

ASTRO-F SURVEY AS INPUT CATALOGUES FOR FIRST

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ABSTRACT

ASTRO-F is the second Japanese space mission for infrared astronomy and is scheduled to be launched into a sun-synchronous polar orbit by the Japanese M-V rocket in February 2004. ASTRO-F has a cooled 67 cm telescope with two focal plane instruments: one is the Far-Infrared Surveyor (FIS) and the other is the Infrared Camera (IRC).

The main purpose of FIS is to perform the all-sky survey with 4 photometric bands in the wavelength range of 50 - 200 μm . The advantages of the FIS survey over the IRAS survey are (1) higher spatial resolution (30'' at 50-110 μm and 50'' at 110-200 μm) and (2) better sensitivity by one to two orders of magnitude. The FIS survey will provide the next generation far-infrared survey catalogs, which will be ideal inputs for observations by FIRST.

The other instrument, IRC, will make deep imaging and low-resolution spectroscopic observations in the spectral range of 1.8 - 26 μm . The IRC will make large-area surveys with its wide field of view ($10' \times 10'$), and will be complementary with the FIRST observations at longer wavelengths.

Key words: Galaxies: formation - Stars: formation - Planets: formation - Missions: ASTRO-F

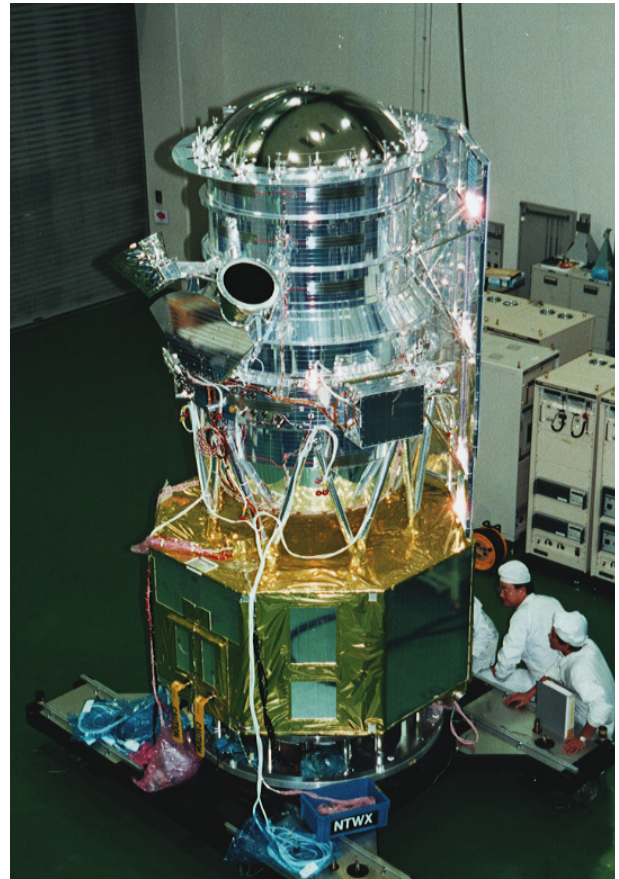


Figure 1. Thermal test model of the ASTRO-F

1. ASTRO-F MISSION

ASTRO-F (Murakami 1998) is the second Japanese space mission for infrared astronomy, following the first successful mission IRTS (Infrared Telescope in Space, Murakami et al. 1996).

The ASTRO-F is designed as the second-generation survey mission. The previous all sky survey by the Infrared Astronomy Satellite (IRAS) (Neugebauer et al. 1984) was a great success. Many new phenomena, such as infrared galaxies and Vega-like stars, were found in the survey, and the IRAS survey catalogues have been essential tools in many fields of astronomy.

However, the spatial resolution (a few arcminutes) and the sensitivity (about 1 Jy) of the IRAS survey are not good enough, compared to those of the surveys at other wavelengths. Hence we plan the next generation infrared

sky survey with ASTRO-F by taking the advantage of the recent development of detector technology.

ASTRO-F has a 67 cm telescope cooled to 5.8 K, and covers wide wavelength range from K-band to 200 μm with two focal plane instruments: Far-Infrared Surveyor (FIS) and Infrared Camera (IRC). FIS will perform the all-sky survey with 4 photometric bands at the wavelength range of 50 - 200 μm using two-dimensional Ge:Ga detector arrays. The sensitivity and the spatial resolution of the ASTRO-F/FIS all sky survey are much better than those of the IRAS survey. IRC is for the near- and mid-infrared ranges, and large-format arrays are employed for deep sky surveys in selected sky regions.

