

**A Superconducting Sub-millimeter Wave Limb Emission Sounder (SMILES)
on the Japanese Experimental Module (JEM) of the Space Station
for Observing Trace Gases in the Middle Atmosphere**

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ABSTRACT

Trace gases such as ClO, BrO, HO₂, etc. from the upper troposphere to the stratosphere play important roles in the depletion of the ozone layer and are closely related to the climate change. Emission spectroscopy using a low-noise heterodyne technique in the sub-millimeter wave range is the most promising method to remotely measure the ozone and these trace gases. The space-borne limb emission sounder can globally observe the 3-dimensional distributions of these trace gases. We submitted a proposal for an experiment of a Superconducting Sub-millimeter Wave Limb Emission Sounder (SMILES) on the Exposed Facilities of the Japanese Experimental Module (JEM) of the Space Station, and the proposal was accepted by the Space Development Board and the Science and Technology Agency of Japan in March 1997. The JEM/SMILES will be operated at 640GHz-band with 10-14GHz IF frequencies. The parallel-connected-twin-junctions (PCTJ) type SIS mixers developed in NAO/NRO will be used for the ultra-high sensitive receiver. The operation conditions for the SIS receiver will be achieved by a compact Joule-Thomson refrigerator combined with a two-stage Stirling refrigerator. In this experiment, we are aiming to demonstrate the effectiveness of the sub-millimeter wave limb emission spectrometry in observing the atmospheric environment from space, to attempt an application of superconduction in space, and to operate a mechanical 4K-refrigerator in space. The JEM/SMILES is a pre-phase of SMILES on an atmospheric environment observing satellite, ATMOS-C1, which is planned to be launched around 2006.

1. BACKGROUND

The depletion of the stratospheric ozone is caused by trace gases, such as ClO, BrO, HO₂, etc., in the stratosphere. Climate change is closely coupled with chemistry interactions in the Lower-Stratosphere and the Upper-Troposphere. Scientific issues for the understanding of Ozone Depletion and Climate Change concern the understanding of the chemical processes related to trace gases, the understanding of the coupling between the dynamic and the chemical processes, and the understanding of the interactions between the Troposphere and the Stratosphere, the Equatorial region and the Mid-latitudes, and the Mid-latitudes and the Polar regions. The first issue, concerning chemical processes related to trace gases, requires the simultaneous observations of ozone, water vapor, and the trace gases in the Stratosphere and the upper Troposphere, together with the atmospheric temperature and pressure. The second issue, concerning dynamic and chemical process coupling, requires high time and spatial resolution. The third issue, concerning regional interactions, requires 3-dimensional global observations, with diurnal and seasonal variations.

Sub-millimeter wave limb emission sounding from space has many advantages in meeting these requirements. Many kinds of the trace species have intense spectral bands in the sub-millimeter wave range (Pickett et al., 1992). Heterodyne spectroscopy can achieve high spectral resolution, such as 1MHz or less, i.e. $\Delta\lambda/\lambda \sim 1E-06$, which is very effective for precise observations. Emission measurements day and night independent of sun-light in any regions are the best way for global observations and are essential for understanding the diurnal cycles of the chemical processes. The limb sounding technique gives high sensitivity and sufficient height resolution of nearly 2km. Figure 1 shows an overview of limb sounding from space. Measurements in the sub-millimeter wave range are less dependent on atmospheric temperature, and are not affected by aerosols and

