640 GHz SIS RECEIVER SYSTEM FOR JEM/SMILES ON INTERNATIONAL SPACE STATION

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ABSTRACT

We are developing a superconductor-insulator-superconductor (SIS) receiver for a submillimeter-wave limb emission sounder (SMILES) on the Japanese Experiment Module (JEM) of the International Space Station. SMILES is a sensitive heterodyne spectrometric radiometer in 640 GHz band, and observe thermal emission lines of stratospheric trace molecules in the limb sounding method. SMILES operates two SIS mixers simultaneously in single-sideband (SSB) mode using only one local source. For the SSB filter we employ a frequency selective polarizer (FSP), which consists of two sets of a wire grid and a flat mirror and operates in the principle of Martin-Puplett interferometer. The SIS mixers and the first low noise amplifiers will be cooled to 4.5 K and 20 K, respectively, by a compact Stirling refrigerator combined with a Joule-Thomson circuit. We succeed in demonstrating the cooling capability of 20 mW at the 4-K stage, 200 mW at the 20-K stage, and 1000 mW at the 100-K stage with a power consumption of 250 W. We expect a system nose temperature below 500 K in the SSB mode. In 2003 SMILES will become the first SIS receiver flown on space.

INTRODUCTION

Stratospheric minor constituents (e.g., O_3, ClOx, NOx) play an important role in the Earth environmental change such as ozone depletion. Although we know that the basic ozone depletion process are caused by man-made chemical substances such as chlorofluorocarbons, researches on the complicated chemical network of the ozone depletion are still in progress. We need data of global distributions of these minor gases and their diurnal and seasonal variations with a high altitude resolution. We are now developing a highly sensitive submillimeter-wave limb emission sounder (SMILES) to promote sciences related to the ozone depletion (e.g., Masuko *et al.* 1997; Manabe *et al.*, 1998). SMILES will be installed on the exposed facilities of the Japanese Experiment Module (JEM) of the International Space Station (ISS). In the limb sounding method, thermal emission from the stratospheric molecules are observed by a sounder on the orbit (e.g., Barrath *et al.*, 1993). Figure 1 shows the schematic drawing of the limb sounding observation by SMILES. We expect to start a operation of SMILES in 2003 for at least one year, and now we are in the final design trade-off of the system. This paper mainly describes the current instrumental design of the 640 GHz SIS receiver system, and also reports some experimental results.

OVERVIEW OF JEM/SMILES

Table 1 summarizes the basic specifications of JEM/SMILES, and Figure 2 shows the signal flow diagram of SMILES. We employ a highly sensitive heterodyne superconductor-insulator-superconductor (SIS) receiver, and observe twelve emission lines of stratospheric molecules as listed in Table 2. The SIS receiver makes it possible to detect extremely weak emissions and reduce the observational time for each observational positions. We retrieve the altitude profile of the molecules at a high altitude resolution over a wide altitude range together with their global diurnal and seasonal variations from the sensitive data set.

A 60 cm x 30 cm main reflector gathers the thermal radiation from the atmospheric limb region at an altitude resolution of 2 km. The 638.4 GHz fixed frequency LO signal is injected into the RF signal by wire grids. In order to measure the intensity of the signal in one sideband precisely, we use the receiver in single-sideband mode (SSB) by a quasi-optical SSB filter. We operate two SIS mixers simultaneously, one for upper sideband (USB) and the other for lower sideband (LSB) detection. The IF signals of 9.8 -14.8 GHz are further down-converted in frequency and amplified to a power level large enough for spectroscopy. In the IF subsystem only frequency ranges around the molecular emission lines of interest are chosen to save the band width of the spectrometer. We use three acousto-optical spectrometers (AOSs) for high resolution spectroscopy. The system noise temperature is expected to be less than 500 K in SSB mode, which gives a sensitivity of 1.3 K for an integration time of 0.2 sec and a spectral resolution of 1.4 MHz.

SUBMILLIMETER ANTENNA

We require several technical specifications in the antenna of SMILES for demonstrating a highly sensitive limb emission technique from the space. First requirement is an altitude resolution of 2 km with precise pointing accuracy of 0.01°. We use an offset Casegrain type elliptical (60 cm x 30 cm) antenna. The long axis of 60 cm is chosen to realize an altitude resolution of 2 km, and another axis is reduced to 30 cm for compactness. The main reflector of the antenna will be polished aluminum, and special attention is paid in the frame structure of the main reflector and thermal insulation around the antenna for minimizing the thermal distortion. We drive the pointing elevation angle of the antenna in a step size smaller than 0.01°. The altitude pointing of the antenna