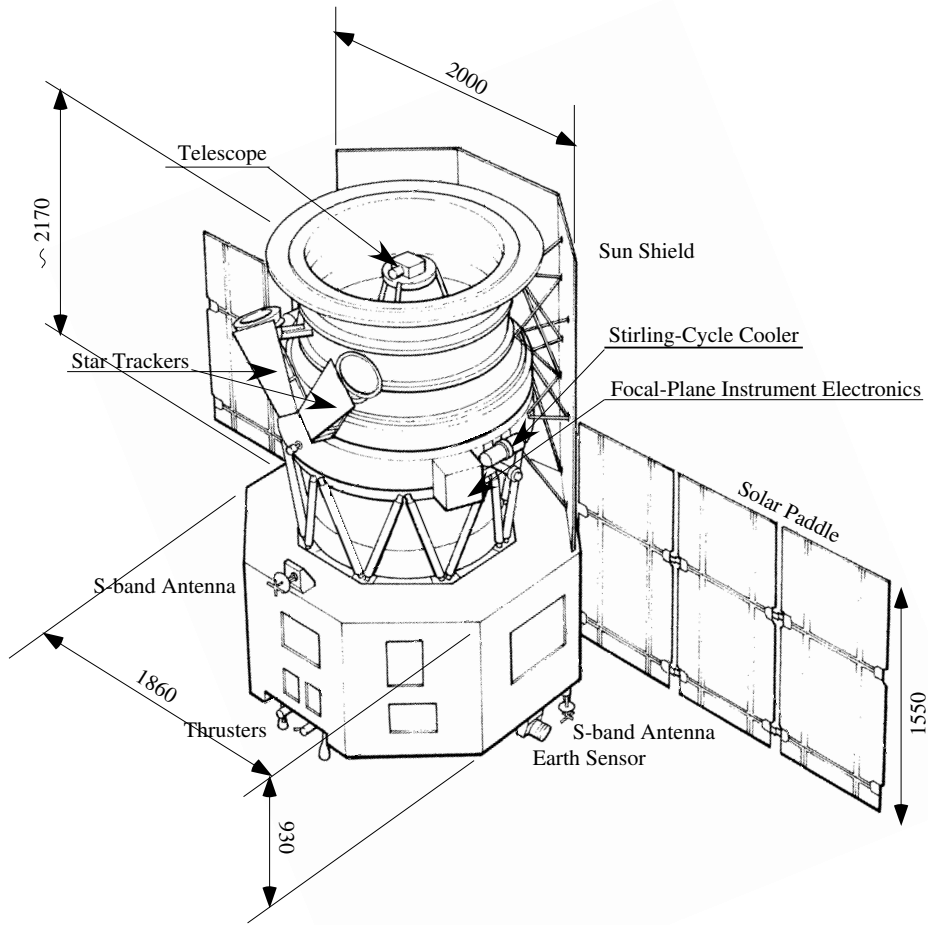


Figure 2. The ASTRO-F system in the observation configuration after the aperture lid is jettisoned.

Table 1. Specifications of ASTRO-F

Effective Aperture	67 cm (Diffraction Limit at 5 μm)
T_{Mirror}	5.8 K
Wavelength Range	1.8 – 200 μm
Orbit	Sun Synchronous Polar Orbit above the twilight zone
Cryogenics	170 liters of liquid helium Two sets of 2-stage Stirling Cycle
Total Mass	960 kg (wet)
Launch Vehicle	M-V Rocket
Launch Year	early 2004

The scientific targets of the ASTRO-F range from distant galaxies to near-by objects in the solar system. The results of the new infrared survey by ASTRO-F will serve as valuable input catalogues for large-aperture space telescopes such as FIRST (Pilbratt 2000) and also for 8–10 m class ground-based telescopes.

Figure 1 shows a picture of the thermal test model of the ASTRO-F satellite, Figure 2 shows a diagram of

ASTRO-F in the observation configuration, and Table 1 shows the specifications of ASTRO-F

2. ASTRO-F HARDWARES

2.1. HYBRID CRYOGENICS

To reduce the total weight of the cryostat, we employed a hybrid cryogenics design; the telescope and focal plane instruments are to be cooled by liquid helium with the help of mechanical cryocoolers.

