Spaceborne superconducting sounder (SMILES-2) for upper-atmosphere observation

Satoshi Ochiai[1,*], Philippe Baron[1], Yoshinori Uzawa[1], Yoshihisa Irimajiri[1], Toshiyuki Nishibori[2], Makoto Suzuki[2], Takeshi Manabe[3], Hiroyuki Maezawa[3], Akira Mizuno[4], Tomoo Nagahama[4], and Masato Shiotani[5]
[1]*National Institute of Information and Communications Technology, Koganei, Tokyo 184-8795, Japan*
[2]*Japan Aerospace Exploration Agency, Tsukuba, Ibaraki 305-8505, Japan*
[3]*Osaka Prefecture University, Sakai, Osaka 599-8531, Japan*
[4]*Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Aichi 464-8601, Japan*
[5]*Research Institute for Sustainable Humanosphere, Kyoto University, Uji, Kyoto 611-0011, Japan*
*Contact: ochiai@nict.go.jp

***Abstract*—The Superconducting Submillimeter-Wave Limb-Emission Sounder 2 (SMILES-2) is a proposed satellite mission for the comprehensive observation of Earth's atmosphere with superconducting receivers. The SMILES-2 mission will have four SIS/HEB receivers with bands near 487, 527 GHz, 557, 576 GHz, 623, 653 GHz, and 1.8, 2 THz to observe spectral lines of atomic oxygen, OH, O_3, O_2, H_2O, CO, NO, NO_2, N_2O, ClO, HCl, and BrO. The atmospheric limb will be scanned in an altitude range from 20 km to more than 160 km in a minute or shorter time. The low-noise superconducting receivers will provide highly qualified limb spectra of a variety of atmospheric species, from which we can retrieve temperature and wind over the whole altitude range encompassing the stratosphere, mesosphere, and lower thermosphere. The global temperature and wind profiles of the whole atmosphere measured by a single instrument will be the most scientifically useful data for studying the lower and upper atmosphere coupling. The wind precision of SMILES-2 measurement is estimated to be better than 3 m/s with an altitude resolution of 3 km in the upper stratosphere and mesosphere, and 10 m/s with an altitude resolution of 5 km in the lower thermosphere. We are now studying the feasible design of the mission to be boarded on a Japanese small satellite.**

Introduction

The millimeter- and submillimeter-wave limb-sounding technique has been used for more than 2 decades to measure Earth's atmosphere from space. It allows us to measure various chemical compositions in the stratosphere and mesosphere, as well as measuring temperature profiles with high altitude resolution and, as demonstrated recently, horizontal winds in a wide altitude range. The demand for temperature measurement in the stratosphere and mesosphere has recently been increasing, because the tops of atmospheric reanalysis models have been extended to the mesosphere, and the upper atmospheric measurements can be assimilated into models or compared with the model representations [1][2]. The unique feature of millimeter and submillimeter limb sounding is that it can provide temperature profiles in the upper atmosphere where microwave sounders on operational meteorological satellites cannot measure or can only measure with very low altitude resolution. Wind is the key parameter for describing atmospheric phenomena in the mesosphere and lower thermosphere. The measurement of the global distribution of wind will reveal the energy and momentum transports between the lower atmosphere and the thermosphere, which are induced by gravity and planetary waves (e.g., [3]). In the thermosphere, the neutral atmosphere, which can be measured by a submillimeter limb sounder, also interacts with ions and is affected by energetic particles coming from above. The observations of wind, atomic oxygen, and other components such as NO will contribute to the study of such couplings between the upper atmosphere and space.

The Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) was operated aboard the Japanese Experiment Module (JEM) of the International Space Station (ISS) during the period from October 2009 to April 2010 and successfully observed submillimeter limb emissions [4]. The SMILES receivers at 625 and 650 GHz use superconductor-insulator-superconductor (SIS) mixers cooled below 4.6 K by a mechanical cryocooler and showed a system noise temperature of 297 K (SSB) in orbit [5]. Because of the ISS non-sun-synchronous orbit, a diurnal variation of atmospheric compositions can be derived from a 1–2-month compilation of the SMILES observation. The SMILES measurement suggests that the diurnal variations of ozone cannot be neglected even in the stratosphere when interpreting and combining measurements taken at different local time [6]. Moreover, SMILES demonstrated the successful measurement of wind between 8 and 0.01 hPa (~35–80 km) [7].