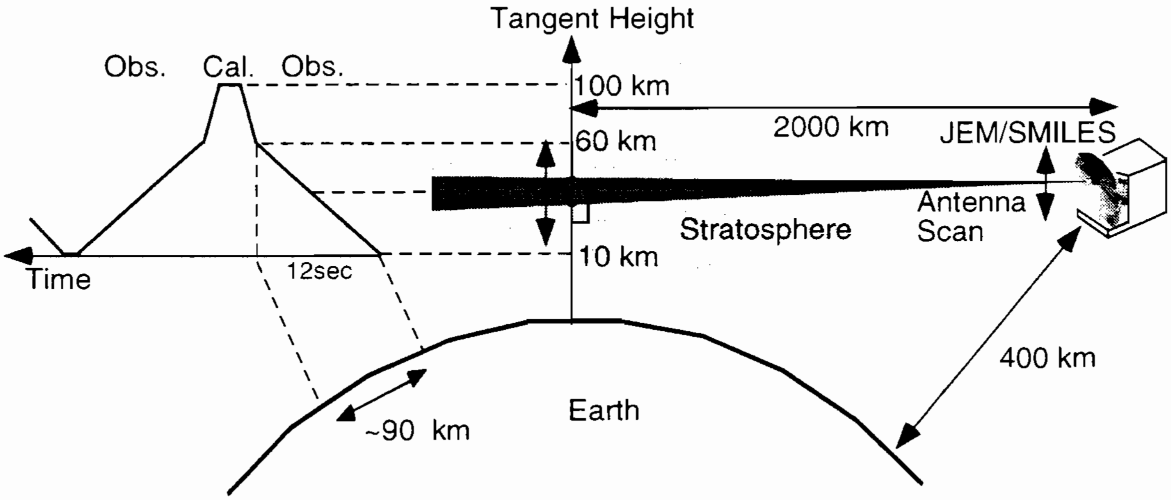

Fig. 1. Schematic view of the limb sounding observation by JEM/SMILE.

Table 1. Basic Specifications of JEM/SMILES

Receiver	Heterodyne Spectrometric-Radiometer
Observation Scheme	Limb Sounding
Observation Platform	International Space Station
Orbit Altitude	~400 km. 51° inclination
Observable Latitude	65°N - 38°S
Observation Altitude	h = 10 - 60 km.
Altitude Resolution	Δh = 2 km
Antenna Type	Offset Cassegrain
Size & Beam width	60 cm, 0.055°(El.), 30 cm, 0.117° (Az.)
Pointing Accuracy	0.01°(El.)
Signal Frequency	624 - 629 GHz (LSB) 649 - 654 GHz (USB)
SSB Separation Method	Quas- optical SSB filter FSP
LO Source	Gunn diode (109.4 GHz) doubler+tripler
Mixer	PCTJ type Nb/AlOx/Nb
Operation Temp.	@4.5K
Low noise Amps.	HEMT amps@20K,100K
Spectrometer	Acousto-Optical Spectrometer (AOS)
Spectral Resolution	1.4 MHz
System Noise Temp.	500 K (SSB)
Mission Life Time	1 year
Weight & Power	500 kg, 500 W
Size	0.8 x 1 x1.9 m
Launch Date	2003

Table 2. Observing Molecular Species

Species	Frequency (GHz)	Brightness Temp. (K)	Comments
O_3	650.733	220	Ozone Lyer,Global Warming
$O^{18}O$	627.773	80	*T* and *P* measurement
ClO	649.45	20	Ozone Depletion
HCl	625.90-93	100	Cl Reservoir
HOCl	628.46	3	Cl Reservoir
NO	651.772	8	Ozone Depletion
N_2O	652.834	30	NOx Reservoir
HNO_3	650.279	5	NOx Reservoir
HO_2	649.701	5	Ozone Depletion
H_2O_2	627.087	0.3	HOx Reservoir
BrO	624.77	0.3	Ozone Depletion
SO_2	624.344	0.2	Aerosol Source