Figure 3 shows a cross-sectional view of the ASTRO-F cryostat with the 67 cm telescope installed. The outer shell of the cryostat is thermally isolated from the spacecraft and is cooled below 200 K by radiation. The cryostat has two vapor-cooled shields (VCS). The inner VCS is cooled not only by evaporated helium gas but also by two sets of 2-stage Stirling-Cycle coolers. This additional cooling power provided by the coolers increases the life time of the liquid helium by a factor of two. Although the amount of liquid helium is small (170 liter), the expected hold time of liquid helium in orbit is as long as 550 days due to

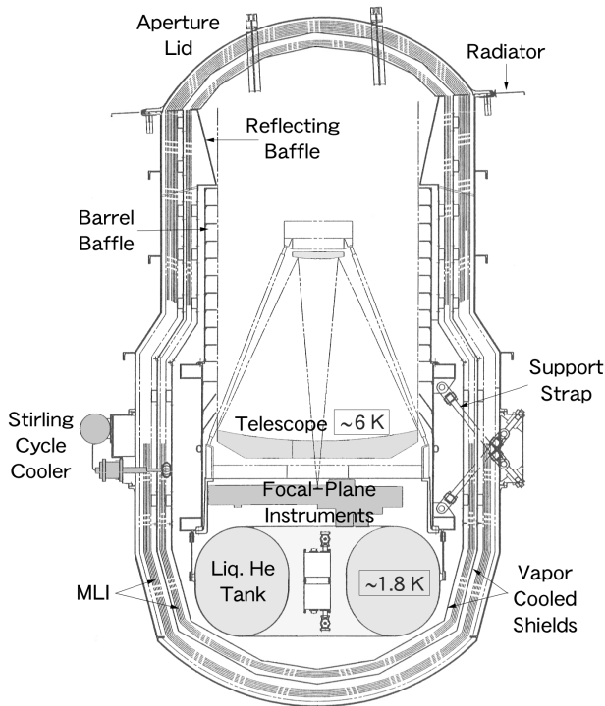


Figure 3. Cross-cut view of the ASTRO-F cryostat, which is a hybrid system with relatively small amount (170 l) of liquid Helium and two mechanical cryocoolers

the cryocoolers. One more advantage of using mechanical coolers is that, as long as the mechanical coolers work properly, we can continue observations at least in the near-infrared even after liquid helium runs out. The cryocoolers are now under extensive tests, and the expected life time of the coolers is longer than 2 years.

The telescope and most of the focal-plane instruments are cooled by the evaporated helium gas, and the expected temperature is 5.8 K. Far-infrared detector arrays require lower temperatures, and are cooled to 1.8 K by the direct thermal connection to the helium tank.

2.2. LIGHT-WEIGHT TELESCOPE

ASTRO-F telescope is a Ritchey-Chretien system with a effective aperture size of 67 cm. Figure 4 shows the whole telescope assembly, which is to be cooled down to 5.8 K. The goal of the image quality is diffraction-limited performance at the wavelength of $5 \mu\text{m}$, including the aberration of the camera optics at the focal plane.

In order to reduce the total weight of the telescope system, we have employed silicon carbide (SiC) for mirror material because of its large Young's modulus and high thermal conductivity. Both the primary and secondary mirrors have a sandwich structure which consists of porous SiC (3 mm thick) as a core and CVD coat of SiC (0.5 mm thick) on surfaces. Porous SiC can be easily machined for light-weight structures, and CVD SiC coat is dense and strong



Figure 4. The telescope assembly of ASTRO-F. Both the primary and secondary mirrors are made of SiC.

enough for smooth polishing. This structure reduces the weight of the primary mirror to 11 kg. The mirrors are coated with Au for good reflectivity with ZnS overcoat for protection.

We plan to measure the surface figure of the primary mirror and the whole telescope assembly both at ambient temperature and at liquid helium temperature. Please see Onaka, Sugiyama & Miura (1998) and Kaneda, Onaka & Yamashiro (2000) for details of the ASTRO-F telescope and its developing program.

2.3. FOCAL PLANE INSTRUMENTS

ASTRO-F has two focal instruments: Far-Infrared Surveyor (FIS) for far-infrared and Infrared Camera (IRC) for near- and mid-infrared.

