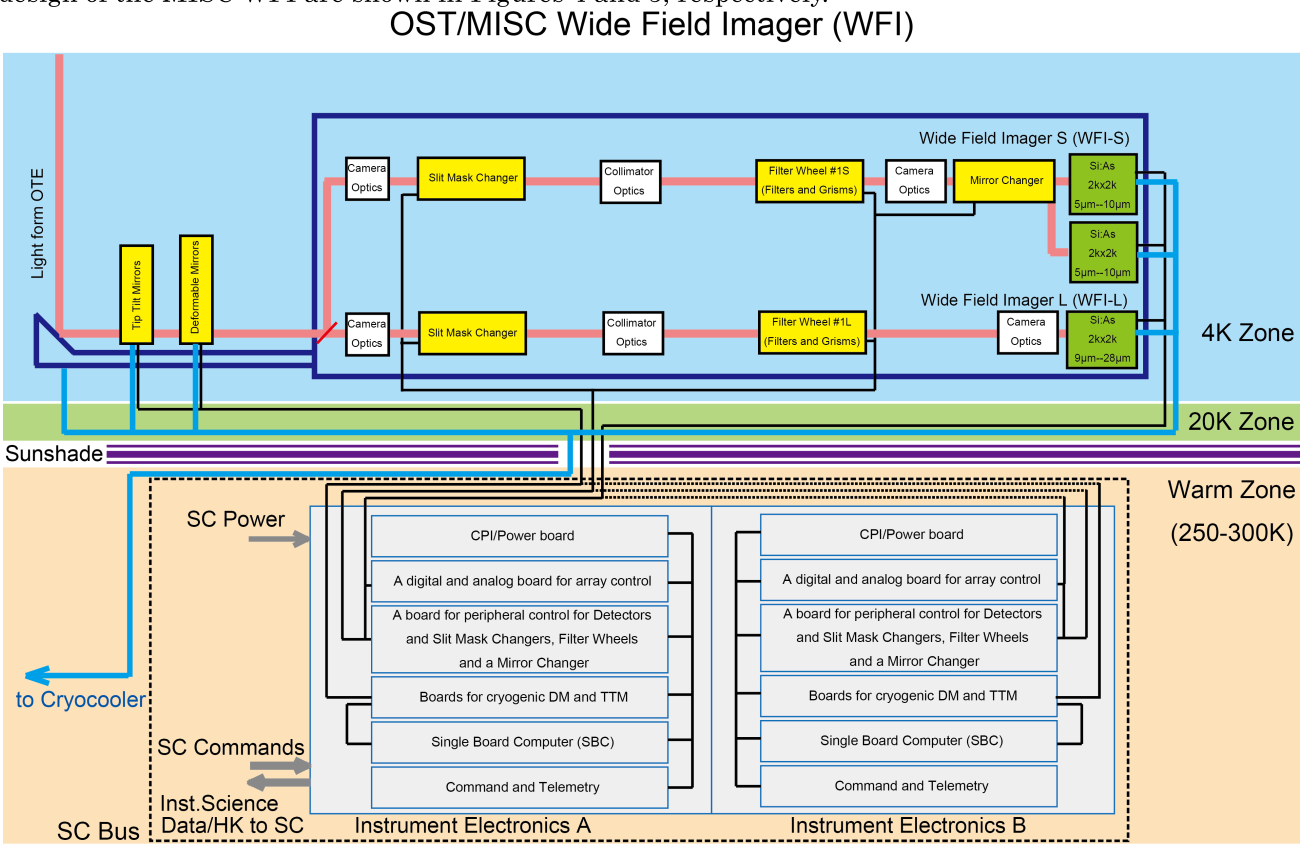

Figure 4. The block diagram of the Wide Field Imager module of the MISC for OST Mission Concept 2.

