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# Need for a Large FIR/SMM Telescope and its Possible Design

By

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**Abstract:** A large aperture far-infrared and submillimeter-wave (FIR/SMM) telescope plan is discussed, which would greatly increase observing sensitivities in the FIR/SMM region. A 10-m primary mirror could be installed in the HII rocket faring by simply folding them into three pieces. The design is based on a radiatively cooled offset primary mirror. The large aperture and low sidelobe design coupled with the cooled optics is suitable for low-background, high-sensitivity and high-angular resolution observations in the FIR/SMM.

Development of a large format submillimeter-wave array using superconducting direct detector technique is also introduced. This type of detector will be suitable for large aperture FIR/SMM telescopes in space.

## 1. INTRODUCTION

The far-infrared region is observable only from above the atmosphere. In addition, cooling requirement of the telescope systems limits the primary mirror sizes. The current SPICA design increases the primary diameter by eliminating the large cryogenic system. However, the size of the rocket faring still limits the telescope diameter to less than a few meters. On the other hand, submillimeter-wave observations have been made with large aperture telescopes on high mountains through the submillimeter-wave atmospheric windows. Larger collecting area would be achieved by the Atacama Large Millimeter/Submillimeter Array (ALMA). Sensitivity and angular resolution for this array are high enough to study details of planetary formation and distant galaxies. However, large area survey is not easy even with the ALMA because of small field of view. Further, ground-based observations always suffer from atmospheric absorption, emission and fluctuation.

Future space-based FIR/SMM telescope should have large collecting area comparable or larger than the ground-based telescopes as well as low background conditions like cryogenic infrared telescopes.

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## 2. CURRENT PROJECTS

There are many far-infrared and submillimeter-wave observing programs recently completed or currently underway, such as ISO and SCUBA deep surveys. There are many high-redshift galaxies revealed in these surveys that are candidate for primeval galaxies. Following these programs, future surveys by space missions such as SIRTF, ASTRO-F and FIRST are in the pipeline.

In this section, the Atacama Submillimeter Telecope Experiment (ASTE), a ground-based submillimeter project and development of a superconducting submillimeter-wave camera for this project are described. Then the requirements for future space FIR/SMM telescope are discussed.

### 2.1 Superconducting Submillimeter-wave Camera for Atacama Submillimeter Telescoep Experiment

The Atacama Submillimeter Telescope Experiment (ASTE) is a project to install and operate a 10-meter submillimeter-wave antenna at Pampa la Bola (4800 m in elevation) in the Atacama, Chile (Matsuo, Sakamoto, & Matsushita 1998; Matsushita et al. 1999). The aim of the project is twofold; to test the antenna on-site as an engineering prototype for the Japanese Large Millimeter and Submillimeter Array (LMSA) as well as to undertake astronomical observations of the southern sky in the submillimeter wavelengths taking advantage of this unique site. In the latter respect, it will be the only large telescope in the south that works at frequencies higher than 400 GHz.

To realize deep survey of galaxies in the submillimeter-wave region, it is important to develop large format arrays with 1000 or more pixels. Currently, bolometers are widely used and are being developed for the future array detectors. Superconducting direct detector is another possible device for high sensitivity submillimeter-wave detection with capablility to realize large format arrays (Matsuo et al. 1998; Matsuo et al. 2000).

Niobium tunnel junctions with low leakage current coupled to antenna structures can be sensitive submillimeter-wave direct detectors with high quantum efficiency and low leakage current. Inhomogeneously distributed junctions coupled to log-periodic antennas can be used to realize this. Input coupling of more than 50% is expected within a bandwidth of more than 50 GHz, centered on 650 GHz, using low current density inhomogeneously distributed junctions. The measured leakage current of 5 pA and a shot-noise of 1.5 $\mathrm{fA}/\sqrt{\mathrm{Hz}}$ ensure that the noise equivalent power of less than $10^{-17}\mathrm{W}/\sqrt{\mathrm{Hz}}$ at operating temperature of less than 0.9 K could be achieved.

Photon detectors, in general, have higher stability than bolometers against electrical interference, vibration or temperature fluctuation. The larger format array could be achieved much easily with photon detectors than with bolometers, because thermal insulation between pixels is not required. Because of its thin film fabrication process, they should also be less affected by cosmic rays. Hence, superconducting direct detectors are most suitable for space-borne applications.

