

## INSTRUMENT OVERVIEW AND OPERATION OF JEM/SMILES

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### Commission VIII, JAXA Special Session

**KEYWORDS:** Atmospheric chemistry, submillimeter-wave, limb sounding, mechanical cryocooler, superconductive mixer, international space station

### ABSTRACT:

The Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES), which was developed jointly by JAXA and NICT, has been successfully launched and attached to the Japanese Experiment Module (JEM) on the International Space Station (ISS). It has been doing observations in the Earth's atmosphere since October 12, 2009 with the aid of 4-K mechanical cooler and superconductive mixer for the submillimeter limb-emission sounding.

The high sensitivity measurement on weak submillimeter waves emitted from minor species can be performed on the basis of a receiver using superconductor-insulator-superconductor (SIS) mixers under the cryogenic conditions that can be achieved by a compact mechanical cooler down to 4.5 K. The cryostat with a Joule-Thomson circuit and a two-stage Stirling refrigerator has been developed and equipped for the atmospheric observation for the first time from space.

## 1. INTRODUCTION

### 1.1 Mission Objectives

The Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES), which was designed to be aboard the Japanese Experiment Module (JEM) on the International Space Station (ISS), measures submillimeter wave radiated from molecules of minor constituents in Earth's atmosphere.

The two major objectives of this mission are:

- (1) Demonstration of superconductive mixer and 4-K mechanical cooler for the submillimeter limb-emission sounding in space
- (2) Observation on atmospheric minor constituents in the middle atmosphere

The former is a target from an aspect of engineering, while the latter is of atmospheric science.

### 1.2 Scientific Target

The main scientific objective of the SMILES mission is to study the recovery and stability of the stratospheric ozone layer. According to model calculations, the recovery of the ozone layer to pre-1980 levels will be around the middle of the 21st century. However, there are still considerable uncertainties, such as bromine budget, inorganic chlorine chemistry, and stratospheric cooling related with increases in greenhouse gases. SMILES will contribute to clarify these uncertainties, with providing useful information, such as ClO and HCl for chlorine chemistry, for bromine budget, and so on.

### 1.3 Mission Operation Overview

SMILES was carried with HTV-1 (HTV: H-II Transfer Vehicle) and launched by Japanese H-IIB launch vehicle. After docking of HTV-1 to the ISS, some initial engineering tests of HTV-1 as

a spacecraft were done, then SMILES was attached to the 3rd port of the Exposed Facility Unit (EFU) of JEM, using the Remote Manipulator System (Robotic Arm).

Soon after the attachment, SMILES was powered on, then several kinds of the initial checkout followed, including health check of all subsystems, such as a cryocooler, star trackers, antenna driving mechanism, superconductor-insulator-superconductor (SIS) mixers, and data communication. After completion of checkout, SMILES has been performing atmospheric observations all the time except for restrictions due to the ISS operation condition.

## 2. INSTRUMENTS

Figure 1 shows the block diagram of SMILES instrument. This hardware can be classified into four main subsystems, which are ANT, SRX, IFA and AOS. General design specification of the instrument is listed in Table 1. The following is the brief description of each component. Their details can be found in SMILES Mission Plan (SMILES Mission Team, 2002).

### 2.1 Submillimeter Antenna (ANT)

An offset-Cassegrain type antenna with an elliptical primary reflector, whose major and minor axes are 40 cm (elevation) and 20 cm (azimuth) in diameter, was equipped. It gives an instantaneous field of view (IFOV) of 0.09° (~3 km) in elevation.

### 2.2 Submillimeter Receiver (SRX)

A superconducting low-noise receiver is one of key instruments of SMILES system. It will reduce receiver noise by a factor of 20 in comparison with the conventional semiconductor diode-mixer receiver, with SIS mixers associated with cryogenically cooled HEMT amplifiers. The two SIS mixers, which are