These two instruments share the focal plane as shown in the left figure of Figure 5. The vertical arrow shows the scan direction. IRC consists of three channels, but the NIR and the MIR-S channels share the same entrance aperture, and there are only two apertures in total for IRC. FIS has two detector modules, and they also share the same entrance aperture. Two sets of FSTS (Focal Plane Star Sensor) are used for pointing reconstruction during the survey mode. The goal of the pointing reconstruction is to determine the telescope direction with the uncertainty less than $3''$, which is required for the identification of observed infrared sources at other wavelengths.

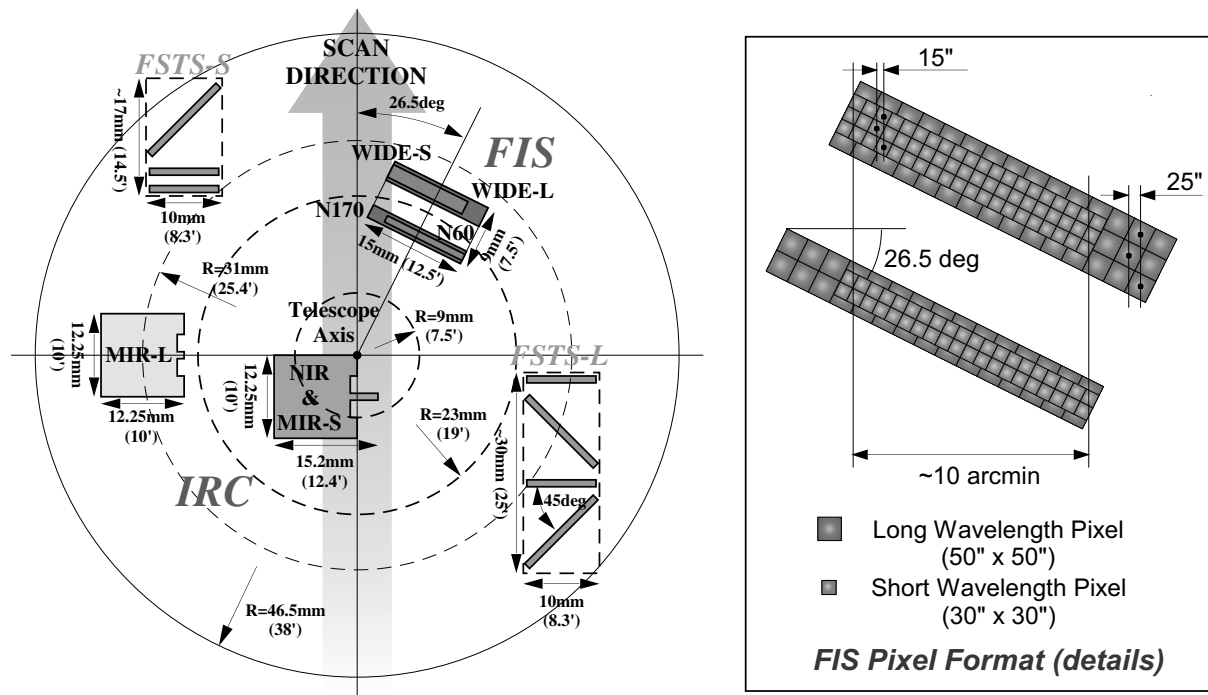


Figure 5. The configuration of the focal plane (left). The vertical arrow shows the scan direction. IRC consists of three channels, and the NIR and the MIR-S channels share the same entrance aperture. FIS has two detector modules, and they also share the same entrance aperture. Two sets of FSTS (Focal Plane Star Sensor) are used for pointing reconstruction during the survey mode. The detector arrays of FIS are tilted against the scan direction by 26.5° (right) to improve the sampling frequency in the cross-scan direction.

2.4. FIS: FAR-INFRARED SURVEYOR

FIS (Kawada 2000, Takahashi et al. 2000) is designed primarily to perform the all-sky survey in 4 photometric bands at wavelength of 50 - 200 μm . FIS also has spectroscopic capability as a Fourier-Transform spectrometer.

Figure 6 shows the optical layout of FIS. The incident beam from the telescope comes from the entrance aperture below the bending mirror. The incident beam is paralleled by the collimator mirror. This parallel beam goes to the filter wheel. This filter wheel determines the mode of operation, i.e. scanner (=photometric imager) or spectrometer.