### 2.2 REQUIREMENTS FOR FUTURE FIR/SMM PROGRAM

There are three major requirements for the space-borne FIR/SMM telescope;

- Large collecting area

Table 1: Performance of the Superconducting Direct Detectors.

| Material | Niobium tunnel junctions |
|---|---|
| Observing frequency | 650 GHz |
| Beam size on 10 m telescope | $11''$ |
| Operating temperature | $< 0.9$ K |
| Leakage current | 5 pA |
| Noise current | $1.5\ \mathrm{fA}/\sqrt{\mathrm{Hz}}$ |
| NEP(expected) | $< 10^{-17}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ |

- Low background observation
- Continuous spectral coverage

Ground-based telescopes on high mountains with large collecting area and with good angular resolution of about $10''$, such as ASTE, will observe many astronomical objects through the submillimeter-wave window. This angular resolution is important to reduce the confusion noise. However, for the ground-based telescopes, the observations will be limited primarily by atmospheric radiation and its fluctuation.

The ISO deep survey by Kawara et al. (1998) revealed many far-infrared galaxies. Analysis of the images by Matsuhara et al. (2000) shows it is dominated by confusion noise by far-infrared galaxies. It is required to observe with higher angular resolution to observe fainter galaxies. The Far-Infrared Space Telescope (FIRST) will reveal much fainter galaxies. However, the angular resolution is still limited compared to the ground-based submillimeter-wave observations.

Continuous spectral coverage is also important for astrophysical observations. Primeval galaxies with high star-forming activity emit most of their radiation in the submillimeter-wave as continuum dust emission and atomic/molecular line emission. An example of the apparent spectral energy distribution of far-infrared galaxies in the submillimeter-wave region is shown in Figure 1. Measurements of SEDs of galaxies as well as their far-infrared atomic lines are important to measure the redshift of the source. It is of great interest to identify red-shifted atomic lines to determine the redshift of the object. To identify galaxies at various redshifts it is required to observe in a wide wavelength range of FIR/SMM.

## 3. SPACE BASED FIR/SMM TELESCOPE WITH A 10-M PRIMARY REFLECTOR

In spite of the projects already described, it is still difficult to make a large area continuum survey with confusion-limited sensitivity and wide band spectral survey in far-infrared and submillimeter-wave bands. To realize these observations a large telescope built in space environment is required. In the space environment, low-background condition can be achieved and detection sensitivity could be higher by two orders of magnitude. Large area survey with enough sensitivity and angular resolution could also be achieved. It is essential that the instrumental background be minimized for the low-background telescope. I now discuss how a large cryogenic telescope with low backgraound could be realized.

A single piece of a 10-m primary mirror is too large to fit into any rocket faring. This is

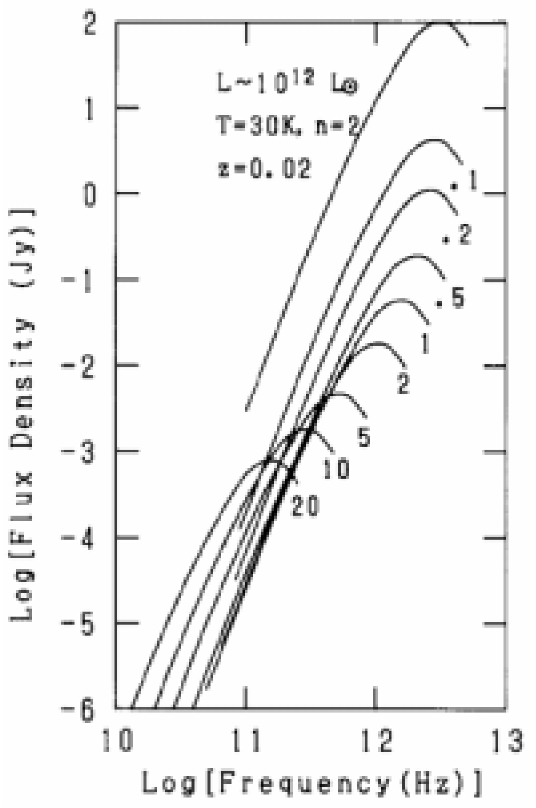


Fig. 1: Spectral energy distribution of high-redshift galaxies. (Matsuo 1989)

the limitation of the current SPICA design with 3 m class primary reflector. To overcome this it is required to deploy a large primary reflector, which is usually a difficult task in space. If the number of pieces of the constructing element is small, the deployment becomes easier.