We are proposing an upgraded version of SMILES, named SMILES-2. The main objectives of SMILES-2 are to measure temperature and wind in the stratosphere, mesosphere, and lower thermosphere, and to measure atomic oxygen, ozone, NO, and other molecules. In this paper, we give an overview of our SMILES-2 mission concept, the progress in technological development, and the status of our proposal to the Japan Aerospace Exploration Agency (JAXA).

Observation requirements for SMILES-2

The coverage of a wide measurement altitude range and high-precision measurement are the most important features of SMILES-2 to fulfill the scientific requirements defined by the SMILES-2 working group. The frequency bands, shown in Table I, are selected for optimizing the retrieval of temperature and wind in the entire altitude range from the stratosphere to the lower thermosphere. The retrieval of temperature and wind depends on strong emission lines in the observed bands. The cluster of ozone emission lines around 655 GHz is efficient in retrieving wind in the altitude range where the ozone signal is strong, i.e., in an altitude range of 40–70 km. In this range, wind can be measured with a precision better than 2 m/s and a vertical resolution of 3 km [8]. SMILES-2 will use the atomic oxygen line at 2.06 THz and can measure wind with a precision better than 10 m/s with a vertical resolution of 5 km in an altitude range between 110 and 160 km [8]. The O_2 line at 487.2 GHz and the H_2O line at 556.9 GHz will contribute to the temperature and wind measurements in an altitude range between 70 and 110 km. Figure 1 shows the estimated single-scan random errors of wind and temperature retrievals synthesized from the 4 frequency bands shown in Table I. The receiver noises are assumed to be 120, 135, 150, and 990 K for the SIS1, SIS2, SIS3, and HEB bands, respectively. The integration time and the tangent height step of the limb scanning are assumed to be 0.25 s and approximately 1.2 km, respectively. The estimated error does not include other errors, e.g., antenna pointing, intensity calibration, frequency, and model parameter errors.

The bands in Table I are also chosen so that the emission lines of the important molecules are included in these bands. The molecules to be observed include atomic oxygen, OH, O_3, O_2, H_2O, CO, NO, NO_2, N_2O, ClO, HCl, BrO, CH_3Cl, H_2CO, and isotopes of some of these molecules. A sensitivity study of the SMILES-2 observation of these molecules is described in [10]. Among these molecules to be observed, atomic oxygen is particularly important in knowing the energy budget of the mesosphere and lower thermosphere. Atomic oxygen in the ground electronic state has only two bright emissions at 2.06 and 4.74 THz. The 4.74 THz line has been measured from balloon, airplane, and spaceborne platforms. Because the 4.74 THz is optically thick in the limb-viewing geometry, it is difficult to retrieve the oxygen density below 130 km using this line with a low-sensitivity broadband detector from space [11]. An indirect measurement of atomic oxygen density in an altitude range of 65–105 km was reported with a larger uncertainty [12]. Recently, THz limb sounder projects, which will observe the oxygen line with heterodyne receivers, have been proposed [13][14]. The SMILES-2 mission will have a 2.06 THz receiver with better sensitivity than that of other projects. We estimate the measurement precision of atomic oxygen to be better than 30 % at an altitude above 100 km.

A non-sun-synchronous orbit with an orbit inclination of 66° and an altitude of about 550 km is expected for the SMILES-2 platform. With this orbit, the measurement local time at a given latitude shifts by 24 h during about 90 days. The highest latitude of the measurement will be up to 80° in one hemisphere and 50° in another hemisphere. To observe northern and southern polar regions, yaw maneuvering of the satellite will be needed because the SMILES-2 antenna sees the atmosphere in only one side of the satellite. The orbit will meet the scientific requirements of both diurnal variation measurement and polar region observation.

TABLE I
SMILES-2 BANDS

SIS1	LO=507 GHz	IF=18-22 GHz	O_2, H_2O, O_3, HO_2 BrO, NO_2
SIS2	LO=566.5 GHz	IF=8.5-10.5 GHz	H_2O, O_3 O_3, CO, ClO
SIS3	LO=638.15 GHz	IF=11.15-19.15 GHz	O_3, HCl, N_2O, BrO O_3, ClO, HO_2, NO
HEB	LO=1836.05 GHz and 2058.8 GHz	IF=1-2 GHz	OH atomic-O