In the scanner mode, the incident filter on the filter wheel is just a hole. The parallel beam goes through the hole and reflected by the flat mirror. Then the beam is divided into two in the spectral domain by a dichroic beam splitter on the same filter wheel (but at the opposite side). The radiation longer than 110 μm goes through the filter and is concentrated onto the long wavelength detector module. The shorter wavelength radiation is reflected by the dichroic beam splitter and is focused on the short wavelength detectors module. Each detector module consists of two detector arrays. Another set of filters just in front of the detector arrays determines the effective photometric bands. Table 2 lists the four photometric bands. The optical efficiency of each band is about 40 %.

Table 2. Specifications of FIS

Band	Wavelength (μm)	Pixel FOV (arcsec)	Array
N60	50 - 75	30	20×2
Wide-S	50 - 110	30	20×3
Wide-L	110 - 200	50	15×3
N170	150 - 200	50	15×2

For the spectrometer mode of FIS, we use a polarized Michelson interferometer (Martin-Puplett type). We need three polarizing filters: input, beamsplitter, and output. The input and output polarizing filters are on the filter wheel and are to be selected for the spectrometer mode. In this mode, the parallel beam is reflected by the input polarizing filter. Then the polarized beam goes into the interferometer, and are divided by the polarizing beam splitter whose polarizing direction is rotated 45° against the polarity of the incident beam. Two beams divided by the beam splitter are reflected by two sets of roof-top mirrors. We move one set of the mirrors to change the optical path difference between the two beams. The two beams are combined again on the beam splitter, and the combined beam goes onto the output polarizing filter. By the output polarizing filter, the beams are divided in the polarity domain, and concentrated by the camera mirrors on each

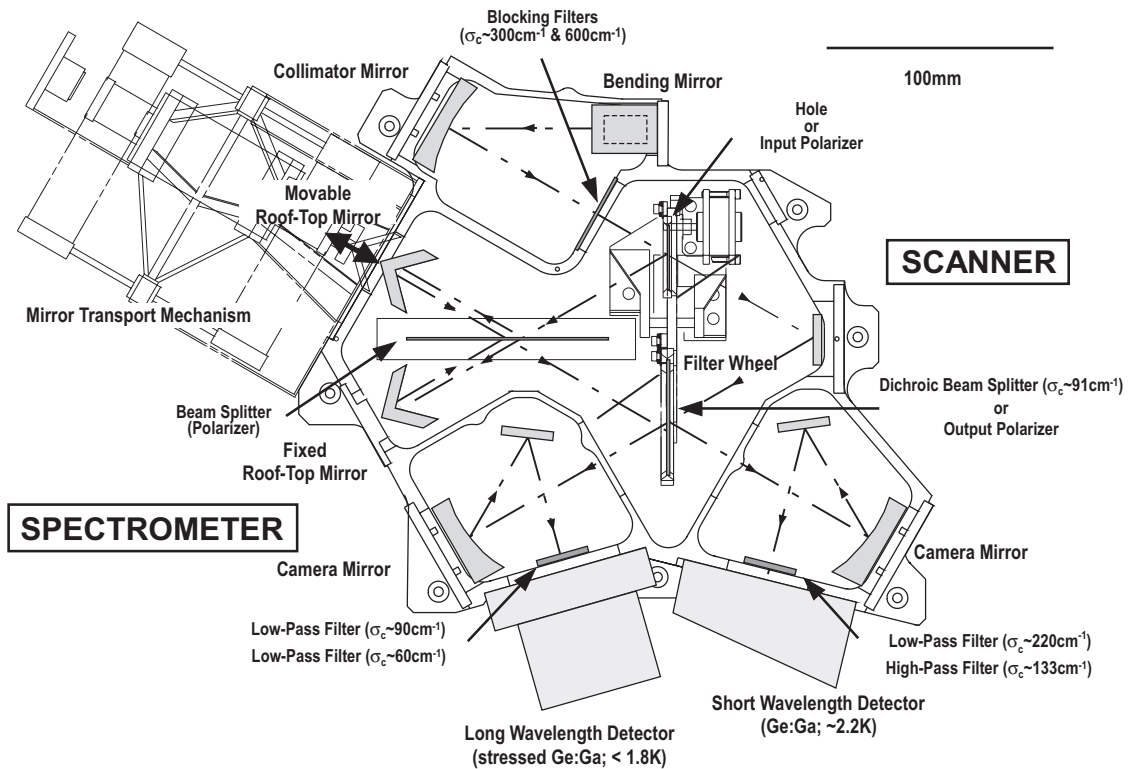


Figure 6. Optical layout of FIS. The entrance aperture is below the bending mirror. FIS has two modes: scanner (or photometric imager) and (imaging) spectrometer. We can switch the modes by changing the filter wheel position.

detector module. The maximum optical path difference is about 50 mm, which corresponds to a spectral resolution of 0.2 cm^{-1} . The big advantage of the spectrometer mode of FIS is that it is an imaging spectrometer suitable for spectroscopic mapping observations of extended sources.