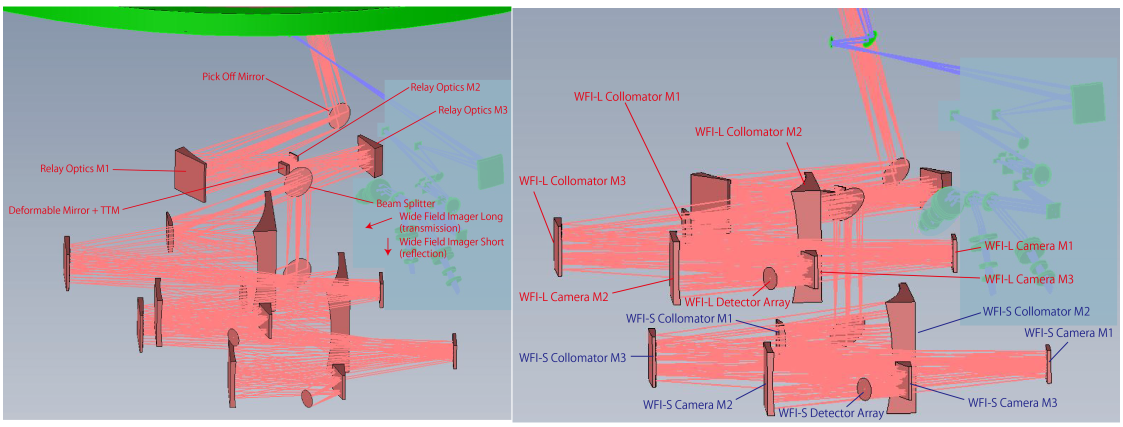

Figure 5. The optical model of the Wide Field Imager module of the MISC for OST Mission Concept 2.

3.2 Transit Spectrometer of the MISC for the OST Mission Concept 2

The MISC TRA for the OST Mission Concept 2 also employs the densified pupil spectroscopy method and the basic designs of pupil slicer optics, collimator optics and the camera lens units are almost the same as that for the OST Mission Concept 1. The block diagram of the MISC TRA and the results of the optical design of the MISC TRA are shown in Figures 6 and 7, respectively. Based on the latest design, TRA-S covers the wavelength from 4.0 to 7.0 μm and TRA-M covers from 6.8 to 13.0μm with the spectral resolution power of R~100. TRA-L covers the wavelength from 12.8 to 22μm with the spectral resolution power of R~300. So far, HdCdTe detector with a calibration source is one of the strong candidates for the detectors of TRA-S and TRA-M and TES or Si:As detector with a calibration source should be a candidate for the detector of TRA-L to attain <5 ppm stability on timescales of hours to days.