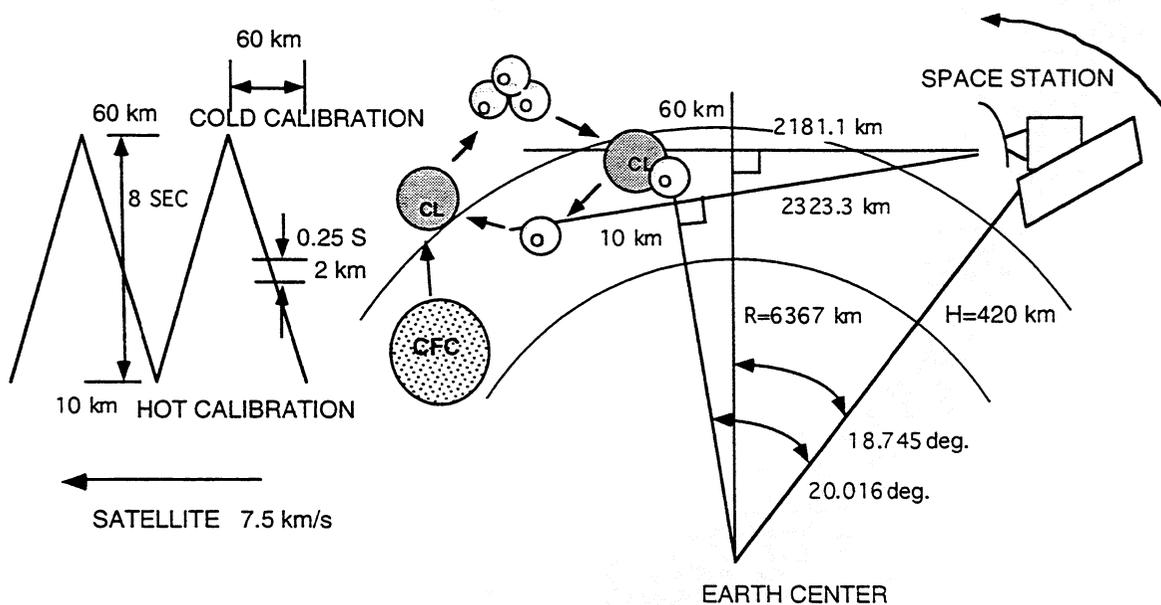


Figure 1. Over view of limb emission sounding.

chemical processes. The conditions make precise observations possible. There are well-provided spectroscopic data bases in the sub-millimeter wave lengths, which are essential for reliable observations. In addition, the heterodyne system can be compacted both in size and weight.

On the other hand, there should be engineering breakthroughs to satisfy the scientific requirements. Measurements of very weak signals with short integration time demand ultra-high sensitivity (ultra-low noise temperature). Figure 2 shows examples of the faint spectra of BrO and HOCl. The best solution to measure such very weak signals is to use a superconductor receiver. Short sub-millimeter waves, such as 0.5mm or less, are profitable for observing the various trace gases up to high altitude range with high signal-to-noise ratio. Figure 3 shows comparison of the ClO spectra in the different frequency bands. Measurements with multiple frequency bands, wide bandwidths in intermediate frequencies (IF), i.e. higher IF, and wide-band spectroscopy are required for simultaneous observations of the trace gases, atmospheric temperature, and pressures. Single-side-band (SSB) operation and high-resolution spectroscopy are needed for reliable quantitative observations.

In order to investigate the sub-millimeter wave limb emission sounding of the trace gases and demonstrate advanced technologies in space, we submitted a proposal for an experiment of a Superconducting Sub-millimeter Wave Limb Emission Sounder (SMILES) for the announcement of opportunity (AO) on the use of the Exposed Facility (EF) of the Japanese Experimental Module (JEM) of the Space Station. The AO had been issued by the National Space Development Agency of Japan (NASDA) in October 1996, according to the decision by the Space Development Board and the Science and Technology Agency (STA) of Japan. The proposal was accepted in March 1997. We describe an overview of the experiment of JEM/SMILES in this report.

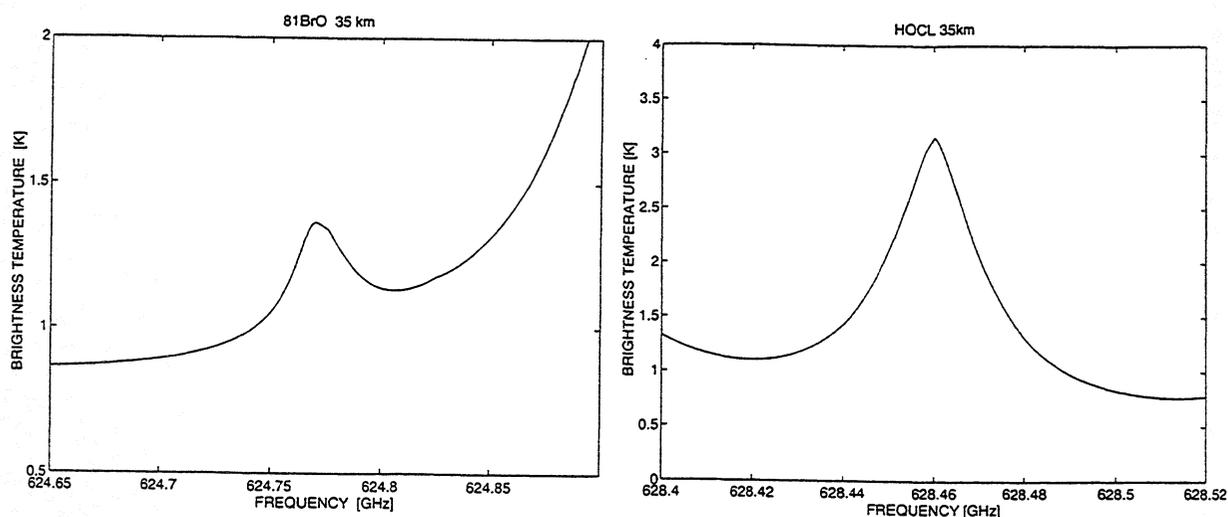


Figure 2. Examples of faint spectra of BrO (left) and HOCl (right) in the sub-millimeter wave range.