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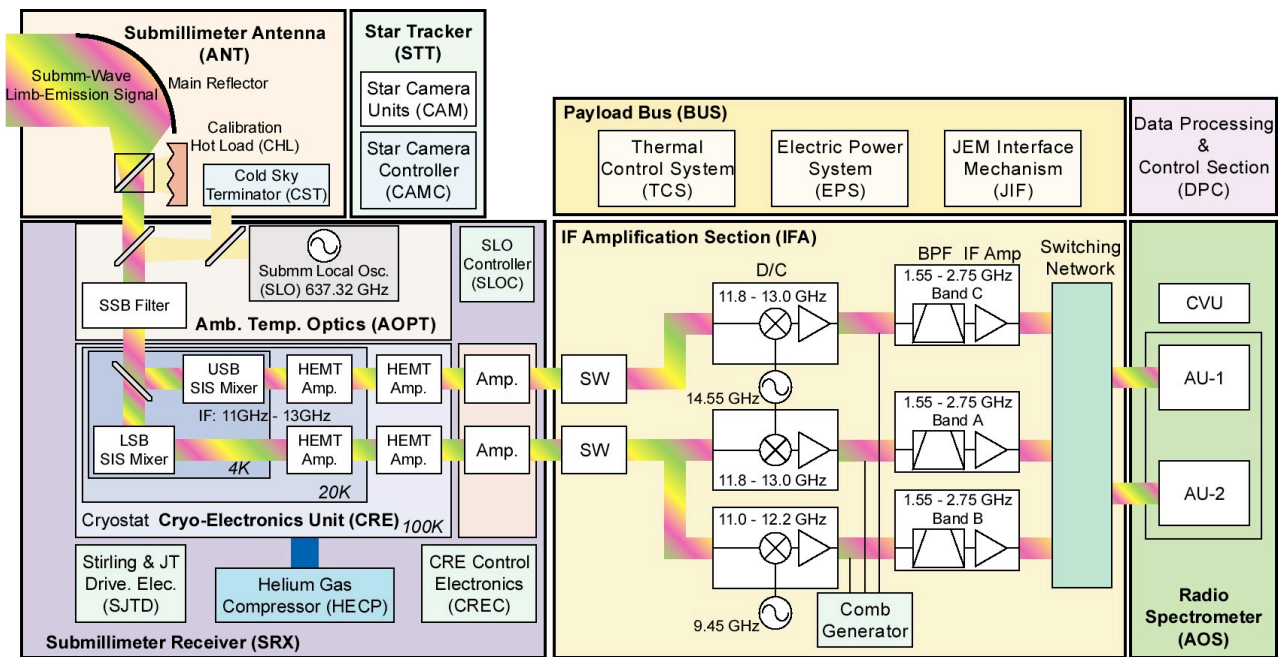


Figure 1. Block diagram of SMILES instrument.

pumped by a single submillimeter local oscillator, receive 640-GHz submillimeter signal, and convert frequency down to 11 – 13 GHz 1st intermediate-frequency (IF) signal.

### 2.3 Intermediate-Frequency Amplification Section (IFA)

This subsystem has functions of frequency down conversion from the 1st IF into 2nd IF (1.55 – 2.75 GHz) and of amplification of signal which is transmitted from SRX to AOS. SMILES is equipped with the three detection bands (See Table 1), each of which has limited width of approximately 1.2 GHz according to the instrument specification. On the other hand, there are two AOS units in the instrument, so SMILES makes simultaneous observations only for two bands among three. So IFA has switching network to control signal flow into AOS units. It has also functions of adjusting the output power level and of generating reference signals (a comb generator) for calibrating frequency drift of AOS.

### 2.4 Radio Spectrometer (AOS)

AOS has two analyzer units (AU1 and AU2), which are employed to transform the 2nd IF signals into their frequency spectra. Each spectrometer unit has frequency coverage of 2nd IF detected by 1728-channel CCD array with a resolution of 1.8MHz FWHM. The two units operate independently.

### 2.5 4-K Mechanical Cooler

The 4-K class mechanical cooler is a key component of SMILES. It is a combined system of a two-stage Stirling cooler and Joule-Thomson circuit to cool SIS mixers and associated optics. With this cooler, the SIS mixers are cooled down to around 4.5K. All the cooled components are contained in a cryostat which is thermally isolated from the ambient temperatures. The coolers are continuously operated with pressurized helium gas supplied by compressors.

### 2.6 Star Tracker (STT)

Two STT cameras are used to determine the real-time attitude of SMILES, because of the attitude of JEM and ISS is very unstable according to various factors. Each camera works unless the sun comes within an angular distance of 30°. STT determines the attitude of the mainframe structure of the instrument from camera image, with respect to the stellar inertia coordinate. The tangent point of SMILES beam is calculated from SMILES attitude with respect to the coordinate fixed to the earth.

Frequency coverage	Band A (624.32 – 625.52 GHz) Band B (625.12 – 626.32 GHz) Band C (649.12 – 650.32 GHz)
Freq. sampling	0.8 MHz
Freq. resolution	1.8 MHz (FWHM)
System noise temp.	< 500 K
Integration time	0.5 s for each obs. tangent point
Noise level in brightness temp.	< 0.7 K
Calibration accuracy	< 1.0 K
Obs. cycle	53 s
Obs. alt. range	10 - 60 km ( <i>nominal</i> )
Vertical sampling	~2 km ( <i>nominal</i> )
Instrumental height resolution	3.5 - 4.1 km ( <i>nominal</i> )
Global coverage	38°S - 65°N ( <i>nominal</i> )
Obs. azimuth angle	-10 – 95 degree (0=north)

Table 1. Design specification of SMILES instrument.