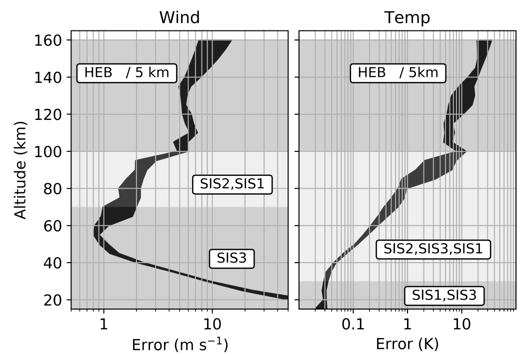

Fig. 1. Random error in wind (left) and temperature (right) retrievals [9]. The vertical retrieval resolution is 3 km below 100 km and 5 km above 100 km. The name of the band which contributes most to the retrieval in a certain altitude range, is indicated. The line thickness shows the range of error variation depending on the local time and latitude assumed in this error estimation.

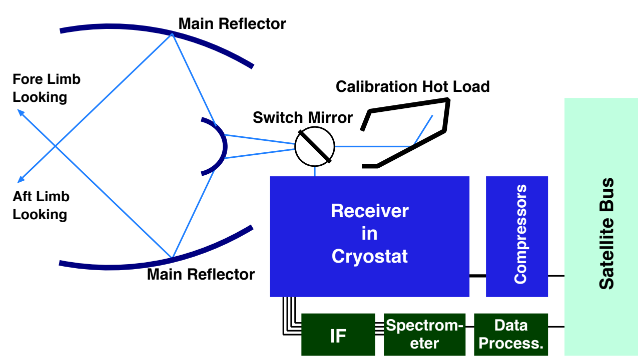

Fig. 2. SMILES-2 schematic block diagram

SMILES-2 PAYLOAD

The block diagram of the SMILES-2 payload is schematically shown in Fig. 2. The SMILES-2 payload is assumed to be aboard a small satellite equipped with a JAXA standardized bus system. The main instruments of the SMILES-2 payload are large twin antennas and a 4 K cooled superconducting receiver.

A. Antenna and limb scanning

Two offset Cassegrain-type antennas are used to see the atmospheric limb in the directions of 45° and 135° from the spacecraft velocity. The antennas are not steerable but can be pointed toward the atmospheric limb and scanned from the bottom of the atmosphere (below 20 km) to the upper atmosphere (above 200 km) by maneuvering the satellite attitude. The scene at the uppermost tangent height is used as a cold reference. During the gap between downward scanning and upward scanning, the receiver beam is switched toward the calibration hot load. The forward looking antenna is used during the upward scan, and backward looking antenna is used on the downward scan. Each scan takes 40–50 s so that one observation sequence is completed in about 100 s. By looking toward the 45° and 135° directions periodically in this way, the same atmospheric vertical column is observed from two perpendicular directions at an interval of 8 min, so that the horizontal wind vector can be derived. The side to observe with respect to the orbital plane, that is, the north side or the south side, depends on the direction of the sun in order to optimize the power generation by a solar array panel and radiation cooling of the instrument.

The main reflector has an aperture diameter of about 1 m. The vertical beam width at 487 GHz corresponds to a vertical resolution of 2 km at the tangent point. To make the large antenna lightweight, a carbon-fiber-reinforced plastic (CFRP) panel will be used for the antenna material. The mirror surface is formed with plasma-sprayed aluminum.

B. Receiver front end

The SMILES-2 mission has three SIS receivers and a hot electron bolometer (HEB) receiver. These are installed in a vacuum cryostat as schematically shown in Fig. 3. The atmospheric signal collected by the antenna is fed into the cryostat via a single window. The signal is split by a frequency-selective surface and a wire grid into the signals that are fed into the corrugated horns of SIS and HEB mixers Two or three SIS mixers share a wide-band corrugated horn. Each mixer is supplied with each local frequency signal via a stainless steel waveguide or a quasi-optical waveguide. Each local signal is generated with a multiplier chain. The local frequencies for SIS mixers are fixed as shown in Table I. The local frequency for the HEB mixer switches to either the frequencies for atomic oxygen of 2.06 THz or that for OH of around 1.8 THz, or occasionally to other frequency. All mixers work in double-sideband mode in order to obtain better precision in temperature and wind measurements by using emission lines in both sidebands for the retrieval.

One of the design images of integrated receiver components in a cryostat is shown in Fig. 4. The design of the cryostat and submillimeter optics is based on that of SMILES. Compared with SMILES, the number of mixers, including the HEB mixer, is doubled in SMILES-2. The diameter of the cryostat cylinder in Fig. 4 is also doubled in comparison with the SMILES cryostat. A much smaller cryostat than that shown in Fig. 4 is being designed by applying the technology of a waveguide multiplexer [15]. The development of the HEB mixer is also ongoing in Japan (e.g., [16]).