Figure 2 shows an example. By folding the 10-m primary mirror into three pieces, the mirror just fits into the largest HII rocket faring. The outside diameter of the faring is 5.1 m, of which 4.6 m is usable for payload instruments. The top view shows the comparison of the faring size, the mirror folded into three pieces and the one deployed. A sub-reflector and a sunshade could be installed in the available space. The sunshade is only indicated in the side view in Figure 2. Although the design of the sunshade is not discussed here, it is very important for the thermal and optical performance of the telescope. When the mirror is deployed, it is warm. After the sunshade is deployed and low radiation input condition is achieved, the mirror cools by radiation cooling.

### 3.1 Optical Design

Simple deployment and low scattering requirement lead to an optical design with an off-axis primary mirror. Because the sub-reflector support structure is away from the main beam of the telescope, there is no direct scattered radiation into the main beam. On the other hand, off-axis designs may have larger aberration compared with on-axis optics.

Figure 3 shows the off-axis Cassegrain optics with a F/D=1.5 primary reflector. Spot diagrams, shown in Figure 4, are calculated for wavelength of 200$\mu$m and 10$\mu$m within field

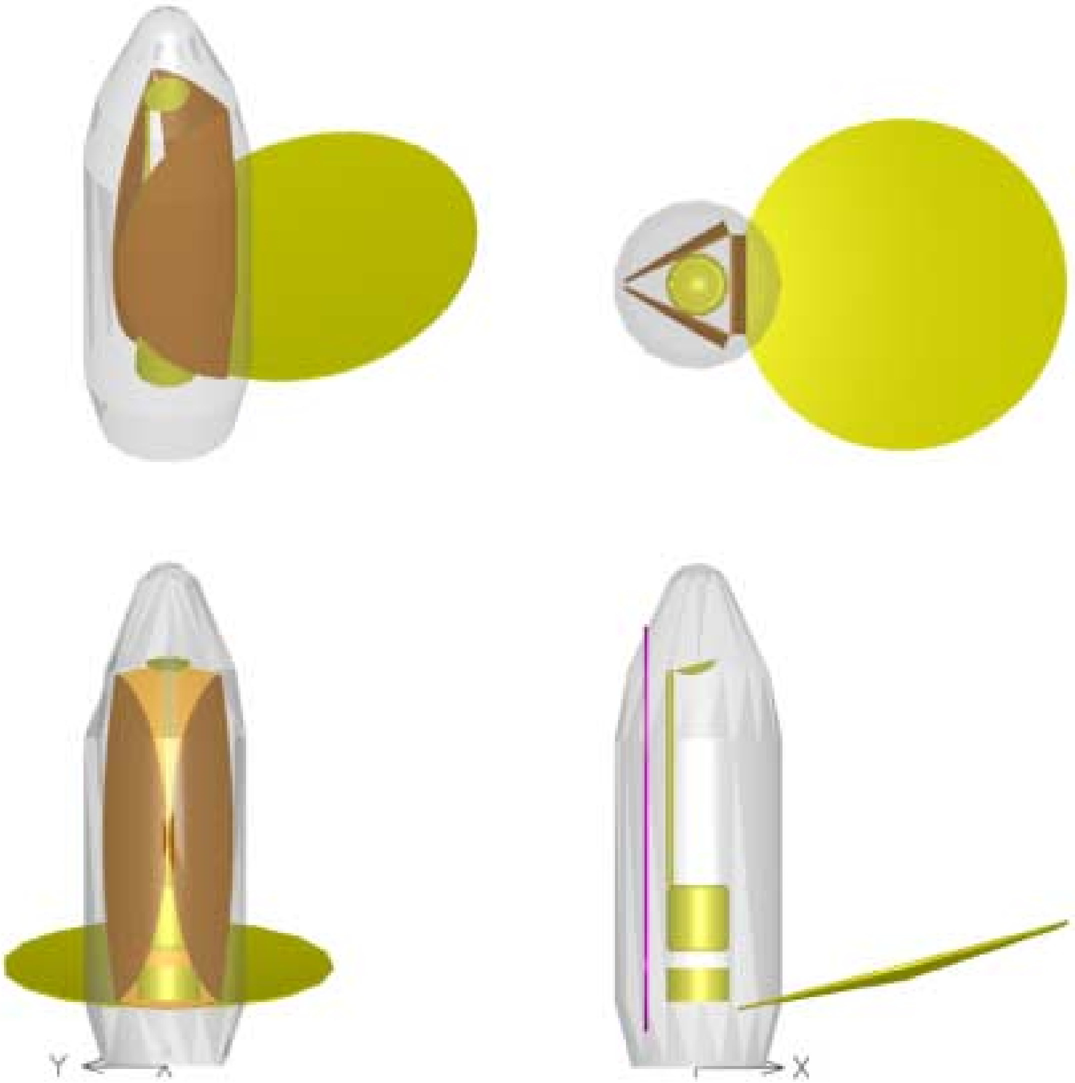


Fig. 2: The possible design of the 10-m class FIR/SMM telescope installed in the HII rocket faring. The primary mirror before and after deployment are shown. Placement of the sun-shield is indicated in the right bottom figure.

of view (FOV) of 12 arcmin and 4 arcmin, respectively. The spot diagram shows acceptable aberration within the FOV. The FOV could be covered by focal plane arrays of ten thousand pixels at 200$\mu$m and one million pixels at 10$\mu$m. In the current design, aberration is dominated by the curvature of the focal plane. Simple correcting optics would improve the aberration, if required. The optical performance is summarized in Table 2.

Because the surface accuracy would be limited for the large primary reflector, a deformable sub-reflector or tertiary mirror may be required, which corrects the error of the primary reflector.

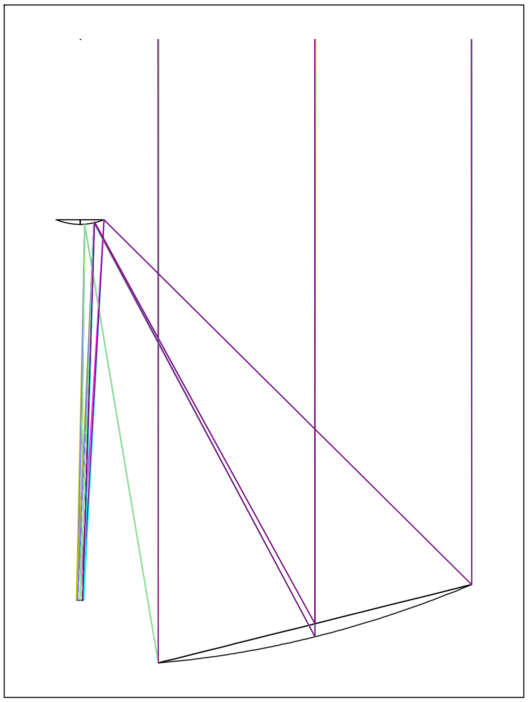
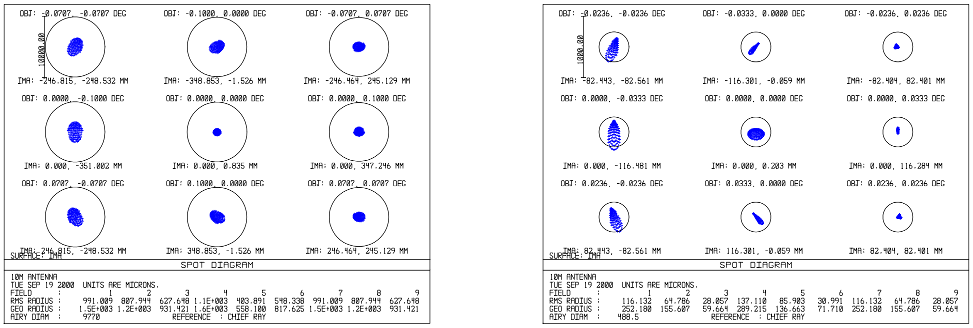


Fig. 3: Optical arrangement and ray tracing of the off-set Cassegrain telescope design.