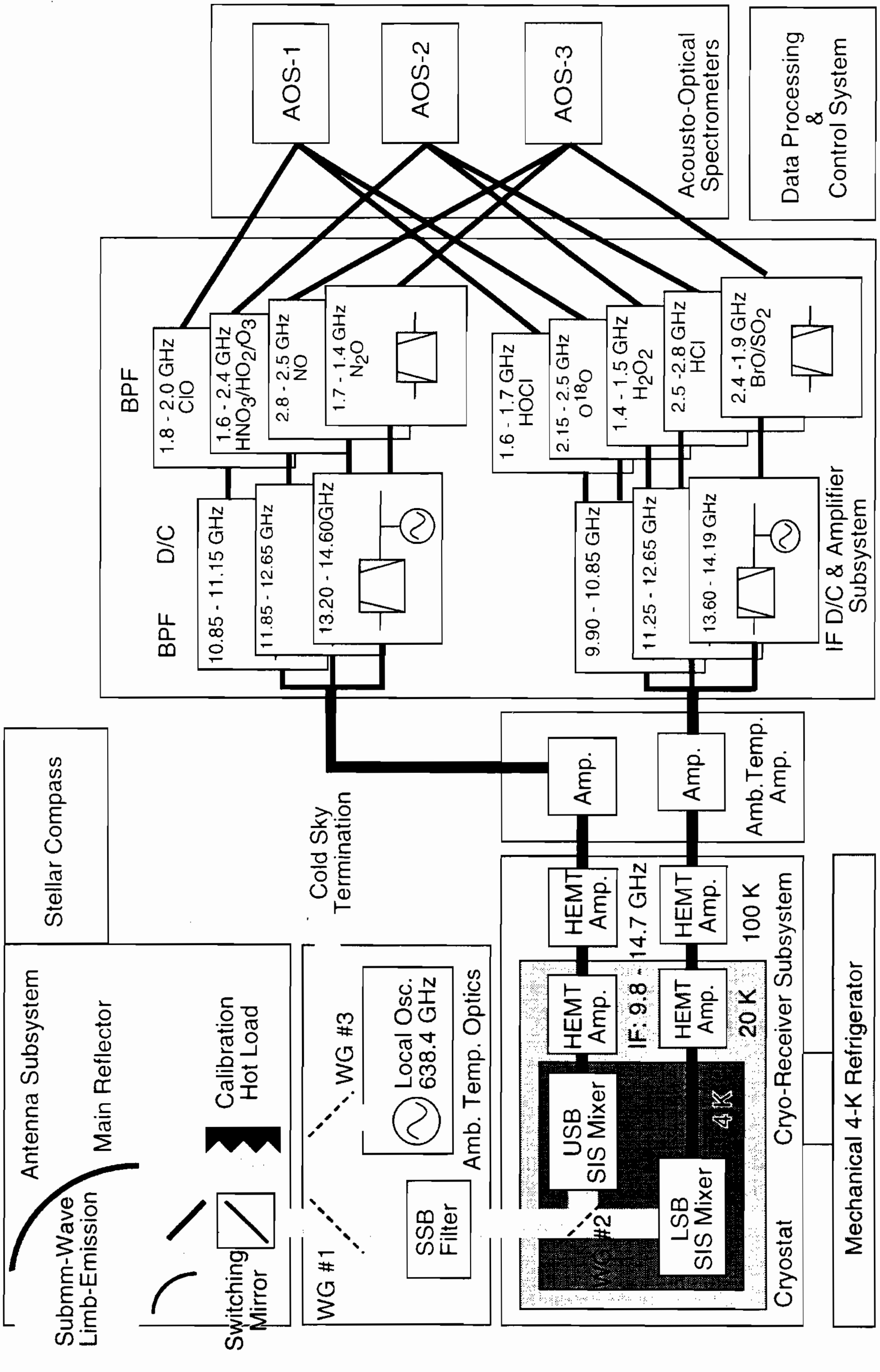

Fig. 2. Signal flow diagram of JEM/SMILES.

support structure is monitored by a stellar compass installed very close to the antenna. We will be able to determine the positions of the antenna with an accuracy of 0.01°.

Second requirement is precise intensity calibration. We require a high main beam efficiency of 95 % so that undesirable emission from the sidelobe should be reduced. The shape of the main reflector is modified to produce the high efficiency main beam, and its surface is polished with an accuracy better than 10 μm to reduce the level of sidelobe. We use a temperature monitored submillimeter-wave absorber at an ambient temperature for a hot load calibration, but we use the main antenna itself for cold load calibration by pointing upward directions. We expect a precise cold load calibration compared with a system looking cold sky by a switching mirror in the beam transportation system, because effect from the surroundings of the optics is kept same during operation. The baseline ripple which appears in the observed spectra due to undesired reflection within the system is also a source for reducing the reliability of calibration. We choose offset type antenna for avoiding the beam reflection in the antenna which may cause baseline ripple in the spectra. We expect a precise intensity calibration better than 10 % in error.