C. Cooling system

The SIS and HEB mixers are cooled below 4.8 K with a He closed-cycle mechanical cooler. The 4 K cooler consists of

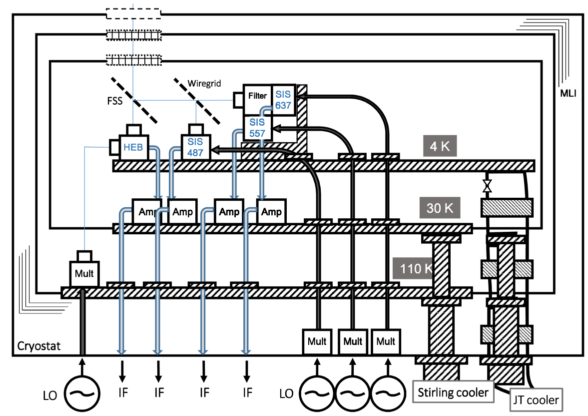

Fig. 3. Block diagram of the SMILES-2 receivers installed in a cryocooler

Fig. 4. CAD image of the SMILES-2 cryoreceiver

a Joule–Thomson (JT) cycle cooler and a two-stage Stirling cooler as a precooler. The 4 K cooler by Sumitomo Heavy Industries, Ltd. (SHI) has been successfully demonstrated in space by SMILES and a Japanese X-ray astronomy satellite ASTRO-H [17]. The JT cooler of SMILES unfortunately stopped after 9 months of operation in space. It was speculated that the cause of the failure is that the He closed cycle was clogged with solidified CO_2 contamination. After the investigation of the SMILES cooler failure, the JT cooler was improved. The JT cooler used in ASTRO-H has a longer lifetime compressor and a getter to trap impurity molecules in the He closed cycle. A ground test of the improved JT cooler has demonstrated a lifetime of more than 3 years [17].

The SHI JT cooler has a cooling capacity of 40 mW at 4.5 K. When the JT cooler is used with a large heat load, large cooling capacities are required for the precooler at the 100 and 20 K stages. In the case of the cryostat shown in Fig. 4, the heat load at the 4 K stage is estimated to be more than 30 mW, so two two-stage Stirling coolers are required for precooling the JT cooler and for cooling the thermal shields on the 100 and 20 K stages. SMILES was able to operate with one two-stage Stirling cooler because its 4 K heat load was about 10 mW and less cooling capacity was required for cooling the 100 K shield, which had a comparatively small surface area. The input power to the SMILES-2 cooling system including the driver electronics for the cooler is estimated to be about 410 W, while that of SMILES cooling system was less than 300 W. The total mass of the receiver front end, cryostat, and cooling system including the driver electronics is estimated to be around 105 kg.

Targeted opportunity to launch

JAXA has a small satellite program with the plan to launch a scientific small satellite via the Epsilon rocket every two years. We will propose SMILES-2 as a mission to be launched in 2023 or 2025. A JAXA small satellite can afford to carry a mission instrument with a weight of 200 kg or more. The total weight of the SMILES-2 mission will meet this requirement. A standard bus of a JAXA small satellite supplies power of only 300 W on average, which may not be sufficient for the SMILES-2 coolers. Studying the possibilities of power system modification on the bus and reduction in the power consumption by the cooling system is ongoing. The proposal of the SMILES-2 mission will be prepared before March 2018 with a solution to the power problem.

Conclusions

The SMILES-2 mission aims to contribute to a broad range of atmospheric studies in the stratosphere, mesosphere, and lower thermosphere by providing observations of the atmospheric parameters over an altitude range between 20 and 160 km and a latitude range between 80S and 80N. SMILES-2 will provide new products, such as a horizontal wind vector in an altitude range between 30 and 160 km and the concentration profile of ground-state atomic oxygen, using SIS/HEB receivers from 487 GHz to 2.06 THz. The SMILES-2 receiver will take over the spaceborne superconducting technology with a 4 K cooling system, which was successfully demonstrated by the SMILES mission. The lifetime of SMILES-2 is expected to be 3 years.

SMILES-2 is under pre-phase A stage at present. The SMILES-2 working group is preparing a mission proposal to be submitted to JAXA. The largest issue in the mission feasibility is whether the power consumption of the SMILES-2 cooling system is consistent with that of the small satellite.