### 3. OPERATION

#### 3.1 Operation of SMILES On-Orbit Observation

The ANT is scanned in elevation at a period of 53 seconds, of which the first 29.5 seconds is allocated to limb atmospheric measurements to cover a tangent-height range of 10 to 60 km. The measurement is followed by 4 seconds of cold calibration, 1 second of frequency calibration, and 4 seconds of hot calibration. Cold calibration is done by directing the main reflector to a reference sky (at higher than 160km), and hot calibration is done by inserting a calibration hot load into the antenna optics with a switching mirror.

Since the ISS is on a circular orbit with an inclination of  $51.6^\circ$  to the equator, the highest latitude which the ISS reach is  $52^\circ$  in north and south. In order to extend the latitudinal coverage toward the northern polar region, FOV of SMILES ANT is deflected  $45^\circ$  at the left hand of ISS flight direction. Thanks to this alignment, SMILES limb-sounding observation provides a latitudinal coverage  $65^\circ\text{N}$  to  $38^\circ\text{S}$  on each orbit.

SMILES makes about 100-point measurements along single orbit, and the total number of observation in one day is about 1600. However, various restrictions from JEM and ISS operation, such as intersection of the solar array paddles, often reduce the actual number of observation points.

#### 3.2 Observation Band Selection

According to the restriction coming from instrument design mentioned above, IFA signals from only two among three detection bands are introduced to AOS to retrieve submillimeter wave spectra. There are 4 settings of the switching network as follows:

- (1) Setting 1: Band B (AU2) and C (AU1)
- (2) Setting 2: Band A (AU2) and C (AU1)
- (3) Setting 3: Band B (AU2) and A (AU1)
- (4) Setting 4: Band C (AU2)

It should be noted that Band A will be measured both with AU1 (in Setting 3) and AU2 (in Setting 2), so the difference of characteristic of AU1 and AU2 should be considered in analyzing the higher product. The same consideration is necessary with Band C, if Setting 4 is used, which is not selected in normal observation mode.

#### 3.3 Results of Initial Check-Out

As a first hurdle of initial check-out, operation of the mechanical cooler is one of the major concerns. Although it took longer time to reach the 4-K stage to specified temperature than the cooling time at ground test, the stage finally cooled down to 4.15K within 80 hours since the power-on of the cryocooler. Figure 2 shows cooling profile of each temperature stage with time.

The reason why it took much time to cool down than the estimation is presumed to be depletion of flow rate of refrigerant inside the cryostat. There are several possible causes of the flow rate depletion.

However, time length for cooling down to target temperature is not the essential problem, comparing the finally attained temperature. In the supposed operation, since the cryostat would not be shut down once it started to operate, it would never be restarted except in the emergency situations. The above mentioned problem is supposed to be not fatal to the whole operation.

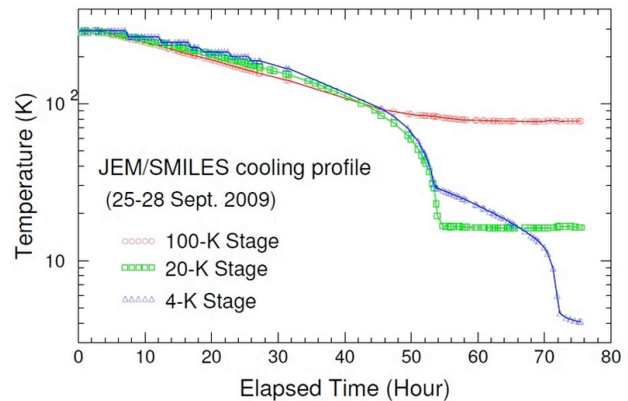


Figure 2. Cooling profile of the cryocooler during initial-check phase.

In order to validate the total performance of the instrument, system noise temperature was calculated for each frequency channel. The average is slightly lower than 400K, which is substantially lower than specification value ( $< 700\text{K}$ ). This value is one order of magnitude smaller than the most sensitive instrument among existing spaceborne sensors (Lee, 2005).