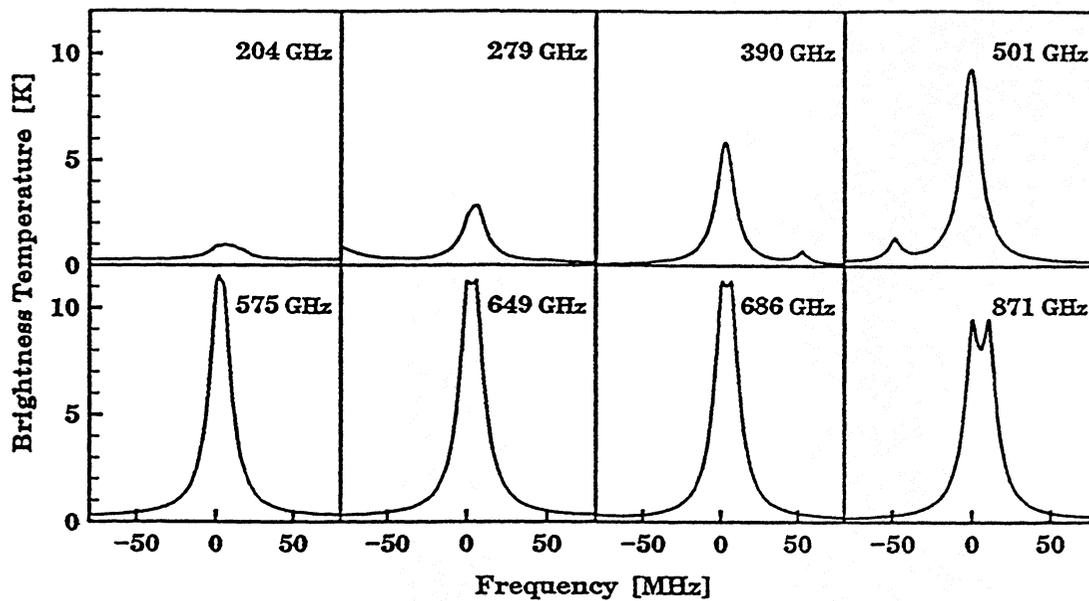


Figure 3. Calculated ClO limb emission spectra in the different frequency bands at the tangent height of 40 km.

2. OBJECTIVES OF THE EXPERIMENT

The experiment of JEM/SMILES has both engineering and scientific objectives. In this experiment, we have proposed to use superconductor-insulator-superconductor (SIS) mixers for the ultra-high sensitive receiver operated around 640GHz. Mechanical cooling is essential for long-term continuous operation of the system. Therefore, the first engineering issue is to establish the key technologies for applications of the sub-millimeter waves, the superconductors (SIS mixers), and the 4K-refrigerator in space. The second engineering issue is to demonstrate the performance of the total system in space. The third engineering issue is to establish the calibration and validation techniques of the system in space.

The first objective for the scientific issues mentioned above is to demonstrate the simultaneous 3-dimensional and global observations of the trace gases in the Stratosphere from space. The second objective is to estimate the accuracy, the possible height range, and other conditions of the observations in each area, i.e. the Equatorial, the Mid-Latitude, and the Polar regions. The third objective is to specifically demonstrate the scientific effectiveness of the observations by investigating the coupling between the chemical processes and the dynamics and regional interactions in the Northern Hemisphere. Recently, the Ozone Depletion processes have been rapidly progressing around the North Pole region.

3. SPACE STATION AND JEM

Figure 4 and 5 show overviews of the configuration of the space station and JEM, respectively. JEM is composed of a pressurized module and a exposed facility. The exposed