Each detector module consists of two bands, and FIS have four bands in total as is shown in Table 2. The detector arrays for WIDE-S and N60 are Ge:Ga detector array which is connected to the cryogenic readout electronics (Hirao et al. 2001) directly by indium (Hiromoto et al. 1998). For the detector arrays of WIDE-L and N170, we use compact stressed Ge:Ga detector arrays (Doi et al. 2000).

The pixel size of each detector array is comparable with the size of the diffraction pattern of the main mirror at each band. Hence if we scan the sky with the detector array whose minor axis is parallel to the scan direction, the sampling frequency in the cross-scan direction is below the Nyquist sampling frequency. In other words, the spatial resolution in the cross-scan direction is worse than that of the diffraction limited size. Hence, we tilted the detector array by 26.5° as shown in the right figure of Figure 5, to increase the sampling frequency and thereby to improve the spatial resolution in the cross-scan direction. This tilt guarantees the Nyquist sampling for each scanning observations, which is critical requirement to achieve the diffraction limited spatial resolution.

Table 3. Specifications of IRC

Channel	Wavelength (μm)	Pixel FOV (arcsec)	Array
NIR	1.8 – 5	1.46	512×412 InSb
MIR-S	5 – 12	2.34	256×256 Si:As
MIR-L	12 – 26	2.34	256×256 Si:As

2.5. IRC: INFRARED CAMERA

IRC (Watarai et al. 2000, Onaka et al. 2000) is another focal-plane instrument onboard ASTRO-F. It is designed for deep imaging and low-resolution spectroscopic observations in the near- to mid-infrared from $1.8 - 26 \mu\text{m}$.

The big advantage of ASTRO-F/IRC is that it can make deep photometric and spectroscopic surveys with wide field-of-views. It will provide a important database for many fields of astronomy.

Figure 7 shows the whole structure of IRC. IRC consists of three channels: NIR, MIR-S, and MIR-L. Table 3 shows the details of each channel. Each channel has a large-format detector array (Table 3), which enables nearly diffraction-limited spatial resolution at each channel with a wide field-of-view of $10' \times 10'$. The NIR and MIR-S channels observe the same sky as is shown in Figure 5, while the MIR-L observes the sky about $20'$ away from the NIR/MIR-S position.