QUASI-OPTICS

Figure 3 is the schematic drawing of the receiver optics of SMILES. Optical system is designed to realize easy alignment and reduce the risk of misalignment caused by variation of environmental condition on space. The optics are divided into two main components: the optics on 4-K stage and that in ambient temperature. The ambient temperature optics guide the beam from the antenna subsystem into the cooled optics. The 638.4 GHz LO signal is injected into the wire grid in the ambient optics. Typical physical size of the mirror is ranging from 30 mm in the 4-K stage and 60 mm on the ambient optics. They are settled around the center of cryostat as close as possible. The center of the cryostat is stable in terms of mechanical structure and thermal conditions, and concentration of them toward the center is suitable for keeping the good alignment conditions.

An outstanding feature of the optics is the realization of SSB operation of two SIS mixers simultaneously using only one local source (Inatani *et al.*, 1998). Two mixers on the 4-K stage receive two perpendicular polarizations each other. One mixer looks at the antenna port in the USB band, while it looks at the cold sky though the LO port in the LSB band. At the same time, the other mixer looks at the antenna port in the LSB band and the cold sky in the USB band. This SSB operation is realized by a quasi-optical SSB filter on the ambient temperature optics. The band suppression ratio of 17 dB is expected at the band edge frequency.

The SSB filter is a key component of the optics. We use a frequency selective polarizer (FSP) as an SSB filter which use the principle of Martin-Puplett interferometer (MPI) (Seta *et al.*, 1999). The FSP consists of two pairs of a flat mirror and a wire grid. Figure 4 shows the operational principle of the FSP comparing that of traditional MPI consisting of two roof-top mirrors and a wire grid shown in Figure 5. The wire grid (WG) #4, whose wire direction is oriented at 45° with respect to the incident linear polarization, divides the input signal into two components. The reflected and transmitted signals are combined again in WG #5 after traveling two different path

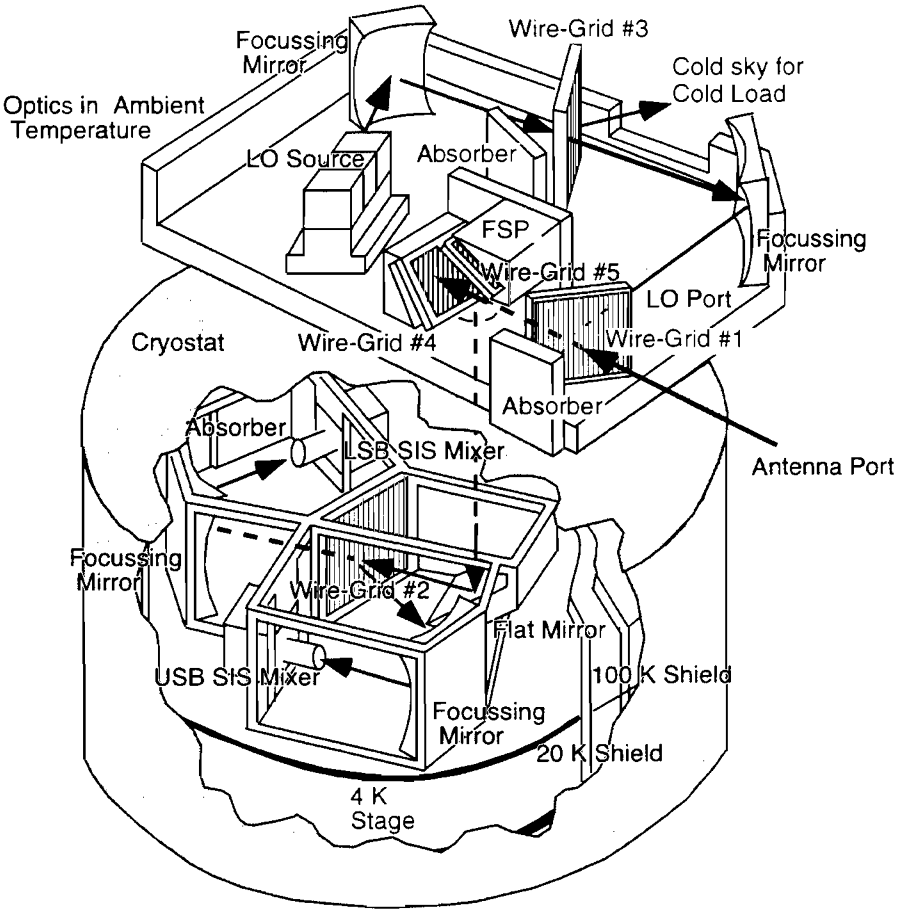

Fig. 3. Schematic view of receiver optics of JEM/SMILES.