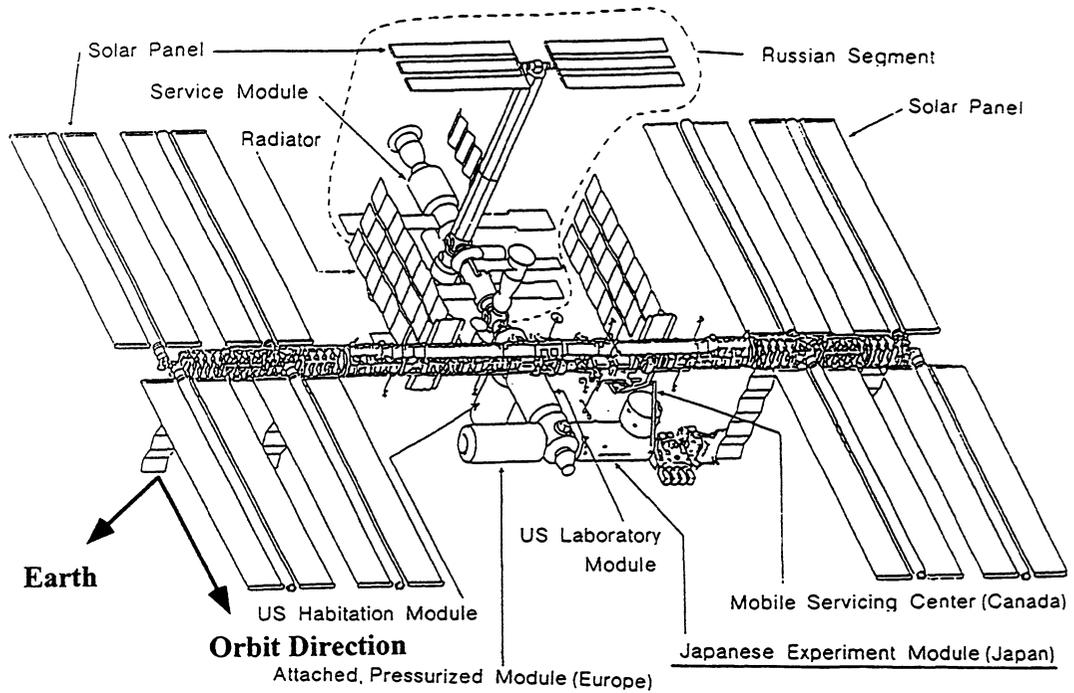


Figure 4. Configuration of Space Station.

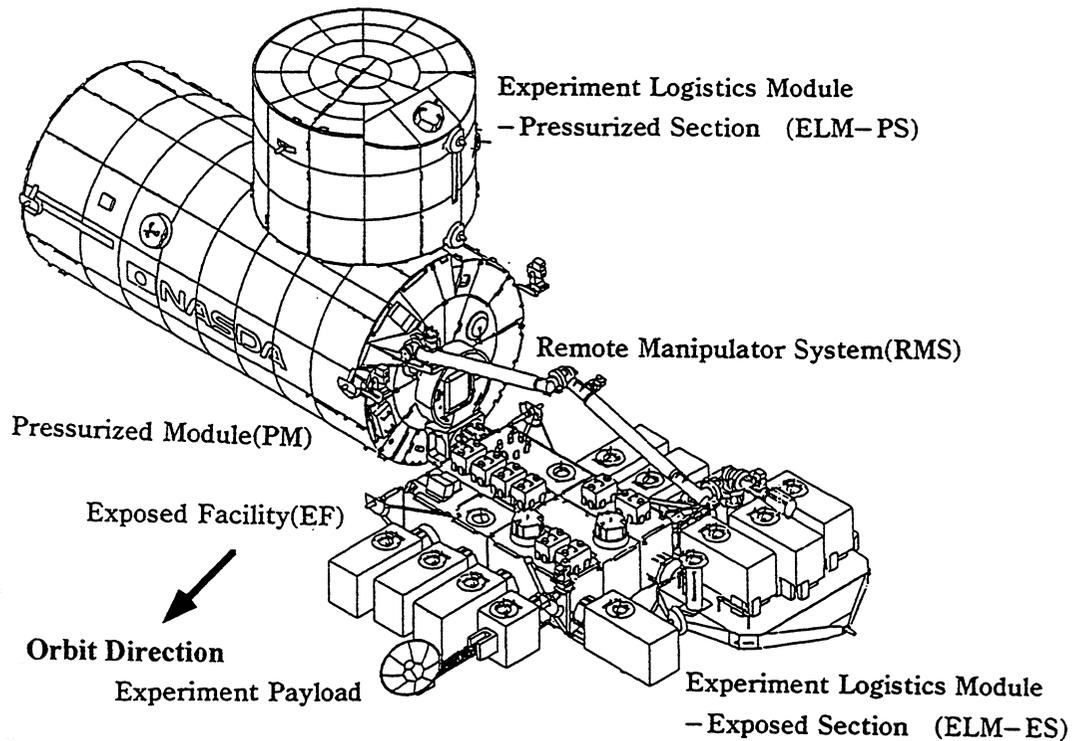


Figure 5. Configuration of the Japanese Experiment Module (JEM).

facility has 10 interface ports to connect the experimental payload units. The use of the interface ports are shared between Japan and US. The AO at this time is for the first use of 4 interface

ports on the Japanese side. Electricity with maximum of 3kW, cooling liquid, and services of signal networks including Ethernet are supplied through the interface ports. The normal interface ports are fit for an experimental payload unit with a maximum weight of 500kg.

The space station has a circular orbit with an inclination angle of 51.6 degrees and a nominal altitude of 407km. No attitude control are made during the inertial flights provided for the microgravity experiments, which results in the attitude drifts up to plus or minus 15 degrees in each of the pitch, roll and yaw directions. In these cases, compensation of the drifts and precise measurements of the attitude become essential for the limb scanning observations.