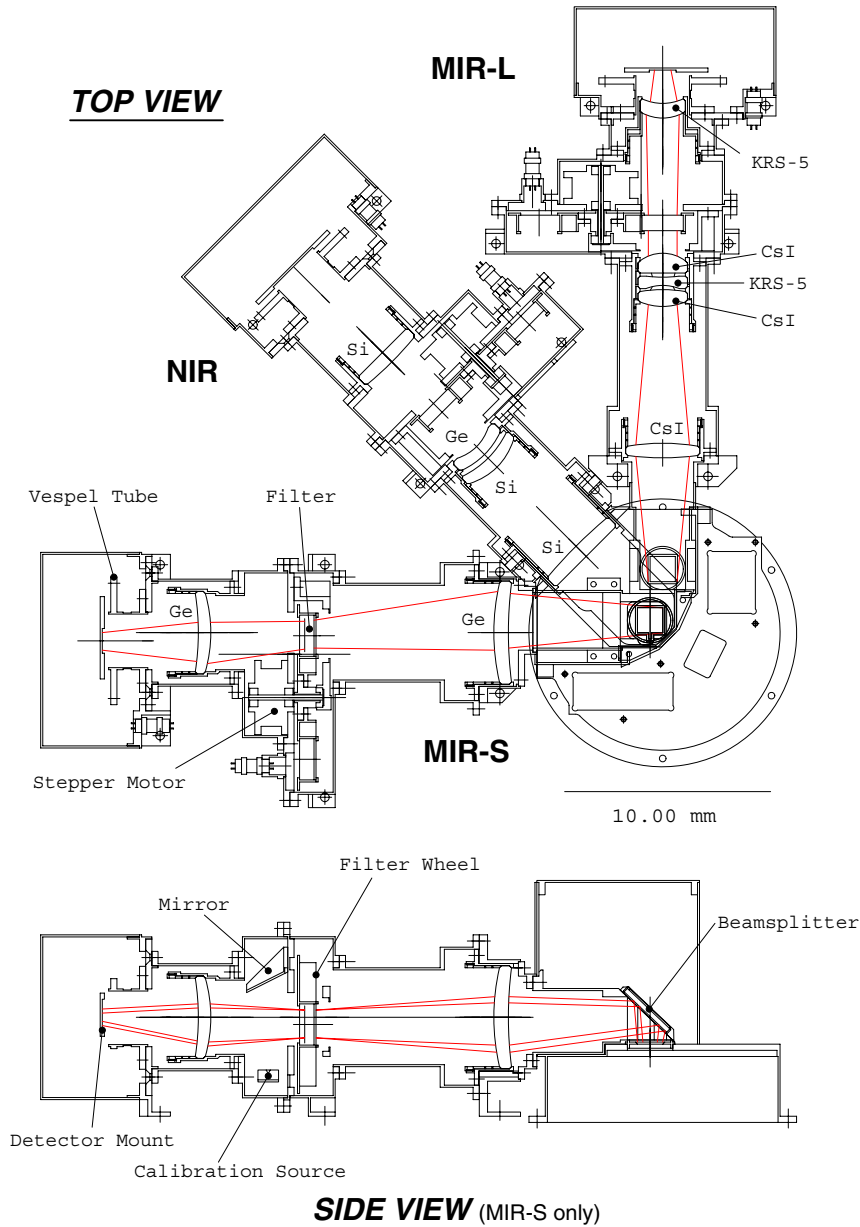


Figure 7. Top view of IRC (top), and side view of MIR-S (bottom), one of the three channels of IRC. The optical configuration for each channel is shown together with the lens material.

3. ASTRO-F OBSERVATIONS

3.1. MODES OF OBSERVATIONS

ASTRO-F is to be launched into the sun synchronous polar orbit with the altitude of 750 km. The trajectory of ASTRO-F is always on the twilight zone. This orbit is similar to that of IRAS, and is suitable for all sky survey observations with severe constraints of avoidance angles toward the sun and toward the earth, as in the case of infrared satellites with cooled telescopes. FIS performs the all-sky survey in the continuous survey mode as is shown in Figure 8. We will concentrate on this mode of observations at least in the first half year of the mission.

For any observations with IRC or spectroscopic observations with FIS, we need pointing observation. In the case of the pointing mode of ASTRO-F, the line of sight of the telescope can be fixed to a specific direction on the sky for about 10 minutes (Figure 8). The nominal attitude is that the line of sight of the telescope is perpendicular to the direction toward the sun. We can change this angle only by $\pm 1^\circ$. Hence the time slot for specific objects to be observed in the pointing mode is strongly restricted. The maximum number of pointing observations we can make in one orbit is three.

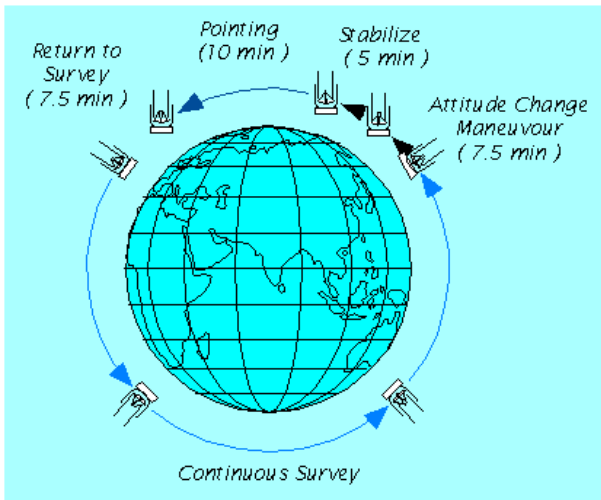


Figure 8. The orbit and the attitude control sequence of ASTRO-F. The basic observation mode is the continuous survey, but also the pointing observation for less than 10 minutes can be made.