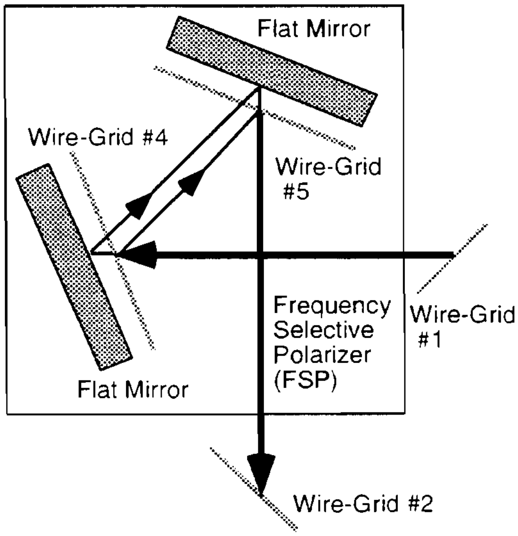

Fig. 4. Schematic drawing of our proposed new type of SSB filter operating in the principle of MPI.

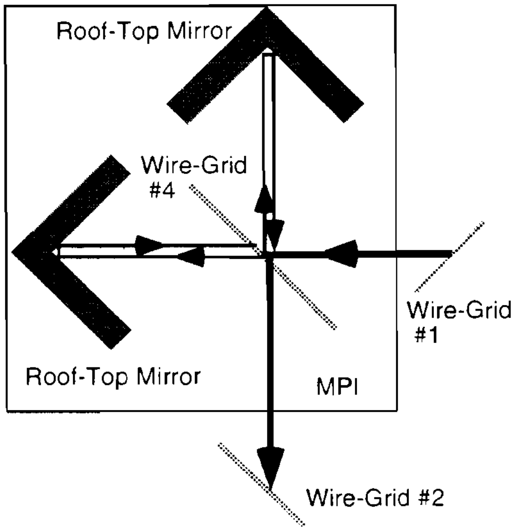

Fig. 5. Schematic drawing of a conventional MPI.

lengths. We can tune the transmission characteristics in frequency from a linearly polarized input signal to a linearly polarized signal in the output port by adjusting the traveling path length difference. The path lengths is adjusted by a gap between the flat mirror and the wire grid, while in the conventional MPI the path difference is controlled by the relative distance difference between the WG #4 and each roof top mirror.

The FSP is superior to the traditional MPI in two reasons for our purpose. Since we use the SSB filter for a fixed frequency, we do not need tuning mechanism. A mechanical tuner may be harmful by increasing possibilities of mechanical troubles in space. So we will use a fixed tuned SSB filter without moving mechanical structure. We adjust the position of the mirror in the ground which works as a tuner, and fix the position tightly once it is tuned. The required alignment accuracy of the mirror is estimated to be 2 μm. In the traditional MPI we must achieve this accuracy for a traveling path length of 50 mm, and this is too difficult to achieve without mechanical tuning structure. On the other hand in case of FSP, we can adjust the mirror position in a accuracy of 2 μm for a path length of 2 mm, which is achieved with careful machine work. The second advantage of the FSP is elimination of standing waves generated on the MPI. In the conventional MPI, the input signal partially returns to the input port due to undesirable transmission and reflection of the wire grid. The returned signal becomes a source of standing wave. This level is estimated to be 20 dB assuming the undesired reflection and transmission of the wire grid is 1%, and it is harmful to our sensitive spectroscopic observation. Although in the FSP we cannot avoid the undesirable reflection and transmission of the wire grid, this component never comes back to the input port.

The LO signal at 638.4 GHz is generated in a phase-locked Gunn diode oscillator followed by a doubler and a tripler, and injected into the FSP through the WG #3. The direction of wires in WG #3 is tilted 10° from the linear polarization plane of the LO source, so that the local power is injected into the FSP by 3 % , while each mixer, in its image band, looks at the cold sky by 97 %. The injected LO power is equally supplied into two mixers. The LO output power, which is expected to be around 200 μW, is sufficient for operation of two 640-GHz SIS mixers.

SUBMILLIMETER SIS MIXERS AND LOW NOISE AMPLIFIERS

The SIS is the ultimate device for sensitive millimeter and submillimeter observations especially for 100 - 1000 GHz. Up to now only a Schottky barrier diode type mixer is used in the space (e.g., Barath *et al.* 1993). SMILES employs the SIS mixer for the first time in the space. We use simple and stable SIS mixers for increasing reliability of the mission.