4. PROPOSED SYSTEM

Almost all of the important trace species, such as ozone, ClO, HCl, HOCl, BrO, HO₂, H₂O-isotope, and O₂-isotope, have absorption bands around 640GHz, and atmospheric opacity is comparatively low around this frequency. Therefore, we have adopted a frequency band around 640GHz for SMILES. Table 1 shows the trace gases observed around this frequency band and the estimated bandwidths to be necessary for the observations. The observation frequencies can be divided into 2 frequency regions. One is used as the lower side-band and the other is used as the upper side-band. Both bands are detected separately under SSB conditions. A candidate for the local frequency is 638GHz. In order to satisfy the wide bandwidth observation, an IF of almost 10-14GHz is required. Figure 6 shows a calculated limb emission spectral profile for the upper

Table 1. Objective trace gases, their observation frequencies, and the required band-width (in parentheses, MHz) considered for JEM/SMILES. Local frequency of 638GHz.

SPECIES	624.2-628.6 GHz	646.9-651.9 GHz	COMMENTS
O ₃	-	647.840 (600)	Depletion & Green-house Gas
O ¹⁸ O	627.773 (600)	-	Temperature/Pressure
ClO	-	649.45 (200)	Ozone Depletion
HCl	625.90-93 (200)	-	Chlorine Reservoir
HOCl	628.46 (100)	-	Chlorine Reservoir
ClO ₂	624.271-272 (100)	-	Ozone Depletion
CH ₃ ³⁷ Cl	627.177 (100)	-	Parent Molecule
⁸¹ BrO	624.77 (100)	-	Ozone Depletion
H ₂ ¹⁸ O	-	647.198 (600)	Parent & Green-house Gas
HO ₂	625.661/664 (100)	-	Ozone Depletion
H ₂ O ₂	-	647.026 (100)	Hydrogen Reservoir
N ₂ O	627.748 (600)	[652.834 (600)]	Nitrogen Reservoir
NO	-	651.771-773 (100)	Ozone Depletion
HNO ₃	-	650.279 (100)	Nitrogen Reservoir
SO ₂	624.344 (100)	-	Volcanic, Aerosol

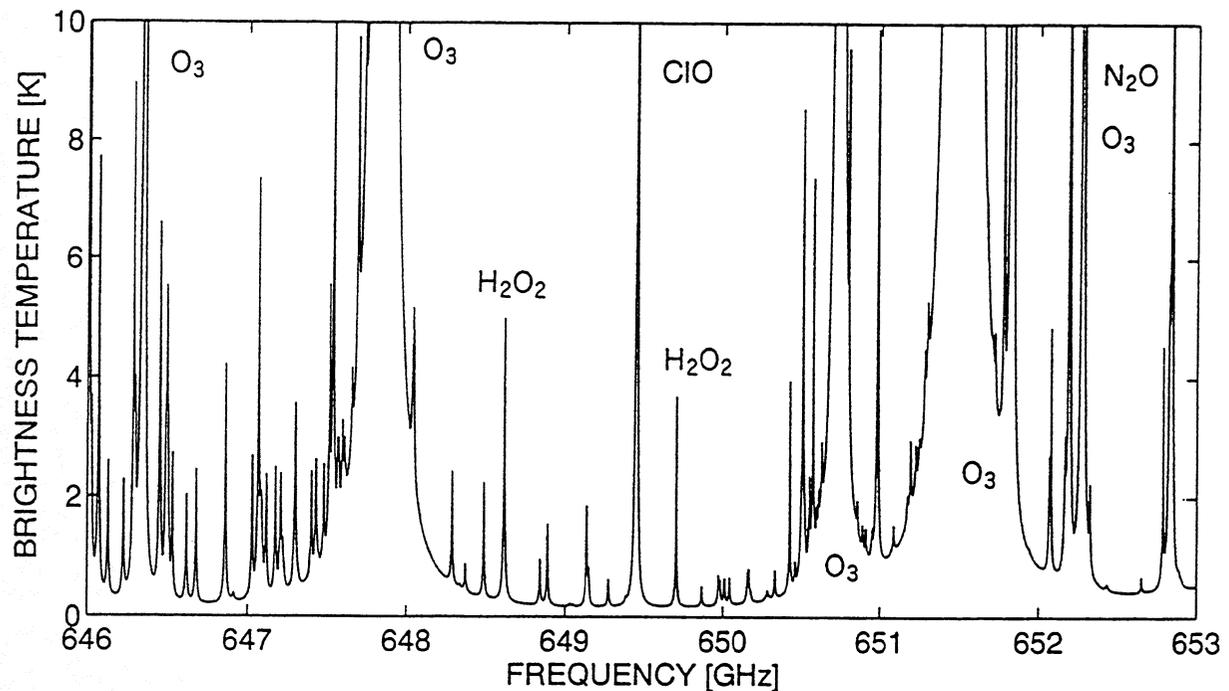


Figure 6. Calculated limb emission spectral profile for the upper side-band region of JEM/SMILES at the tangent height of 35km.

side-band region.