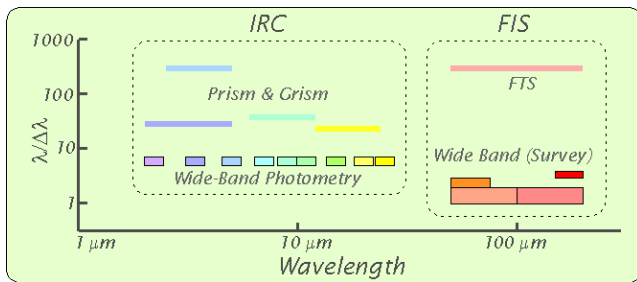


Figure 9. Schematic view of the wavelength coverage and the spectroscopic capability of IRC and FIS onboard ASTRO-F.

3.2. CAPABILITY

Figure 9 shows a schematic view of the wavelength coverage and the spectroscopic capability of IRC and FIS onboard ASTRO-F. ASTRO-F covers wide spectral range both in the photometric mode and in the spectroscopic mode with moderate resolution.

Figure 10 shows the sensitivity of ASTRO-F for point sources. The FIS sensitivity during the survey mode at the wavelength longer than 100 μm is limited by the confusion noise, and the sensitivity cannot be improved even with longer integration time. The sensitivity of the all sky survey of ASTRO-F/FIS is better than that of IRAS by more than an order of magnitude. Hence the results of the ASTRO-F/FIS will serve as a legacy for the astronomical community for a long time and will be ideal inputs for observation planning of FIRST.

IRC also achieved almost confusion-limited sensitivity over a wide range of spectral region. The big advantage of IRC is that it has a wide field of view (10' × 10'). The database of IRC observations will be very important to

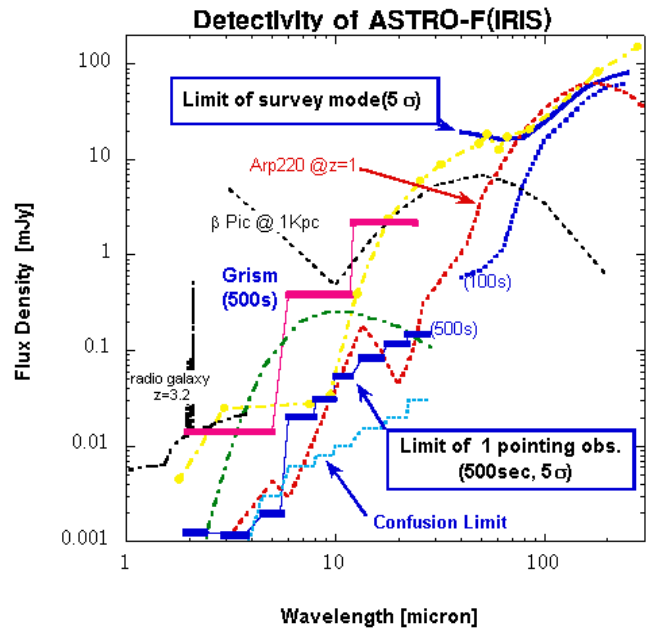


Figure 10. Sensitivity of ASTRO-F for point sources. The FIS sensitivity during the survey mode at the wavelength longer than 100 μm is limited by the confusion noise, and the sensitivity cannot be improved even with longer integration time.

determine the spectral energy distribution of many sources to be observed by FIRST at longer wavelengths.

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APPENDIX A: COMPARISON WITH SIRTf

NASA's infrared mission SIRTf (Gallagher & Simmons 2000) is to be launched in 2002. The telescope size of SIRTf is 85 cm, which is slightly larger than that of ASTRO-F, and the spectral coverage of SIRTf is similar to that of ASTRO-F. Hence ASTRO-F and SIRTf have very similar specifications in many points. SIRTf has better sensitivity than ASTRO-F especially in far-infrared due to its slightly larger telescope size and finer spatial sampling. On the other hand, the FOV of the focal plane instruments on ASTRO-F is wider than those on SIRTf. Hence ASTRO-F is more suitable for efficient observations of wide areas. Especially, the all sky survey at far-infrared is a unique program of ASTRO-F.

APPENDIX B: COLLABORATION WITH ESA

We have started the discussion with ESA on possible collaboration concerning the data analysis activity and supports of tracking stations for ASTRO-F. The goal of this collaboration is to enable quick release of ASTRO-F survey catalogues. We are also discussing the possibility to open some fraction of pointing observations for European community.