We use a parallel-connected-twin-junctions (PCTJ) type SIS mixer composed of 1.25-micron scale Nb/AlOx/Nb junctions, which are developed at the Nobeyama Radio Observatory (Noguchi *et al.*, 1995; Shi *et al.*, 1997; 1998). The mixer with this device achieves a broad-band performance without a mechanical tuning structure. We place the SIS device in a wave guide type mixer-mount in a typical size of 20 mm. A corrugated type feed horn is attached to the mount, and superconducting magnets are integrated in the mount to suppress the Josephson current. One model of the mixer covers both USB (649-654 GHz) and LSB (624-629 GHz), which is advantageous in performing space qualification tests such as vibration and radiation. The mixer block is attached to the rigid 4K-optics directly with screws. An independent battery will be used for a DC bias of the mixer for stable operation. Our experiment already demonstrated the mixer noise of Tmix = 60-140 K in DSB in the frequency range of 600-650 GHz (Irimajiri *et al.*, 1998).

We require broad band and low power consumption low noise amplifiers for IF amplifiers. SMILES requires a bandwidth of 5 GHz in the 640 GHz band to detect important molecules listed in Table 2, and the IF amplifiers should be low noise over the frequency band for high sensitivity. The power consumption of IF amplifiers should be low for using compact refrigerator. We are developing a high-electron-mobility transistor (HEMT) amplifier with a bandwidth of 5 GHz. We expect a noise temperature below 25 K and a gain of 20 dB with a power dissipation of 20 mW at the operational temperature of 20 K. We succeed in demonstrating this performance in the engineering model of the HEMT amplifiers.

CRYOSTAT AND MECHANICAL REFRIGERATOR

The SIS mixer needs to be operated below 4.5 K. We chose mechanical refrigerator as a cooling system. The mechanical refrigerator is superior to liquid helium type cooler for space use mainly for two reasons, even though it needs lager electric power. First it can be made smaller and lighter, because we do not need large helium tank. Second there is possibilities to expand the life time keeping its smallness and lightness.

We have been developing a compact and low power consumption type refrigerator for space use. Inatani *et al.* (1997) reported the experimental results of thermal prototype of the refrigerator, and concluded that an SIS receiver cooled by a compact 4-K mechanical refrigerator is feasible for space use. Based on this successful experiment we are developing an advanced type of a compact refrigerator system for JEM/SMILES, which satisfies the launching condition of SMILES. Figure 6 shows the schematic view of our cryostat. In the cryostat, we place two SIS mixers, two HEMT amplifiers, other two HEMT amplifiers on the 4-K, 20-K, and 100-K stages, respectively. The cryostat is equipped with a Joule-Thomson circuit and a two-stage Stirling refrigerator (Kyoya *et al.*, 1994). Table 3 shows the thermal analysis of the cryostat. The 4-K stage is surrounded with radiation shields at 20 K and 100 K, and the effect of thermal radiation is minimized with a set of carefully installed multi-layer insulators. For reducing the thermal radiation through an RF signal window, we place two IR filers made of porous polytetrafluoroethylene (PTFE) between the 100-K stage and the outer shell. The cooling capacity is designed to be 20 mW at the 4-K stage, 200 mW at the 20-K stage, and 1000 mW at the 100-K stage with an electric power consumption less than 250 W at the AC power supply to the refrigerator system.

Mechanically the three stages are supported by a number of glass-fiber reinforced plastics (GFRP) straps from the outer shell of the cryostat. The 4-K and 20-K stages are connected by poles made of carbon-fiber-reinforced plastic (CFRP) and 20-K and 100-K stage is connected by poles of GFRP. The GFRP and CFRP keep the thermal conductance as small as possible while surviving the vibrating environment during the launch. Mylar film is used for outer shell window