Figure 7 shows the block diagram of the JEM/SMILES system. The system is composed of an antenna sub-system, receiver optics, a phase-locked oscillator, a cryogenic sub-system, a 4K refrigerator, an IF sub-system, spectrometers, and a sub-system of signal processing and system control, in addition to JEM interface equipment and related sub-systems. Table 2 shows the performance required for JEM/SMILES.

The antenna has an elliptical feature with a long axis of nearly 60cm and a short axis of nearly 30cm. The beam width in the vertical direction is designed to be less than 0.06 degrees, by which a height resolution of nearly 2 km can be obtained. An offset Cassegrain type is proposed. The surface accuracy of the antenna is designed to be 9 μm , in order to obtain a high beam efficiency larger than 90%. A thin membrane will be attached in front of the antenna to prevent thermal distortion caused by direct illumination of sunlight. The antenna beam is tilted 45 degrees to the right-hand side, in order that JEM/SMILES can observe the areas with a longitude up to nearly 65 degrees north. The antenna can be moved nearly from -10 to -25 degrees in the elevation direction to mainly compensate for the attitude change in pitch direction. The attitude drift is expected to be very slow. In order to observe the tangent height from 10 to 60km, the antenna is scanned at every 0.05 degrees step in the elevation range of 1.27 degrees. A star sensor will be used for obtaining the precise pointing information. Real-time pointing control is not used in the system.

The quasi-optical transmission system includes reference, calibration, and local signal

Table 2. Performance of JEM/SMILES

Frequency	640 GHz-Band (624-653 GHz)
IF	10-14 GHz
IF Band-width	Around 4 GHz
System Noise Temperature	Less than 400 K
Integration Time	0.25 seconds
Dynamic Range	10 - 300 K
Spectral Resolution	1 MHz
System Sensitivity	0.8 K
Total Spectral Band-width	2,400 MHz or wider
Observing Species	O ₃ , O ¹⁸ O, ClO, HCl, BrO, H ₂ ¹⁸ O, etc.
Expected Observation Accuracy	3 % for O ₃ , Temperature/Pressure, H ₂ O 10 % for ClO, HCl, BrO
Data Compression	Band-width Compression by Frequency Synthesis
Quantization	12 bits
Data Rate	150 kbps
Antenna Aperture	0.6 m (vertical) by 0.3 m (horizontal)
Antenna Beam-width	0.055 deg., (elevation) by 0.11 deg. (azimuth)
Height Resolution	2 km
Antenna Scan Range	-10 to -25 deg. in elevation direction only
Observation Height Range	10 - 60 km
Antenna Scan Range for Observation	1.27 deg.
Antenna Scan Step	0.05 deg.
Observation Direction	45 deg. tilted to the right-hand side
Observation Latitudes	65 deg. North - 38 deg. South
Antenna Surface Accuracy	9 μm
Antenna Efficiency	90 % or more
Attitude Precision	Less than 0.05 deg. (Pitch/Roll), 0.1 deg. (Yaw)
Mission Life	1 year
Power	450 W
Mission Weight	224 kg or less
Size	0.8 m (W) by 1 m (H) by 1.85 m (L)

injection. A combination of a Martin-Puplett interferometer (MPI) and a wire-grid polarizer will be used for separate detection of both the lower side-band and the upper side-band signals. The local signal is produced by multiplying 6 times the signal of a phase-locked Gunn oscillator operated at 106.3GHz. The local signal is simply coupled by a thin dielectric film with an efficiency of 5%. A vibrating mirror will be adopted for smoothing standing ripples.

The advantages of the use of SIS mixers is that they are to be able to obtain ultra-low noise temperature and low conversion loss under low local power conditions. A noise temperature of lower than 200K and a conversion loss of less than 5 dB are required for JEM/SMILES. The parallel-connected-twin-junctions (PCTJ) type Nb-AlO_x-Nb SIS mixers developed in National Astronomy Observatory, Nobeyama Radio Observatory (NAO/NRO) (Noguchi, et al., 1995) will be used for obtaining ultra-high sensitivity in a wide frequency range under nontuning conditions for space use. The required operation bandwidth is nearly 30GHz, i.e. nearly 5% of the operating frequency. The SIS mixers are used in the waveguide-mount conditions. In addition, to achieve ultra-low noise receivers, we must develop high IF amplifiers (HEMT) operated under cooled conditions with low noise, wide bandwidth, and low power for space use.

The operation conditions of the SIS mixers and the HEMT amplifiers are achieved by a compact-sized low-weight 4K-refrigerator and cryostat system. The 4K-refrigerator is composed of a Joule-Thomson refrigerator combined with a two-stage Stirling refrigerator. The design goal of the cooling capacities is nearly 1.5W for the first stage of 100K, 200mW for the second stage of 20K, and 30mW for the third stage of 4.5K. The total power and weight of the refrigerator will be nearly 250W and 60kg, respectively. The main body of the cryostat is designed to be about 500mm long and to have a diameter of 350mm. The cryostat needs a structure to cut thermal radiation from the outside through the windows, which is one of the largest heat loads for the first stage. Another important issue for the space-qualified cryostat is the mechanical structures to prevent the refrigerators and cooling stages from vibration and launch shock. We have already succeeded in demonstrating the operation of a sub-millimeter wave mixer mounted in the thermal structure model of the cryostat by using a prototype model of the 4K-refrigerator in laboratory level, in collaboration with Sumitomo Heavy Industries, Ltd. (SHI) (Inatani, et al., this issue).