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10M ANTENNA
TUE SEP 19 2000  UNITS ARE MICRONS.
FIELD      :         1        2        3        4        5        6        7        8        9
RMS RADIUS :   991.009  807.944  627.648 1.1E+003  403.891  548.338  991.009  807.944  627.648
GEO RADIUS :  1.5E+003 1.2E+003  931.421 1.6E+003  558.100  817.625 1.5E+003 1.2E+003  931.421
AIRY DIAM  :   9770                REFERENCE  : CHIEF RAY
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10M ANTENNA
TUE SEP 19 2000  UNITS ARE MICRONS.
FIELD      :         1        2        3        4        5        6        7        8        9
RMS RADIUS :   116.132   64.786   28.057  137.110   85.903   30.991  116.132   64.786   28.057
GEO RADIUS :   252.180  155.607   59.664  289.215  136.663   71.710  252.180  155.607   59.664
AIRY DIAM  :   488.5               REFERENCE  : CHIEF RAY
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Fig. 4: Spot diagrams at 200$\mu$m and 10$\mu$m within 12$'$ and 4$'$ field of view.

Table 2: Optical Performance.

| Wavelength | angular resolution | FOV | number of pixels |
|---|---|---|---|
| $10\mu$m | $0.25''$ | $4'$ | $10^6$ |
| $200\mu$m | $5''$ | $12'$ | $10^4$ |

### 3.2 Thermal Design

By placing the telescope near the L2 point of the Sun and Earth system, it is possible to avoid thermal radiation from the Sun, the Earth and the Moon by a solar radiation shield. With an appropriate thermal design, it is possible to cool the telescope effectively by radiation cooling. In principle, unavoidable radiation is the 3 K Cosmic Background Radiation and radiation from stars, zodiacal dust, interstellar dust and plantes.

It is assumed that an aluminum plate with 3 mm thickness is placed behind the radiation shield. Back side of the mirror is blackened to radiate toward the 3 K background radiation field. The configuration is shown in Figure 2. In this configuration, the front surface of aluminum with low emissivity reflects most of the radiation coming from the solar radiation shield. Pure aluminum at low temperature has high conductivity; hence has less than 1% emissivity and absorption in the far-infrared region (Matsuo et al. 1994).

Figure 5 shows a simulated result for the radiation cooling. In this calculation, it is assumed that there is no radiation input to the front surface of aluminum and the blackened back surface has 80% emissivity. Temperature dependence of the specific heat of aluminum is taken into account in this calculation.

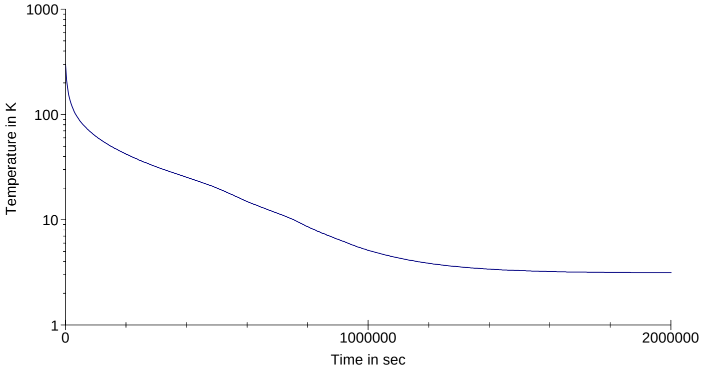

Fig. 5: Radiation cooling of a 3-mm thick aluminum plate with blackened back surface.

Within 4 days, the temperature of the aluminum plate becomes about 30 K and in 2 weeks it reaches equilibrium temperature near the background radiation. Zodiacal dust radiation would raise the equilibrium temperature slightly. This effective cooling is realized because the area of the radiating surface is very large and the small heat capacity of the aluminum plate.

Conductive and radiative heat inputs from the focal plane instruments and the solar radiation shield should be considered. Conductive heat input could be removed by using a mechanical refrigerator that only cools the conduction path from the instruments to the primary mirror. To reduce the radiative input from the solar radiation shield, the shield has to be multi-layered and the innermost shield should have low emissivity at temperatures less than 30 K. Because of the low emissivity of the inner radiation shield and the primary mirror, radiation input from the 30 K radiation shield becomes comparable to or less than the cosmic background radiation.

## 4. CONCLUSION

The 10-m FIR/SMM telescope concept with folded mirror design is discussed. In spite of difficulties in deploying a large primary reflector, it looks attractive for high sensitivity observation in the far-infrared, especially for survey and identification of distant galaxies. The following is a summary of conclusions.

- By folding the mirror into three pieces, a 10-m primary mirror could be installed in the large HII rocket faring.
- A simple off-set Cassegrain optics can be used to realize diffraction limited images within the required field of view in FIR/SMM.
- By an effective radiation cooling design, a large cryogenic telescope can be realized at the L2 point of the Sun-Earth system.

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