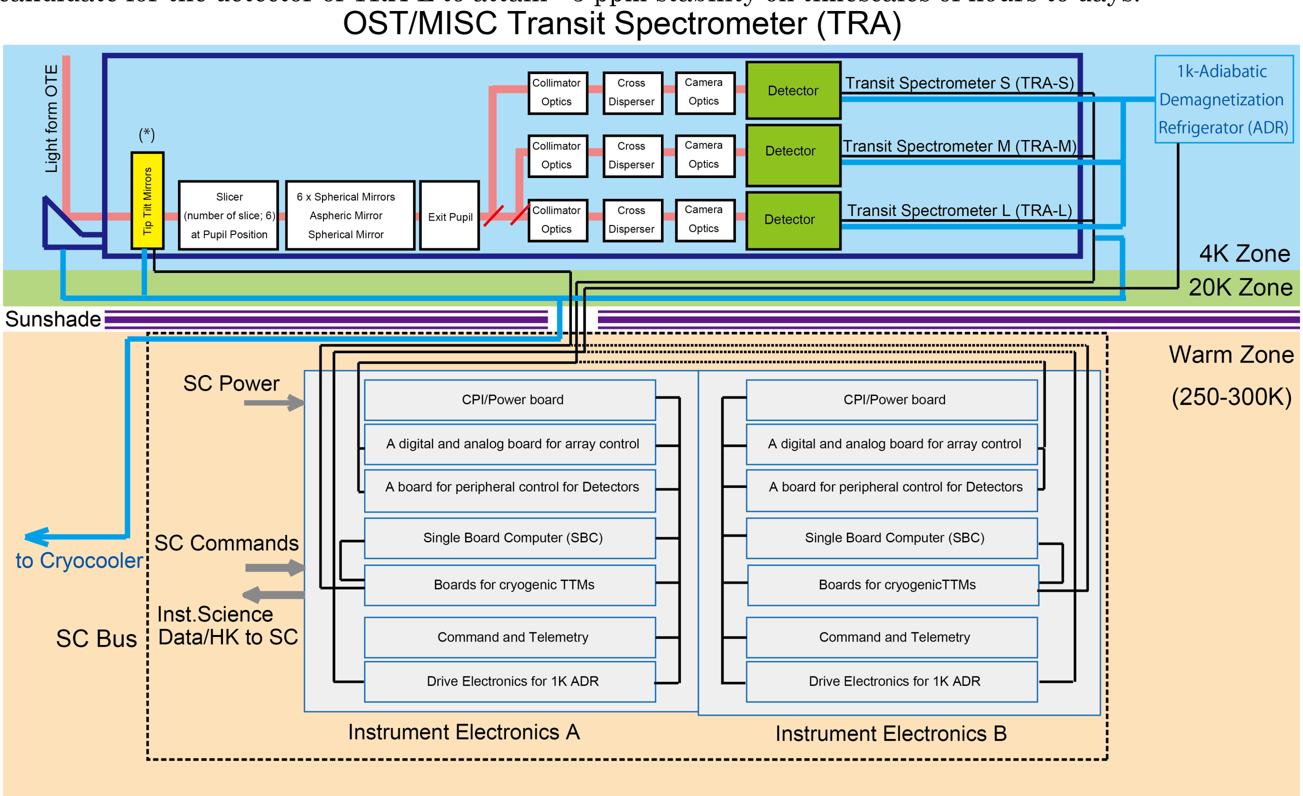

Figure 6. The block diagram of the Wide Field Imager module of the MISC for OST Mission Concept 2.

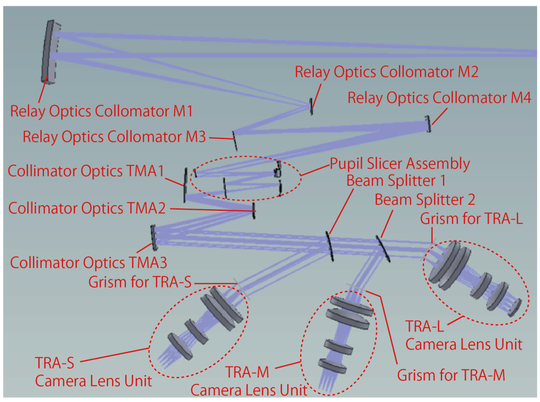

Figure 7. The optical model of the Transit Spectrometer module of the MISC for OST Mission Concept 2

3.3 Fact Sheet of the MISC for the OST Mission Concept 2

The basic measurement capabilities of MISC for the OST Mission Concept 2 are summarized in Table 2.