Acknowledgment

The authors would like to acknowledge the SMILES-2 working group. The hardware development and feasibility studies are funded by the National Institute of Information and Communications Technology (NICT) and the Japan Aerospace Exploration Agency (JAXA). The cryostat design and the estimation of the cooling capacity were made by Sumitomo Heavy Industries. Ltd. (SHI).

References

[1] R. Gelaro, *et al.,* "The Modern-Era Retrospective Analysis for Research and Applications," *J. Climate*, **30**, 5419–5454, 2017, doi:10.1175/JCLI-D-16-0758.1.

[2] Y. Harada, *et al.,* "The JRA-55 Reanalysis: Representation of Atmospheric Circulation and Climate Variability," *J. Meteor. Soc. Japan*, **94**, 3, 269–302, 2016, doi:10.2151/jmsj.2016-015.

[3] Y. Miyoshi, *et al.,* "A global view of gravity waves in the thermosphere simulated by a general circulation model," *J. Geophys. Res. Space Physics*, **119**, 5807–5820, 2014, doi:10.1002/2014JA019848.

[4] K. Kikuchi, *et al.,* "Overview and early results of the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES)," *J. Geophys. Res.*, **115**, D23306, 2010, doi:10.1029/2010JD014379.

[5] S. Ochiai, *et al.,* "Receiver Performance of the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) on the International Space Station," *IEEE Trans. Geosci. Remote Sensing*, **51**, 7, 2013, doi:10.1109/TGRS.2012.2227758.

[6] T. Sakazaki, *et al.,* "Diurnal ozone variations in the stratosphere revealed in observations from the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) on board the International Space Station (ISS)," *J. Geophys. Res. Atmos.*, **118**, 2991–3006, 2013, doi:10.1002/jgrd.50220.

[7] P. Baron, *et al.,* "Observation of horizontal winds in the middle-atmosphere between 30S and 55N during the northern winter 2009–2010," *Atmospheric Chemistry and Physics*, **13**, 13, 6049, 2013, doi:10.5194/acp-13-6049-2013.

[8] P. Baron, *et al.,* "Measurement of stratospheric and mesospheric winds with a submillimeter wave limb sounder: results from JEM/SMILES and simulation study for SMILES-2," *Proc. SPIE 9639, Sensors, Systems, and Next-Generation Satellites XIX*, 96390N, 2015, doi:10.1117/12.2194741.

[9] S. Ochiai, *et al.,* "SMILES-2 mission for temperature, wind, and composition in the whole atmosphere," submitted for publication.

[10] M. Suzuki, *et al.,* "Sensitivity study of smiles-2 for chemical species," *Proc. SPIE 9639, Sensors, Systems, and Next-Generation Satellites XIX*, 96390M-15, 2015, doi:10.1117/12.2194832.

[11] K. U. Grossmann, *et al.,* "A global measurement of lower thermosphere atomic oxygen densities," *Geophis. Res. Lett.*, **27**, 9, 1387–1390, 2000.

[12] M. G. Mlynczak, *et al.,* "Atomic oxygen in the mesosphere and lower thermosphere derived from SABER: Algorithm theoretical basis and measurement uncertainty," *J. Geophys. Res.: Atmospheres*, **118**, 5724–5735, 2013, doi: 10.1002/jgrd.50401.

[13] S. P. Rea, *et al.,* "The Low-Cost Upper-Atmosphere Sounder (LOCUS)," *Proc. 26th Int. Symp. Space THz Technol.*, M1-3, 2015.

[14] D. L. Wu, *et al.,* "THz limb sounder (TLS) for lower thermospheric wind, oxygen density, and temperature," *J. Geophys. Res. Space Physics*, **121**, 7301–7315, 2016, doi:10.1002/2015JA022314.

[15] T. Kojima, *et al.,* "Design and Development of a Hybrid-Coupled Waveguide Multiplexer for a Multiband Receiver," *IEEE Trans. RHz Sci. Tech.*, **7**, 1, 10–19, 2017, doi:10.1109/TTHZ.2016.2627220.

[16] Y. Irimajiri, *et al.,* "Development of a Superconducting Low-Noise 3.1-THz Hot Electron Bolometer Receiver," *IEEE Trans. THz Sci. Tech.*, **5**, 6, 1154–1159, 2015.

[17] K. Narasaki, *et al.,* "Lifetime Test and Heritage On-Orbit of SHI Coolers for Space Use," *Cryocoolers* **19**, 613–622, 2016.