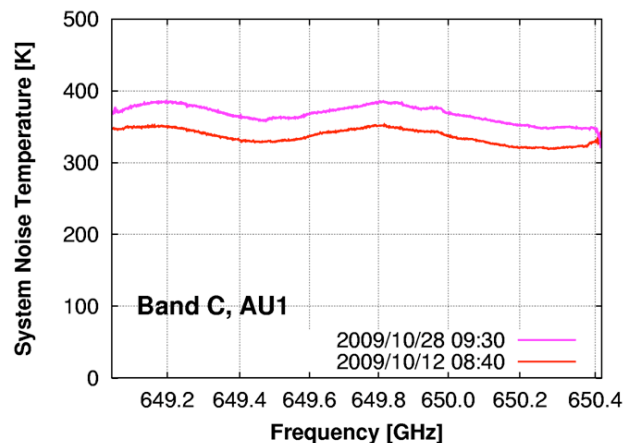
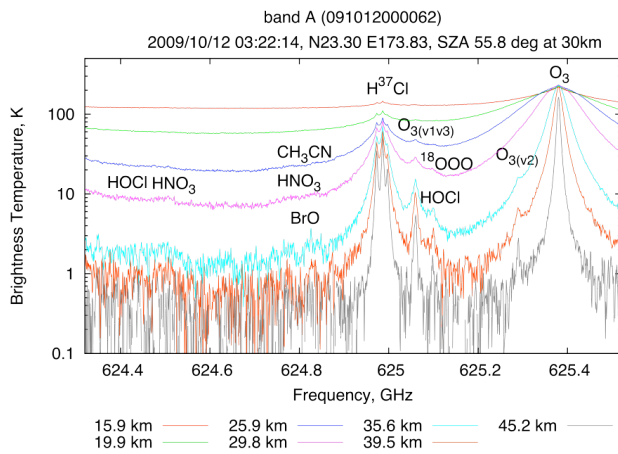


Figure 3. System noise temperature calculated for each frequency channel of submillimeter-wave measurement.

#### 3.4 Results of Submillimeter-Wave Limb Sounding

Figure 4 shows an example of the spectra of the brightness temperature in Band A for several tangent altitudes obtained in the first-light observation after launch. Band A includes strong ozone and  $\text{H}^{37}\text{Cl}$  lines with other minor peaks of  $\text{HOCl}$ ,  $\text{HNO}_3$ ,  $\text{BrO}$  and ozone isotopes. The noise level of the brightness temperature is found to be lower than its specification. Spectral undulations due to standing waves recognized in the measured spectra were less than the noise level. The spectral frequencies agree with line parameter database within 100 kHz precision after a Doppler correction taking the ISS motion and the Earth's rotation into account. At first glance, short- and long-term calibration stabilities seem to be fairly good (Kikuchi et al., 2010).



**Figure 4. Observed spectra at several altitudes for Band A. Measurements were done on October 12, 2009 at 23.30°N and 173.83°E; latitude-longitude information is defined at altitude of 30 km along the scan.**

### 3.5 Regular Operation

In the initial checkout phase, all test items defined in the checkout plan has been done. According to good evaluation result for each test item, it was confirmed that SMILES instrument satisfied the requirements defined in the development specification. This was followed by the judgment that the initial checkout has been completed without any major problems. As a result, SMILES operation moved into the regular operation phase on November 6, 2009.

In the regular operation, the observation band selection is switched daily in accordance with the schedule shown in Table 2 on a week-to-week basis. However, the observation may be done without this rule, in case of under restriction from ISS operation etc.

Day	Setting	Band
1 (Sunday)	1	B / C
2 (Monday)	2	A / C
3 (Tuesday)	1	B / C
4 (Wednesday)	3	A / B
5 (Thursday)	2	A / C
6 (Friday)	1	B / C
7 (Saturday)	2	A / C

**Table 2. Weekly schedule of switching of observation band selection.**

## 4. SUMMARY

SMILES was successfully launched and started atmospheric observations, and has been functioning very well so far. In-orbit performances of JEM/SMILES instruments were verified in initial checkout phase. All subsystems satisfied their specifications.

Thanks to use of a 4-K mechanical cooler and superconductive mixers for the submillimeter wave range, SMILES has been doing limb-emission sounding measurement to get extremely low-noise spectra. Now it is in the regular operation phase and has been performing global observations, with whose data we were able to obtain some preliminary results. The outcomes from the observation will demonstrate its high potential abilities to observe the minor constituents in the middle atmosphere.

**Note:** At the time of writing, SMILES observation has been suspended since late April of 2010, due to the failure of a submillimeter-wave component in the receiver subsystem.

## ACKNOWLEDGEMENTS

We thank H. Masuko of NICT establishing an early stage of the SMILES mission. We also thank J. Inatani and T. Noguchi of National Astronomical Observatory of Japan for developing the core of the SMILES instrument.

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