For the effective use of the bandwidths of the spectrometers mentioned below, band compression will be made in the IF sub-system. The frequency bands of each species are divided from the output signals of the HEMT amplifiers, and are synthesized after down-conversion to produce the second IF signals supplied to the spectrometers.

Wide bandwidth, high spectral resolution, and low power are required for the spectrometers to be used for SMILES. A candidate for the spectrometer is an acousto-optical spectrometers (AOS) with a bandwidth of larger than 1.2 GHz and a spectral resolution of about 1 MHz. We are planning to use the 2 AOSs for the JEM/SMILES system.

The acquired data will be transmitted via satellite link prepared on the JEM. The data rate is estimated to be less than 150kbps.

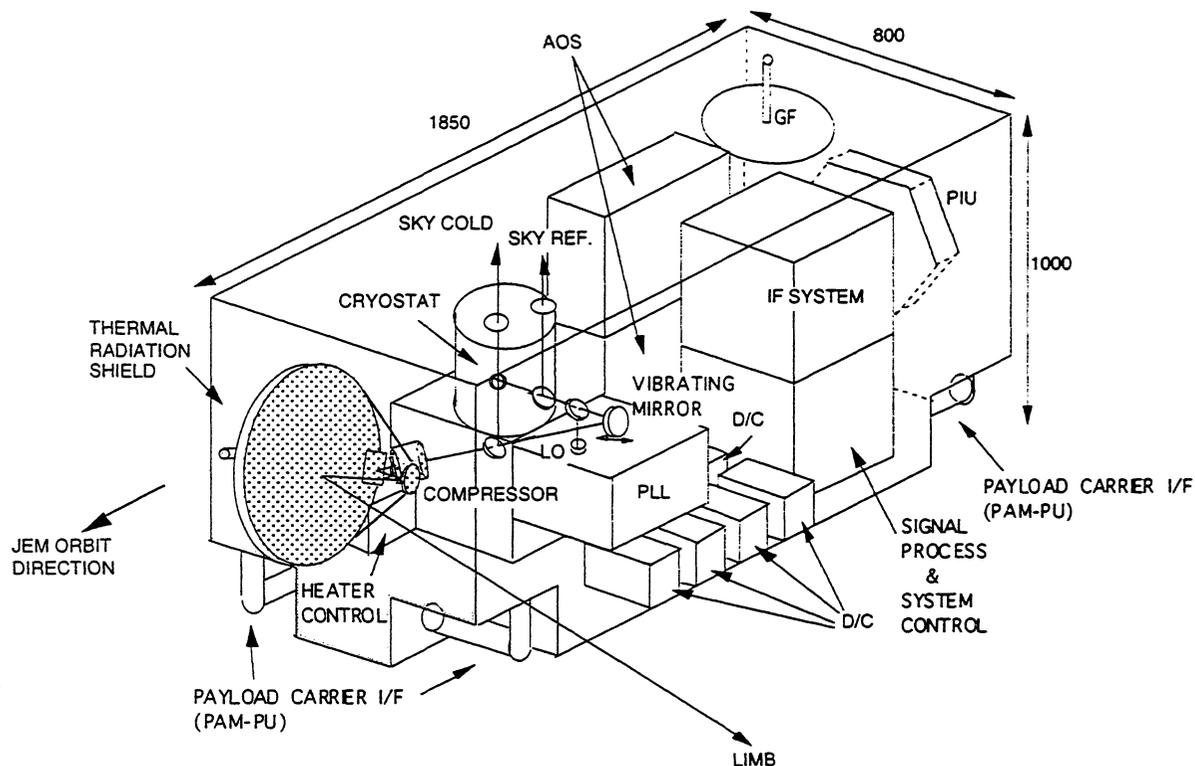


Figure 8. Overview of JEM/SMILES.

The estimated total power and mission weight are 450 W and 224 kg, respectively. The regular size of the JEM/EF experimental unit is 0.8 m (W) by 1.0 m (H) by 1.85 m (L). Figure 8 shows an overview of JEM/SMILES.

4. SCHEDULE AND PLANS

Figure 9 shows the schedule of the JEM/SMILES experiment. According to the present conditions, JEM/SMILES will be launched in 2003 by an H-IIA transportational vehicle (HTV) from the launch site in the Tanegashima-island, Japan. One year of the experiment in space is scheduled. The development period is short, i.e., about 5 years including many kinds of tests for space use. In order to shorten the development period and to decrease the cost, the engineering flight model modified from the engineering model will be launched.