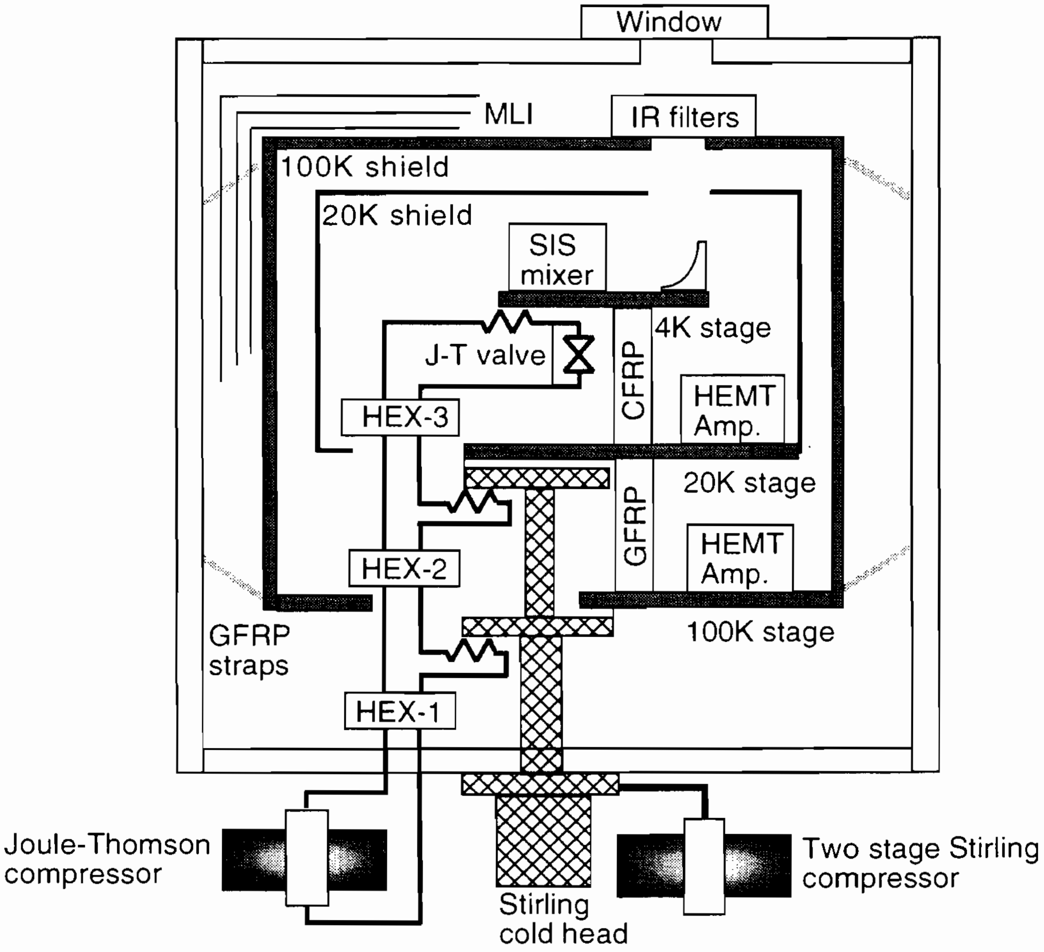

Fig. 6. Schematic view of a small Joule-Thomson circuit combined with two stage String refrigerator.

Table 3. Calculated thermal balance of 640 GHz receiver for SMILES

Items	Types	Heat load at each stage (mW)		
		100-K stage	20-K stage	4-K stage
RF input window	radiation	150	3	2.4
Wall (with MLI)	radiation	370	19	0.1
Supporting structure	conduction	230	47	2.4
IF cables	condition	90	42	13
DC bias cables	conduction	28	5	0.6
Bias current	heat source	9	3	1
Monitor cables	conduction	11	4	0.6
HEMT amps	heat source	30	20	-
J-T gas cooling	heat source	170	87	-
Total load (mW)		970	210	20
Equilibrium temperature (K)		99	22	4.5

to keep the vacuum of cryostat during testing of the receiver on the ground.

By using the engineering model of our cryostat we succeeded in demonstrating the cooling capability and also demonstrated that the vibration expected during the launch did not change the capability. The detail of the refrigerator will be given elsewhere (Narasaki *et al.*, in preparation).

IF SUBSYSTEM AND SPECTROMETER

In retrieving altitude profiles from the spectral data, frequency resolution restricts the altitude resolution in the profile, and the frequency bandwidth restricts the lower altitude limit of the profile. We employ AOS for getting high spectral resolution and wide bandwidth. AOS is superior in terms of weight, size, and power consumption compared with other frequently used digital or filter-bank type of spectrometers. We use three AOSs and achieve a total bandwidth of about 4 GHz with a frequency resolution of 1.4 MHz. We convert a readout data of the CCD in the AOS into a 16 bit digital data every 10 msec, and we integrate it for 200 msec.

In order to save the bandwidth of the spectrometer, only limited frequency ranges of molecular lines of interest are chosen from the broad band width of 5 GHz, and band-pass-filtered into sub bands. The divided band is again combined into three AOS input ports for spectroscopy. We realize observational bandwidth of 800 MHz for O_3 using this technique.

CONCLUDING REMARKS

In this paper we reported the basic design of the 640 GHz submillimeter receiver system of the JEM/SMILES mission, and also reported some experimental results of the engineering model. SMILES employs a sensitive 640 GHz SIS receiver. We operate two SIS mixers simultaneously in the SSB mode. We use a frequency selective polarizer (FSP) as an SSB filter. The SIS mixer will be cooled 4 K by a compact Joule-Thomson circuit combined with two stage String refrigerator. In the engineering model of the refrigerator, we demonstrated the cooling capability of 20 mW at the 4-K stage, 200 mW at the 20-K stage and 1000 mW at the 100-K Stage. We use three AOSs for spectrometer, and achieve a frequency resolution of 1.4 MHz and total bandwidth of 4 GHz. We expect a system noise temperature of 500 K in the SSB mode.