Table 2. The Fact Sheet of MISC for the OST Mission Concept 2

Module	MISC Wide Field Imager	MISC Transit Spectrometer
	Imaging / Low-Res Spectroscopy with Grisms	Densified Pupil Spectroscopy
	WFI-S1, S2/WFI-L	TRA-S/-M/-L
Operating Modes	[1] MIR Imaging [2] MIR Low-Resolution Spectroscopy (slit) [3] MIR Low-Resolution Spectroscopy (slitless) [4] MIR Scan Mapping	[5] MIR Super Stable Spectroscopy
Bandpass (μm)	6--28	4--22
Angular Resolution	0.21 arcsec @5 μm, 0.38 arcsec @9 μm, 0.68 arcsec @16 μm, 0.98 arcsec @23 μm, 1.18 arcsec @27.6 μm	Angular resolution is not important
Spectral Resolution	5-10 for MIR Imaging 300 for MIR Low-Resolution Spectroscopy	>100 (TRA-S, TRA-M) 300 (TRA-L)
Full FOV	3 arcmin x 3 arcmin [Imager]	10 arcsec x 10 arcsec
Slit for Spectroscopy	Length; 3 arcmin Width; 0.38 arcsec (WFI-SG1), 0.68 arcsec (WFI-LG1), 1.18 arcsec (WFI-LG2)	N/A
Detectors	three 2kx2k Si:As arrays - two for WFI-S - one for WFI-L	TRA-S (4.0-7.0μm); HgCdTe array with calibration source TRA-M (6.8-13.0μm); HgCdTe array with calibration source TRA-L (12.5-22.0μm); TES bolometer array with calibration source or Si:As IBC array with calibration source (TBD)
Pixel Scale	0.088 arcsec/pix	0.1 arcsec/pix
Scanning Speed	MIR Scan (width; 180 arcsec) Maximum 1.5 [arcsec/sec] -- 22.5 [arcsec/sec]	N/A
Specification (Sensitivity/ Stability)	**Sensitivity [Imager] ;** *1-hour 5σ Continuum Sensitivity for a Point Source* 0.06 μJy @5 μm, 0.25 μJy @9 μm, 0.64 μJy@16 μm, 0.96 μJy @23 μm, 1.93 μJy @25 μm **Sensitivity [Low-Res Spec.];** *1-hour 5s Line Sensitivity for a Point Source* (R=300) 5.0E-21 W/m2 @6μm, 4.5E-21 W/m2 @8μm, 5.3E-21 W/m2 @10μm, 4.3E-21 W/m2 @12μm, 5.2E-21 W/m2 @18μm, 5.4E-21 W/m2 @24μm, 1.1E-20 W/m2 @26μm, 5.4E-19 W/m2 @28μm	**Photometric stability;** 5 ppm with a goal of 1 ppm on timescales of hours to days

SUMMARY

The Mid-infrared Imager, Spectrometer, Coronagraph (MISC) is one of the instruments studied both for the Origins Space Telescope (OST) Mission Concept 1 and 2. The MISC for OST Mission Concept 1 consists of the MISC imager and spectrometer module (MISC I&S), the MISC coronagraph module (MISC COR) and the MISC transit spectrometer module (MISC TRA). The MISC I&S offers (1) a wide field (3 arcmin×3 arcmin) imaging and low-resolution spectroscopic capability with filters and grisms for 6-38 μm, (2) a medium-resolution (R~1,000) Integral Field Unit (IFU) spectroscopic capability for 5-38 μm and (3) a high-resolution (R~25,000) slit spectroscopic capability for 12-18 μm and 25-36 μm. The MISC COR module employs PIAACMC coronagraphy method and covers 6-38 μm achieving 10^{-7} contrast at 0.5 arcsec from the central star. The MISC TRA module employs a densified pupil spectroscopic design to achieve 3-5 ppm of spectro-photometric stability and covers 5-26 μm with R=100-300. The MISC for OST Mission Concept 2 consists of the MISC wide field imager module (MISC WFI) and the MISC transit Spectrometer module (MISC TRA). The MISC WFI offers a wide field (3 arcmin ×3 arcmin) imaging and low-resolution spectroscopic capabilities with filters and grisms for 6-28μm. The MISC TRA module in the OST Mission Concept 2 also employs the densified pupil spectroscopic design to achieve <5 ppm of spectro-photometric stability and covers 4-22 μm with R=100-300. The highest ever spectro-photometric stability achieved by MISC TRA enables to detect bio-signatures (e.g., ozone, water, and methane) in habitable worlds in both primary and secondary transits of exoplanets and makes the OST a powerful tool to bring an revolutionary progress in exoplanet sciences. Combined with the spectroscopic capability in the FIR provided by other OST instruments, the MISC widens the wavelength coverage of OST down to 5μm, which makes the OST a powerful tool to diagnose the physical and chemical condition of the ISM using dust features, molecules lines and atomic and ionic lines. The MISC also provides the OST with a focal plane guiding function for the other OST science instruments as well as its own use.

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