The development of JEM/SMILES will be made under the collaboration of Communications Research Laboratory (CRL), National Astronomical Observatory (NAO), and National Space Development Agency (NASDA) of Japan. CRL and Nobeyama Radio Observatory (NRO) of NAO are responsible for the development of the sub-millimeter wave SIS mixers, the cryostat, and related sections. NASDA is in charge of the development of the antenna sub-system, the 4K-refrigerator, the IF sub-system, etc., together with the construction and the tests of the whole system.

The data processing and distribution are made by NASDA. CRL supports the processing

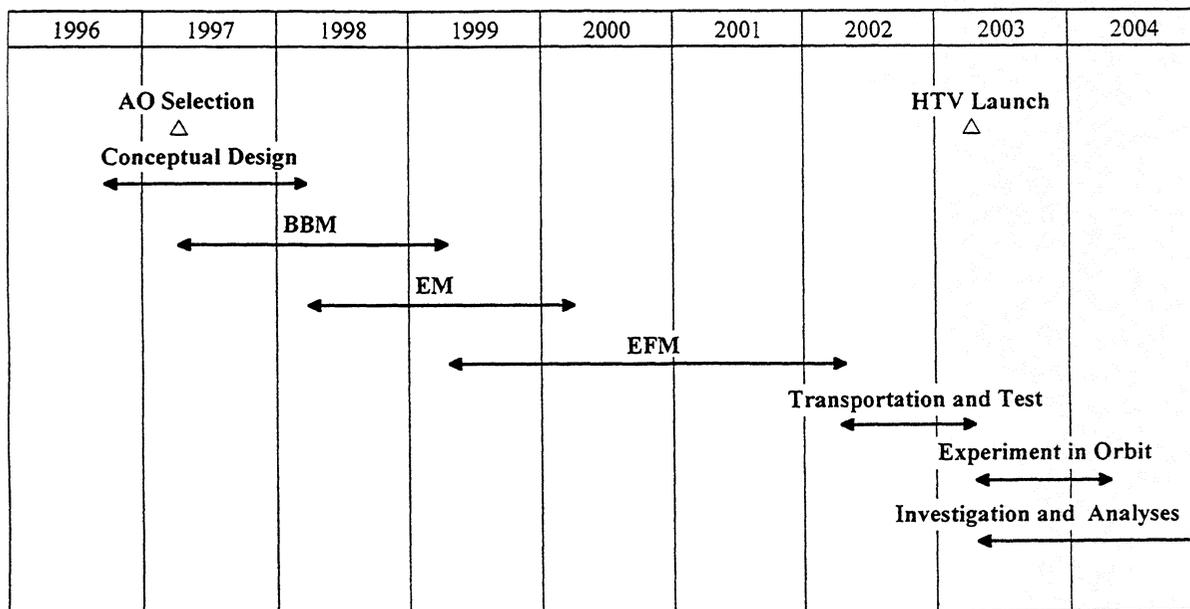


Figure 9. Schedule of the JEM/SMILES experiment.

of the higher level products. A scientist group supported by NASDA and CRL are responsible for the algorithm development and the scientific investigations of the JEM/SMILES experiment including the calibration and validation studies. A research announcement (RA) for the data applications will be issued in near future. The data will be distributed via Internet or an FTP site.

5. SUMMARY

A space-borne limb emission sounder system can globally observe the 3-dimensional distributions of trace gases for the understanding of Ozone Depletion and Climate Change. Communications Research Laboratory (CRL), National Astronomical Observatory (NAO), and National Space Development Agency (NASDA) of Japan are planning to make an experiment for a Superconducting Sub-millimeter Wave Limb Emission Sounder (SMILES) on the Japanese Experimental Module (JEM) of the Space Station to be launched in 2003.

JEM/SMILES will be operated at 640 GHz-band with 10-14 GHz IF frequencies. The PCTJ-type SIS mixers developed in NAO/NRO will be used for the ultra-high sensitive receiver. The operation conditions for the SIS mixers will be achieved by a compact Joule-Thomson refrigerator combined with a two-stage Stirling refrigerators. We are aiming to demonstrate the effectiveness of sub-millimeter wave limb emission spectrometry for observing atmospheric environment from space, to apply superconducting in space, and to operate a mechanical 4K-refrigerator in space. The JEM/SMILES is a pre-phase of SMILES on an atmospheric environment observing satellite, ATMOS-C1, which is planned to be launched around 2006 (ATMOS-C1 Team, 1996).

In addition, extended use of the engineering results of JEM/SMILES can be expected in

wide areas of other fields, such as biological and medical applications, material science and technology, astronomy, and many kinds of precise measurements in space.

In achieving the JEM/SMILES experiment, we are expecting various collaborations with and support from both the scientific and engineering areas in the world.

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