We are now making a final design trade-off for JEM/SMILES, and the specifications described here may be subject to minor changes. In 2003, SMILES will be transported to ISS by a Japanese transporter vehicle HTV launched by the H-IIA rocket. The SMILES will observe twelve stratospheric molecules and reveal interesting phenomena relating to the ozone chemistry. This mission will also demonstrate the feasibility and effectiveness of the SIS receiver as a sensitive system for monitoring trace gases in the stratosphere. The success of this new technique will open new possibilities of submillimeter wave observation in earth science and in astronomy.

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Heavy Industries, Ltd. for development of the refrigerator, Nihon Tsushinki Co. Ltd. for development of HEMT amplifiers, Paris-Meudon Observatory for design of AOS, Thomas Keating Ltd. for design of optics, Radiometer Physics GmbH for design of LO system, and space instrumentation group of Technical University of Denmark for design of stellar compass. In developing SIS junctions we are collaborating with Nobeyama Radio Observatory (NRO). We thank Dr. S.-C. Shi and Dr. T. Noguchi of NRO for technical support and discussions.

REFERENCES

F. T. Barath *et al.*, The Upper Atmosphere Research Satellite Microwave Limb Sounder Instrument, *J. Geophys. Res.*, 98, D6, 10751, 1993.

J. Inatani *et al.*, A Submillemeter SIS Receiver Cooled by a Compact Stirring-JT Refrigerator, Eighth Int. Symp. on Space Terahertz Tech., Harvard Univ., March, 1997.

J. Inatani, S.C. Shi, Y. Sekimoto, H. Masuko, and S. Ochiai, Single Sideband Mixing at Submillimeter Wavelengths, Ninth Int. Symp. on Space Terahertz Tech., Pasadena CA, March, 1998.

Y. Irimajiri, T. Manabe, H. Masuko, S. Ochiai, M. Seta, Y. Kasai, T. Noguchi, and S.C. Shi, Waveguide Heterodyne SIS Receiver for Balloon-borne Superconducting Submillimeter-Wave Limb Emission Sounder at 640-GHz-band., 23rd, Int. Conf. on IR and MM Wave, Essex, September, 1998.

M. Kyoya, K. Narasaki, K. Ito, K. Nomi, M. Murakami, H. Okuda, H. Murakami, T. Matsumoto, and Y. Matsubara, Development of Two Stage Small Stirling Cycle Cooler for Temperature below 20 K, *Cryogenics*, 34, No5, 431, 1994.

T. Manabe *et al.*, Space-Station Borne Submillimeter-Wave Limb-Emission Sounder for Observing Stratospheric Minor Constituents, URSI Commission F Int. Triennial Open Symp. Wave Propagation and Remote Sensing, September, Aveiro, 1998.

H. Masuko, S. Ochiai, Y.irimajiri, J. Inatani, T. Noguchi, Y. Iida, N. Ikeda, and N. Tanioka, A Superconducting Sub-millimeter Wave Limb Emission Sounder (SMILES) on the Japanese Experiment Module (JEM) of the Space Station for Obsrving Trace Gases in the Middle Atmosphere, Eighth Int. Symp. on Space Teraherzt Tech., Harvard, MA, March, 1997.

T. Noguchi, S.-C., Shi, and J. Inatani, An SIS Mixer Using Two Junctions Connected in Parallel, *IEEE trans. Appl. Supercond.*, 5, 2228, 1995.

M. Seta, T. Manabe, H. Masuko, J. Inatani, H. Harada, T. Noguchi, S.-C. Shi, K. Narasaki, and Y. Abe., Submillmemeter -Wave SIS Receiver System for JEM/SMILES, Advances in Space Research, in press, 1999.

S.C. Shi, T. Noguchi, and J. Inatani, Analysis of the Bandwidth Performances of SIS Mixers with Distributed Junctions Arrays, Eighth Int. Symp. on Space Terahertz Tech., Harvard Univ., March, 1997.

S.C. Shi, T. Noguchi, J. Inatani, Y. Irimajiri, and T. Saito, Experimental Results of SIS Mixers with Distributed Junction Arrays, Ninth Int. Symp. on Space Teraherzt Tech., Pasadena, CA, March, 1998.